



UNIVERSITY of  
RWANDA

COLLEGE OF SCIENCE AND TECHNOLOGY

School of Architecture and Built Environment. Master of Science in Geo-Information Sciences  
for Environment and Sustainable Development

(MSc GI-ESD)

**Spatial Modeling of Mining-induced Soil Erosion Risks on  
Vegetation Cover in Rwanda: A Case Study of Rugendabari Sector  
in Muhanga District**



Mr. Jean Claude Hakorimana

October ,2025



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By

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College of Science and Technology

**Supervisor:** DR. Innocent Ndikubwimana

October ,2025

**Declaration**

This is to declare that this master’s research entitled “Spatial Modeling of Mining-induced Soil Erosion Risks on Vegetation Cover in Rwanda: A Case Study of Rugendabari Sector in Muhanga District” is submitted in respect of all requirements of the University of Rwanda, College of Science and Technology (CST), the School of Architecture and Built Environment (SABE).

The thesis is submitted in full originality and high quality for obtaining a Master’s in Geo-Information Science for Environment and Sustainable Development

This is my work except where specifically acknowledged.

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## Abstract

Soil erosion is a persistent environmental concern in Rwanda, particularly in regions affected by concentrated mining and steep topography. The main problem investigated was the inadequately understood spatial distribution of soil erosion risk caused by mining activities and its subsequent impact on vegetation cover in the Rugendabari sector of Muhanga District. This study examined the spatial distribution of soil erosion risk caused by mining activities using the Revised Universal Soil Loss Equation (RUSLE) combined with Geographical Information Systems (GIS) and remote sensing techniques, the study models soil loss by analyzing key factors including rainfall erosivity, soil erodibility, slope length and steepness, cover management, and conservation practices using satellite imagery (Landsat 8, ESRI LULC) and other relevant spatial data from 2017 to 2024. The results from the RUSLE model indicate that the mean annual soil erosion rates range from 0 to 2652 tons/ha/year. Where the soil loss value between 0-177tons/ha/year affected the 36.9% of total area with 1532.2 ha found in very low class, soil loss between 177-458tons/ha/year affected the 28.9% of total area with 1198.4 ha found in low class, soil loss between 458-780tons/ha/year affected the 21% of the total area with 870.7ha found in moderate class, soil loss between 780-1217 tons/ha/year affected the 10.8% of the total area found in high class and the soil loss range between 1217-2652 tons/ha/year affected 2.4% of the total area with 101.3 ha found in very high class. The field measurement made to determine the TSS found in Birikana stream showed that TSS increased in the sediment load of Birikana stream, with an estimated 234,026.5 tons of sediment discharged annually into the Nyabarongo River. The results reveal that extensive excavation, deforestation, and particularly the improper management of mining waste, such as unconsolidated rock debris and tailings on steep slopes, are primary drivers of erosion in the Rugendabari sector. This substantial sediment yield not only degrades water quality and damages critical infrastructure but also harms aquatic habitats. The findings indicate that mining activities significantly contribute to soil loss, sediment yield, and vegetation loss, especially around active and unrehabilitated mine sites. Erosion rates were highest in areas with exposed steep slopes and minimal vegetation cover. The results emphasize the urgent need for sustainable land use planning, effective erosion control measures, and ecological restoration in mining areas.

**Keywords:** Mining Activities, Soil Erosion, RUSLE Model, Vegetation Cover, Rugendabari Sector & Muhanga District.

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# Contents

<b>List of Figures</b> .....	<b>viii</b>
<b>List of Tables</b> .....	<b>ix</b>
<b>List of Acronyms and Abbreviations</b> .....	<b>x</b>
<b>Chapter One: Introduction</b> .....	<b>1</b>
1.1. Background .....	1
1.2. Problem Statement .....	3
1.3. Objectives.....	5
1.4. Research Questions .....	5
1.5. Motivation and Significance .....	6
1.5.1. Motivation .....	6
1.5.2. Significance .....	6
1.6. Thesis structure .....	7
<b>Chapter Two: Literature Review</b> .....	<b>8</b>
2.1. Soil erosion and its process .....	8
2.2. Types of soil erosion .....	8
2.2.1. Splash erosion .....	8
2.2.2. Rill erosion .....	9
2.2.3. Gully erosion .....	10
2.2.4. Sheet erosion.....	10
2.3. Factors that trigger soil erosion.....	10
2.3.1. Rainfall intensity and runoff.....	10
2.3.2. Slope gradient and length .....	11
2.3.3. Soil type and climate change .....	11
2.3.4. Vegetation cover.....	11
2.4. Soil erosion modeling.....	12
2.4.1. RUSLE model.....	12
2.4.2. Research on soil erosion around the world using the RUSLE model .....	12
2.4.3. Research on the soil erosion model in Rwanda.....	13
2.5. Sedimentation.....	14
2.5.1. Sediment calculation.....	15
2.6. History of mining in Rwanda .....	15
2.7. Existing mining methods in Rwanda .....	16
2.7.1. Principal legal and regulatory framework.....	17
2.7.2. Primary legislation: the 2024 Mining Law .....	17
2.7.3. Complementary laws and regulations .....	18
2.7.4. Institutional framework.....	19
2.7.5. National development frameworks .....	20
2.8. Mining activities in Rugendabari sector.....	21

2.9. Mining activities on soil erosion .....	21
2.10. Types of erosion appeared in the Rugendabari Sector .....	22
2.11. Mining activities on the vegetation cover .....	24
2.12. Soil conservation practices review in Rwanda.....	25
<b>Chapter Three: Materials and Methods .....</b>	<b>27</b>
3.1. Study Area Description .....	27
3.1.1. Climate.....	28
3.1.2. Population density .....	28
3.1.3. Soil characteristics.....	29
3.3. Data analysis and interpretation .....	30
3.3.1. Revised Universal Soil Erosion Equation (RUSLE) .....	31
3.1.4. Land use in the Rugendabari sector.....	42
3.2. Data collection methods and techniques .....	44
3.4. Soil loss determination.....	45
3.5. Sediment yield in Birikana stream .....	50
3.6. Assessing the contribution of mining activities to sediment yield.....	50
3.7. Soil erosion initiated by mining activities on the vegetation cover .....	52
3.8. Influences that make conservation practice be adopted .....	53
<b>Chapter Four: Results .....</b>	<b>55</b>
4.0. RUSLE model parameters.....	55
4.1. Rainfall erosivity .....	55
4.2. Soil erodibility (K) .....	56
4.3. Slope Length steepness factor (SL).....	57
4.4. Cover management factor (C) .....	58
4.5. Conservation support practice factor (P).....	60
4.6. Soil loss .....	61
4.7. Soil loss estimation by field measurement.....	64
4.7.1. Stream flow.....	64
4.7.2. The amount of suspended soil .....	64
4.8. Contribution of mining activities to the sediment load from Rugendabari streams .....	65
4.9. Impacts of soil erosion initiated by mining on vegetation cover .....	67
<b>Chapter Five: 5. Discussions .....</b>	<b>69</b>
<b>Chapter Six: Conclusion and Recommendation .....</b>	<b>71</b>
6. 1. Conclusion.....	71
6.2. Recommendation.....	72
<b>References .....</b>	<b>74</b>
<b>ANNEX .....</b>	<b>82</b>

## List of Figures

<b>Figure 1:</b> Location map of Rugendabari sector.....	27
Figure 2: Population distribution of Muhanga district.....	29
<b>Figure 3:</b> Rugendabari soil map.....	30
<b>Figure 4:</b> RUSLE model flowchart .....	33
<b>Figure 5:</b> Meteo-stations used to estimate precipitation in study area using the IDW method.....	35
<b>Figure 6:</b> The LULC of Rugendabari sector in 2025 .....	43
<b>Figure 7:</b> Birikana stream and which heads to the Nyabarongo River.....	46
<b>Figure 8:</b> Birikana stream measurement (Cross-section area and Velocity) .....	47
<b>Figure 9:</b> Birikana stream water sampling .....	48
<b>Figure 10:</b> TSS concentration measurement .....	49
<b>Figure 11:</b> Sedimentation in Birikana stream.....	50
<b>Figure 12:</b> Sediments from an active mine polluting Rugendabari streams.....	51
<b>Figure 13:</b> Rainfall erosivity (R-Factor) .....	55
<b>Figure 14:</b> Soil erodibility (K-Factor) .....	56
<b>Figure 15:</b> Slope length steepness factor (SL-factor).....	57
<b>Figure 16:</b> ESRI vegetation cover classifications .....	58
<b>Figure 17:</b> Cover management factor (C-factor).....	59
<b>Figure 18:</b> Conservation support practice factor (P-factor) .....	60
<b>Figure 19:</b> Annual soil lost in Rugendabari sector.....	62
<b>Figure 20:</b> Rugendabari soil erosion classification .....	63
<b>Figure 21:</b> Birikana stream discharge in m <sup>3</sup> /sec.....	64
<b>Figure 22:</b> One of the mining sites prone to soil erosion in Rugendabari Sector .....	65
<b>Figure 23:</b> Birikana stream erosion feeds into Nyabarongo River .....	66
<b>Figure 24:</b> Vegetation behavior of Rugendabari sector in 2014 .....	67
<b>Figure 25:</b> Vegetation behavior of Rugendabari sector in 2025 .....	68

## List of Tables

<b>Table 1:</b> Legislation Governing Rwanda's Mining Sector (2024).....	20
<b>Table 2:</b> Comparative effectiveness of terracing techniques .....	25
<b>Table 3:</b> Annual rainfall in Rugendabari Sector from 2016 to 2025 .....	28
<b>Table 4:</b> Soil features and the corresponding k factor.....	38
<b>Table 5:</b> Land Use-Land Cover type, and C factor .....	39
<b>Table 6:</b> Support practice factor values as per soil conservation practice.....	42
<b>Table 7:</b> The LULC of Rugendabari sector in 2025.....	42
<b>Table 8:</b> Band types provided by Landsat 8.....	53
<b>Table 9:</b> The Rugendabari sector affected area by soil erosion level.....	63
<b>Table 10:</b> The TSS amount in Birikana stream .....	64

## **List of Acronyms and Abbreviations**

<b>AGNPS</b>	Agriculture Non-Point Source Model
<b>APHA</b>	American Public Health Association
<b>DEM</b>	Digital Elevation Model
<b>ESRI</b>	Environmental Systems Research Institute
<b>EUROSEM</b>	European Soil Erosion Model
<b>GIS</b>	Geographical Information System
<b>GLADA</b>	Global Assessment of Land Degradation
<b>IDW</b>	Inverse Distance Weighting
<b>LULC</b>	Land Use Land Cover
<b>MMF</b>	Morgan-Morgan-Finney
<b>MUSLE</b>	Modified Universal Soil Loss Equation
<b>NASA</b>	National Aeronautics and Space Administration
<b>NDVI</b>	Normalized Difference Vegetation Index
<b>NIR</b>	Near Infrared
<b>NSIR</b>	National Institute Statistics of Rwanda
<b>RED</b>	Red light
<b>REMA</b>	Rwanda Environmental Management Agency
<b>RMB</b>	Rwanda Mining and Petroleum Gas Board
<b>RS</b>	Remote Sensing
<b>RUSLE</b>	Revised Universal Soil Loss Equation
<b>SOMIRWA</b>	Société Minière du Rwanda
<b>SWAT</b>	Erosion Productivity Tool
<b>TSS</b>	Total Suspended Solids
<b>UNEP</b>	United Nations Environment Programme
<b>USLE</b>	Universal Soil Loss Equation
<b>UTM</b>	Universal Transverse Mercator
<b>WGS84</b>	World Geodetic System 1984

# Chapter One: Introduction

## 1.1. Background

Soil erosion is the natural environmental process by which soil materials are removed, transported, and deposited in downstream regions by agents like water, wind, and gravitational force (Adediji et al., 2010). The soil erosion results from the interaction of soil erodibility, rainfall erosivity, irregular terrain, topography, and human activities such as deforestation, agriculture, overgrazing, and mining (Knapen et al., 2006). Water erosion begins with raindrops detaching soil, followed by surface runoff carrying the dislodged sediment (Anteneh et al., 2018).

Different research indicates that water-induced soil erosion significantly impacts both the eroded land and the surrounding area, leading to problems such as reduced land and water quality, sediment buildup, release of soil carbon, lower crop yields, and harm not only to biodiversity but also to ecosystems (Ghosh et al., 2016). The negative consequences of soil erosion risk differ geographically due to variations in agroecology, biodiversity, and microenvironments globally. For developing countries heavily dependent on fertile soil for their livelihoods, the loss of the nutrient-rich topsoil has resulted in significant economic and environmental damage (Amsalu & Mengaw, 2014).

Soil erosion is a major problem that challenges the world, as population growth affects the demand for natural resources like food and minerals, which puts more stress on land and leads to soil instability in its natural state (Stringer, 2012). The total surface of land subjected to human-induced activities is estimated to be 2 Billion hectares, about 1.1B hectares of land degraded by water erosion and 550 million ha degraded by wind erosion (Balasubramanian, 2017). According to UNEP's project Global Assessment of Land Degradation (GLADA) (Bai et al., 2008), about 1.1 billion hectares of global land has been degraded by soil erosion, where 48% of it degraded in Asia, 21% in Africa, 15% in Latin America and Caribbean, 10% in Europe, 8% in Oceania, and 5% in North-America.

The global average soil loss is  $2.4 \text{ t ha}^{-1} \text{ yr}^{-1}$  (Wuepper et al., 2020); the soil erosion in Iran accounts for 20 to 40 tons per hectare per year of soil loss, the erosion in Asia, Africa, and South America averages  $30\text{-}40 \text{ tons ha}^{-1} \text{ year}^{-1}$  (Ostovari et al., 2016), about  $16.4 \text{ tons ha}^{-1} \text{ year}^{-1}$  of soil lost for India every year, and 29% of it is carried in the sea, and 10% is deposited in reservoirs,

affecting their storage capability (Pandey et al., 2009). For the recent studies, Naipal et al. (2018) showed that soil erosion caused by human activities has led to total potential soil organic carbon loss of 74Pg between 1850 and 2005, of which 79%-85% occurred in agricultural land and grassland.

Similar to farming, mining activities lead to soil loss and contribute to streams' sediments; however, the sediment types differ (Wantzen & Mol, 2013). Mining includes different stages, including exploration, prospecting, development, extraction, processing, and refining processes, where the minerals are removed from the land, thus potentially adversely impacting on natural environment, especially vegetation (Kitula, 2006). The mining activities cause threats to the environment, resulting in vegetation reduction, water pollution, soil contamination, air pollution, and biodiversity loss. They also release impurities and waste materials containing toxic elements into rivers, agricultural soil, and settlements, which can affect human health and production qualities (Mondal et al., 2013).

Similarly, mining activities trigger erosion through barren waste rock left and abandoned open pits (Haidula et al., 2011). Mining jetting often dislodges inorganic soil from the upper 1 to 10 meters, while agricultural sheet erosion carries more organic matter and fine particles (Choi & Song, 2016). The erosion of bare hills, mine waste areas, and the subsequent silting up of waterways can severely affect nearby regions. According to Douglas and Lawson (2000), the production of 57,000 megatons of mine waste during extraction practices results in annual transportation of 22,000 megatons driven into oceans through the river system.

The soil erosion depends on factors that include climate, soil type, slope steepness and length, vegetation cover, erosion control measures, and how water flows in the mined area. Mining operations often drastically alter these factors, leading to significant sediment runoff from places such as stored topsoil, waste piles, exposed soil, steep slopes, ramps, and channel ways (Ramli et al., 2020). Many existing techniques for measuring soil erosion and sediment movement were created using data from agricultural lands (Byizigiro et al., 2020). While surface mining areas haven't been studied as extensively, their sedimentation patterns are generally comparable to farmland. The most commonly recognized and used method for estimating soil erosion is the revised universal soil loss equation (RUSLE)(Chang et al., 2016).

Soil erosion in Rwanda is a very big problem that has become severe nowadays. As reported by RWB and IUCN. (2022), Muhanga district ranked as the most affected by soil erosion of 46 tons  $\text{ha}^{-1} \text{ year}^{-1}$ , followed by Ngororero, whose 45 tons  $\text{ha}^{-1} \text{ year}^{-1}$ , and the least eroded districts are Rusizi, Rwamagana, Gatsibo, and Nyagatare, with 3.8 tons  $\text{ha}^{-1} \text{ year}^{-1}$  soil loss.

Rugendabari sector is one among eight sectors of the Muhanga district. This region consists of steep, long hills rich in mineral content such as coltan, cassiterite, beryllium, tungsten, and lithium. This area is one of the areas affected by soil erosion, where mining activities and agriculture are the most economically important activities conducted by the local people. In this area, mining activities, especially those worked in artisanal and small-scale ways, have accelerated the removal of topsoil and vegetation, creating steep, unstable slopes and gully systems that intensify surface runoff and sediment displacement.

Even if mining became a vital economic activity and a good livelihood for Rugendabari people, its environmental consequences became the target of researchers. Current interventions mainly target agricultural erosion, but not the spatially fragmented on mining erosion on vegetation cover. This research addresses the gap by quantifying and mapping erosion risk, specifically focused on mining, connecting terrain disturbance with vegetation loss, and informing targeted land management strategies that reconcile economic activities with ecological conservation.

## **1.2. Problem Statement**

According to Tamene et al. (2006), soil erosion is the most serious global issue that results in soil loss, water contamination, destruction of aquatic animals, and enhanced flooding. Soil erosion is composed of the detachment, transport, and deposition of soil particles caused by one or more natural or human-made activities (rain, runoff, wind, gravity, tillage, agriculture, grazing, mining, etc.) (Sun et al., 2021). Human activities like mining, grazing, and deforestation, coupled with the effects of climate change, are known to cause significant soil erosion (Han et al., 2021). The topography of Rwanda is characterized by tropical precipitation and human activities that are the special sources of soil disturbance across Rwanda (Shema & Lanhai, 2024). When you look at different rivers of Rwanda, most of them are brown-red due to severe erosion from the highlands (Nyesheja et al., 2019).

The Rwanda mining industry is experiencing significant growth, increasing revenues, attracting international investors, and generating employment opportunities in rural communities. Nevertheless, the establishment of new mining sites, the abandonment of old ones, poor mining practices from the 20<sup>th</sup> century, and the ongoing expansion of the sector are causing environmental damage (Runge & Nguenjouo, 2018). Activities involve excavation, deforestation, and construction of access roads, underground mining, mineral processing, use of gear oil, and other activities contribute to soil loss (Haidula A.F. et al., 2011). Mining activities contribute to soil erosion and threaten the environment, especially vegetation; according to the report on environmental issues done in 2015, the waste rocks from mining activities were not managed as the law stipulates (Finances, 2015); these waste rocks destroy the surrounding vegetation.

According to the RWFA (2019) report, Muhanga district is ranked as the highest in erosion risk, with 63% of its land. Rugendabari, as one among the sectors of Muhanga district, is found in the Gatumba concession, a region that contains significant ecological and economic importance, characterized by different minerals, including coltan, cassiterite, beryllium, wolfram, and lithium (Lehmann B. et al., 2013). This concession has been the site of both small-scale and large-scale mining operations for coltan and cassiterite; however, by observing the area reveals environmental neglect, evidenced by soil erosion, abandoned piles of mining wastes, open pits, and contaminated water. Even the area previously mined by big mining companies still offers opportunities for smaller miners. The failure to properly restore the sites after past mining activities has worsened topsoil loss as the heavy rainfall continues to erode unprotected mining areas (Bucagu et al., 2008).

The concession lacks adequate oversight of mining operations, and these harmful practices have resulted in a degraded and polluted environment. The mining activities have produced substantial quantities of waste, including soil and rock debris, processing plant tailings, wastewater, and most of these wastes readily flow into rivers, further intensifying the severe erosion already occurring in the steepest areas and agricultural activities (Rukazambuga et al., 2008). The absence of monitoring mining activities in the concession suggests an unspoken allowance for artisanal mining that affects the local population to be engaged in illegal mining activities and polluting nearby rivers; furthermore, the dumping of waste rock from rare metal mines in undisturbed areas generates mine spoils that ultimately harm the surrounding vegetation (Bizimana et al., 2021).

Although environmental and mining laws in Rwanda have advanced day by day, and different inspections for mining activities are carried out in the Rugendabari sector, but the issue needs to be addressed is at how much amount of soil loss due to the mining activities in the Rugendabari sector and why extraction of mineral cannot be recovered without damaging vegetation cover. While soil erosion impacts are recognized in Rwanda, the impacts of mining-induced soil erosion on vegetation cover within the Rugendabari sector remain inadequately understood. Therefore, this study aims to address a critical knowledge gap by employing spatial modeling techniques to assess and model the spatial distribution of mining-induced soil erosion risk on vegetation cover within the Rugendabari sector. The findings will provide insights into the complex interactions between mining activities, soil erosion, and vegetation changes, and will inform the development of targeted interventions to safeguard the ecological integrity and promote sustainable management in the vulnerable parts of the Rugendabari sector, and contribute to other parts of the country facing similar challenges.

### **1.3. Objectives**

#### **1.3.1. General Objective**

The study's main objective is to use the RUSLE model to model the mine-induced soil erosion risks on vegetation cover associated with the Rugendabari sector and propose soil conservation practices.

#### **1.3.2. Specific Objectives**

1. To determine the spatial distribution of soil erosion risk in the Rugendabari sector
2. To analyze the contribution of mining activities to the soil erosion of the Rugendabari sector.
3. To determine the impact of soil erosion on vegetation cover caused by mining activities in the Rugendabari sector.
4. To propose suitable soil conservation practices for reducing mine-induced soil erosion risks in the Rugendabari sector?

### **1.4. Research Questions**

The following research questions will be addressed in my research:

1. What are the spatial patterns of soil erosion in the Rugendabari sector?

2. To what extent do mining activities contribute to the soil erosion rate of the Rugendabari sector?
3. How does soil erosion caused by mining activities affect vegetation cover in the Rugendabari Sector?
4. What soil conservation practices are most suitable for reducing soil loss in Rugendabari sector?

## **1.5. Motivation and Significance**

### **1.5.1. Motivation**

The key aim of doing this research is to measure the amount of soil loss due to mining activities in the Rugendabari area, where degraded land is noticeable. Also, to propose conservation practices to protect nature. Even if mining is an economic activity in Rwanda but it disrupts the natural environment and threatens ecological stability and livelihoods. The Rugendabari sector is rich in valuable minerals and is experiencing soil loss due to its topography, high rainfall, and intensive mining operations. The soil loss due to erosion not only diminishes soil volume but also contributes to downstream water pollution and ecosystem disruption. By developing spatial modeling, the destruction of topography and land cover will be modeled and estimated to understand the effects of mining activities on vegetation cover and develop strategies to mitigate these negative consequences on the environment.

### **1.5.2. Significance**

The significance of the study will depend on providing a clear understanding of the extent and spatial patterns of the erosion in the Rugendabari sector. The results will quantify the relationship between mining, vegetation loss, and soil erosion types. The research will identify the area that requires urgent intervention and conservation efforts. The research will inform the development of targeted and effective soil conservation strategies in active mines and also in closed mines. The research will support sustainable land management practices that balance economic development through mining with environmental protection, and also assist in EIA for future mining projects in the study area. The research will contribute to the broader national efforts in Rwanda to combat soil erosion and ensure environmental sustainability. From the results, this research will inform policy decisions and guide land use planning and promote

responsible mining practices that minimize environmental damage and support the long-term well-being of the Rugendabari ecosystem and the community that depends on it. While previous research in Rwanda has extensively modeled soil erosion using the RUSLE model in agricultural contexts, this study fills a critical gap by focusing specifically on small-scale and often unregulated mining activities and their ecological consequences. Unlike previous works, it combines GIS, remote sensing, and field data to quantify the direct contribution of mining operations to sediment yield and vegetation loss, contributing a fine-scale, spatial understanding of erosion patterns.

## **1.6. Thesis structure**

The research is composed of six chapters. The first one holds the background of the study, statement of the problem, objectives, questions, motivation, and significance of the study. The second chapter holds the review related to soil erosion modeling and mining impacts on soil. The third chapter provides materials and methods in my research. The fourth chapter shows the results of the research. The fifth chapter contains discussions. Finally, the last chapter provides the conclusion and recommendations.

## **Chapter Two: Literature Review**

### **2.1. Soil erosion and its process**

Soil erosion is the process of removing topsoil by natural physical forces like wind and water. It can be a slow process and occur at different rates and causing different losses of topsoil. The soil compaction, low organic matter, loss of soil structure, poor internal drainage, salinization, and acidity issues are also other soil degradation conditions that can accelerate the soil erosion process. Soil erosion involves three different actions includes soil detachment, soil movement, and soil decomposition. Nowadays, soil erosion is largely accelerated by human activities, primarily caused by deforestation, agriculture, and mining. The rate of soil erosion varies due to different types of human activities (Telkar et al., 2015).

The eroded materials from soil erosion impact both on-site and off-site. The effects are intensified by inter-reactions and intra-reactions within the ecosystem. In the areas with high numbers of human activities, soil erosion is a major problem (Ding et al., 2015). Soil erosion mainly occurs in places that are susceptible to high topography, long-duration rainfall, and inadequate vegetation cover (Rohrman et al., 2013). To recognize the vulnerable areas susceptible to soil erosion and their impacts, there is a need to conduct studies that monitor the soil erosion process in the area.

### **2.2. Types of soil erosion**

#### **2.2.1. Splash erosion**

Splash erosion is defined as a complex process caused by the detachment of soil particles by raindrops when these drops hit the soil surface and create a flow from the soil surface (Angulo-Martínez et al., 2012). Moreover, splash erosion has a great role in the release of soil organic carbon, as carbon-rich particles dislodged by raindrop impact are carried away when surface runoff develops. Depending on soil properties, splash erosion can propel particles up to 1.3 m vertically and more than 5 m horizontally, especially when it is helped by wind. Additionally, when the raindrops strike uncovered soil surfaces, they can lead to compaction and crust formation, increasing soil bulk density (Ryzak et al., 2015).

While soil crusting eventually leads to a smoother surface, the initial impact of raindrops causes soil particles to splash and create tiny craters and increase surface roughness. The size of these

microcraters varies with soil type, texture, structure, and moisture content. Soil crusts impede the growth of plants by hindering seed germination and seedling development, and they also reduce the rate at which water soaks into the soil. This reduces infiltration and can lead to water pooling on the surface of the soil (Rodrigo Comino et al., 2016). While surface water, like ponding and shallow overflow, can shield the soil from the direct force of raindrops, similar to a mulch layer, these conditions also reduce how quickly water soaks into the ground, limiting the water available for plants. Similarly, loose, detached soil particles on the surface can offer temporary protection to the soil beneath. If this layer of loose particles is thick enough to absorb the impact of raindrops, only the topmost loose material will be displaced (Kinnell, 2005).

### **2.2.2. Rill erosion**

Rill erosion manifests as numerous small channels, typically less than 30 cm in depth, that can be smoothed out by farming practices (Cerdan et al., 2002). The rill erosion process is composed of detachment, entrainment, and transport of soil particles (Sun et al., 2013). Huo et al. (2011) summarized rill processes into five stages, including knickpoints, head cut extension, intermittent rill, continuous rill, and rill networks.

Rill erosion, representing a transition between surface runoff and larger gully formation, involves soil detachment processes distinct from those in interrill erosion. The removal of topsoil and essential nutrients by rill erosion diminishes soil fertility, while the eroded sediment deposited elsewhere can lead to sedimentation and a decline in the water quality of rivers and reservoirs (Romero et al., 2007). In rills, the erosive power of focused water flow is the main cause of soil detachment, unlike the area between rills, where raindrops are the dominant factor. Given that concentration flow can dislodge and move far more soil than rainfall, the development of rills leads to a substantial increase in the total erosion occurring on slopes (Auerswald et al., 2009).

Soil crusts can significantly decrease the rate at which water soaks into the ground, thereby increasing the erosive power of runoff and potentially initiating rill erosion. Conversely, these same crusts can also make the soil more resistant to erosion by increasing its strength and reducing the ease with which soil particles are detached by flowing water. Some experiments simulating rainfall on slopes have demonstrated that the formation of a sealed or crusted soil surface can lead to a great amount of sediment being eroded through rill formation. (Hussein et al., 2010).

### **2.2.3. Gully erosion**

Gully erosion mostly happens in mountainous regions and is particularly widespread in tropical or Mediterranean regions due to the mineralogical and climate characteristics (Descroix et al., 2008). The gully erosion mostly appeared in cultivated areas and was triggered by inappropriate cultivation, overgrazing, and log haulage (Valentin et al., 2005). The factors that boost gully formation are the catchment area and slope length. The sediment yield increased as the repletion of different gullies increased in the catchment; however, it will decrease if the catchment area increases (Poesen et al., 2003). Existing studies showed that the slope gradient of soil surface (S) at the critical drainage area (A) is important to produce sufficient runoff, which will cause gully incision, and thus will cause vegetation biomass to decrease and make unresistant topsoil by tillage operations (Descroix et al., 2008).

### **2.2.4. Sheet erosion**

Sheet erosion is also known as laminar erosion. This type of erosion is also characterized by the detachment of fine topsoil elements caused by rainfall impact and overland surface flow. Then, the mixture of soil particles and water flows across the hills down as a sheet, and soil is eroded by the following layers (Descroix et al., 2008). The clay and silt soils are more prone to sheet erosion due to their fine particles. This is the greatest threat from many developing countries. Sheet erosion doesn't affect the vegetation area like in semi-arid or peri-glacial catenae; however, it affects the disturbed soils and area of low relief in tropical or subtropical climates (Mathys & Descroix, 2003).

## **2.3. Factors that trigger soil erosion**

### **2.3.1. Rainfall intensity and runoff**

The intricate relationship between rainfall and the resulting water flow (Runoff), along with the associated soil erosion, is influenced by a multitude of interacting elements. Some research shows that the nature of rainfall itself and features of the land area are the main drivers of how much water runs off and how much soil is lost (Ran et al., 2012). The rainfall characteristics include rainfall intensity, duration, moving velocity, moving direction, wind, and rainfall temporal resolution (Schmidt & Mauersberger, 2009).

Numerous experiments have explored how different qualities of rainfall impact the way water behaves in a landscape and the amount of soil eroded. The intensity and duration are the main key

factors determining how the landscape responds to water flow. The heavy rainfall led to larger surges of runoff, particularly if the rainfall rate changes a lot over time. The area over which a storm occurs doesn't usually cause a bigger runoff surge unless it concentrates the rain into a short period (de Lima et al., 2009).

### **2.3.2. Slope gradient and length**

Soil erosion processes include three main physical processes such as detachment, transportation, and deposition (Zhao et al., 2015). These processes are subordinated to rainfall characteristics, overland flow, and soil properties to form soil erosion.

According to Ran. et al. (2012), the rainfall intensity and slope gradient are the two dominant factors that contribute to soil erosion. The steepness of land is a significant feature of its shape and is frequently seen as a key factor influencing how particles move across the landscape; the steeper the land result in increase the rate of soil erosion (Wang G. et al., 2014).

### **2.3.3. Soil type and climate change**

Soil erosion led to a decrease in soil fertility, nutrient loss, and crop production. Different factors, including natural factors such as climate, soil types, and geomorphology, are the main factors that are susceptible to soil erosion when they are triggered by rainfall. These natural factors are site-specific and not changeable during the short period (García & J. M., 2010).

### **2.3.4. Vegetation cover**

The majority of rainfall reaches the ground either falling straight down or dripping from plant stems and leaves (Chirino et al., 2006). A small amount is held on the leaves and later evaporates. However, the water that reaches the soil surface either soaks into the ground and is stored within the soil layers, flows downhill across the surface as runoff, or seeps down to become groundwater. How much water infiltrates or becomes runoff is influenced by various factors, including the properties of the soil, the kind of plant cover present, and the network of roots (Mohammad & Adam, 2010). Different studies show that the vegetation cover affects in reduction of soil erosion and is taken as the best methodology to minimize the runoff that results in soil erosion (Kothyari et al., 2004). Thus, vegetation controls erosion by its characteristics, like roots, canopy, and litter components. It also depends on the composition, structure, and growth pattern of the plant

community. Loss of vegetation causes the formation of a soil seal that increases the runoff and causes erosion (Gyssels et al., 2005).

## **2.4. Soil erosion modeling**

The models developed to estimate soil erosion are classified based on different parameters: empirical (statistical), conceptual(empirical), and physics-based. These models are categorized depending on the processes simulated, the description of these processes, and the type of data they use. By comparing these, empirical models are the simplest compared to the remaining two because they depend on analyzing the observed data. Most of these models need information on land use, soil type, climate, and topography during soil loss estimation. The models like Universal Soil Loss Equation (USLE) (Wischmeier WH & DD, 1979), Modified Universal Soil Loss Equation (MUSLE) (Smith SJ et al., 1984), Morgan-Morgan-Finney (MMF), Agriculture Non-Point Source Model (AGNPS), Erosion Productivity Tool (SWAT), and European Soil erosion Model (EUROSEM) (Morgan R CP et al., 1992) were developed. The most utilized method for estimating soil erosion is the RUSLE method(Chang et al., 2016).

### **2.4.1. RUSLE model**

The revised universal loss equation (RUSLE) model analyzes soil erosion and explains how it affects the environment. The combination of remote sensing and GIS integrates different sources of information used to generate a model of the study area. Soil conservation planning necessitates accurate soil loss measurement and application of suitable management practices. However, manually conducting soil erosion risk assessments is often costly and time-consuming. So, the integration of GIS, RS, and field data will use soil erosion models' parameters to create a sustainable development demanding focused management through strategic planning. RS and GIS together create erosion models that can guide decisions designed for mitigating the soil loss of the area of target(Ghosh et al., 2022).

### **2.4.2. Research on soil erosion around the world using the RUSLE model**

The governments worldwide are attempting to address the soil loss issue, even if it's not well understood how much actual individual nations have over their erosion rates. Over 35 million observations and a spatial regression discontinuity design to quantify the extent to which countries influence global soil erosion and to identify which national characteristics and policies are linked to this effect (Alewell et al., 2008).

Different research on soil erosion was carried out across the world. For instance, the research carried out in the Gobebe Watershed, East Hararghe Zone, Ethiopia, aimed to quantify soil loss, assess changes in erosion risk over time, and propose conservation practices. Using the RUSLE model with remote sensing data in the ArcGIS environment, researchers estimated soil loss for the years 2000 and 2006. The results indicated that the total estimated soil loss for the watershed decreased from 1,390,130 tons in 2000 to 1,022,445 tons in 2016, with the average erosion rate falling from 51.04 tons/ha/year to 34.26 tons/ha/year, respectively. Yet, a detailed change analysis of erosion risk classes between the two years revealed a more complex situation, while the risk level in most of the area (70.80%) remained the same, the area that shifted to a higher erosion risk class (19.67%) was more than double the area that improved to a lower risk class (9.53%), indicating an overall worsening of erosion risk conditions across the watershed (Woldemariam et al., 2018).

As well IMHA watershed was susceptible to severe erosion due to its steep terrain and mountainous composition. To analyze the erosion, the RUSLE model was combined with GIS techniques to evaluate the spatial distribution of soil loss under different land uses. The model was used to predict the mean annual erosion and predicted the rate as 3,450 tons/ha/year (Kim & Julien Pierre, 2006). The RUSLE model assessed soil erosion loss in a mid-Himalayan watershed in Uttarakhand, India. The findings revealed that agriculture is the dominant land use with 59% and significant portions of the watershed exhibited steep slopes greater than 40%. The erosion risk analysis categorized areas in six classes with an average annual erosion rate of 65.85 tons/ha/year, varying considerably across the different land use (Kalambukattu & Kumar, 2017).

#### **2.4.3. Research on the soil erosion model in Rwanda**

Different studies carried out in Rwanda show that soil erosion in Rwanda is predominantly affected by anthropogenic activities, especially agricultural activities (Karamage et al., 2016) (Nyesheja et al., 2019). The high rate of soil erosion is prevalent across various parts of Rwanda due to the country's topography, high rainfall, and different anthropogenic activities (REMA,2015).

There was a study conducted in the Rukarara catchment in the south of Rwanda. This study utilized the revised universal soil loss equation (RUSLE) within a GIS environment to predict soil erosion and identify high-risk areas in the mountainous Rukarara watershed. By analyzing factors such as rainfall, soil type, topography, land cover, and conservation efforts, the research estimated annual

soil loss. The findings indicated an average erosion rate of 39.96 tons/ha/year with a range of 54 to 134 tons/ha/year. Although the study area is generally characterized by low soil erosion rates consistent with other tropical regions, it specifically identified agricultural lands as erosion hotspots, where the average soil loss was significantly high at 61.29 tons/ ha/year (Rizinjirabake et al., 2023).

Another study was conducted in the Satinsyi catchment located in the Ngororero district, the western part of Rwanda, by implementing the RUSLE model in a GIS environment (Byizigiro et al., 2020). The model integrated various factors, including slope, rainfall, soil type, conservation practices, and land cover, to quantitatively assess how soil loss varies with topography and land use patterns. The findings showed an average soil loss of 38.4 tons/ha/year. The key factor is the steep topography, as 91% of the study area has slopes exceeding 15 degrees, exposing the land to severe erosion rates between 31 and 41 tons/ha/year. In addition to steep slope, the study concluded that changes in land use also significantly contribute to high soil erosion rates within the catchment.

Another research was conducted in the Congo Nile ridge region using the RUSLE model, which integrated spatial data across the key factors, including rainfall, soil, topography, cover management, and support practice. Nyesheja et al. (2019) found that the vast majority of the area, 85.5%, was susceptible to unsuitable soil loss rates exceeding 1 ton/ha/year. In these erosion-prone areas, the average estimated soil loss was over 63.62 tons/ha/year, resulting in a total predicted annual loss of approximately 44 million tons in 2016. The high erosion risk is linked to the steep slopes and heavy annual rainfall common to most districts in the region. The impact on agriculture was particularly severe, with over 88.8% of croplands experiencing unsuitable soil loss. The analysis also identified potential solutions, indicating that terracing could reduce soil loss on farmland by 64.4% while strip cropping could achieve a 10.4% reduction. The results of this study provided the baseline for guiding soil erosion mitigation and land-use planning in the area of Rwanda.

## **2.5. Sedimentation**

Sedimentation occurs when the eroded soil particles settle and accumulate as bed load and suspended load (Dutta, 2016). Sedimentation is a crucial factor because it can help predict how much storage capacity remains in a reservoir over time, thus indicating its lifespan, as storage capacity and reservoir life are directly linked. Specifically, the rate of sedimentation in a given

reservoir depends on the sediment yield, which is the amount of sediment carried by a river out of a specific drainage area over a certain period. Soil erosion within the catchment area is also significant because it directly influences the sediment yield. To address the issue of sediment buildup in reservoirs caused by erosion, efforts have focused on understanding the relationship between soil erosion, sediment yield, and reservoir sedimentation, as these three factors directly or indirectly determine how long a reservoir will be useful (Dutta, 2016).

### **2.5.1. Sediment calculation**

Suspended sediments are calculated using two methods. The first method involves collecting water samples from a representative point in the river's cross-section, then filtering, drying, and weighing the sediment to determine its concentration. The second measures water turbidity using an optical approach and subsequently calculates sediment concentration accurately, reflecting the entire river's cross-section, allowing for the total suspended load to be calculated by multiplying the sediment concentration by the river's total discharge. More advanced sampling methods involve integrating measurements across different water depths to obtain even more representative samples (Lecce, 2009). While collecting large datasets for suspended sediment can potentially be automated, sampling the bed load presents a much greater challenge, being more complex, time-consuming, and labor-intensive, thus incurring high costs. The most common technique for bed load involves deploying sampling baskets to the stream bed. Various researchers have suggested typical bed load contributions as a percentage of the total sediment load. Generally, literature frequently cites bed load as 10%-20% of the total load, through this can increase to 20% to 40% in mountain rivers (MUSABYIMANA, 2022).

## **2.6. History of mining in Rwanda**

Mining in Rwanda started in 1930 by colonials in different parts of Rwanda, including the Gatumba concession encloses the Rugendabari sector. Mining activities were carried out in an artisanal way, even if conducted by strong companies like SOMIRWA, owned by the government, which started to conduct mine operations in 1973 before it went bankrupt and was replaced by COPIMAR, a private company that owns 49% of mining works from 1988 to 1988. This company was replaced by REDEMI, which had the aim of doing exploration. The mining operations continued in artisanal ways until 1997, when this sector showed that it should be the source of potential revenue, and the government created OGMR to privatize mining companies. In 2007,

RMB was created with the aim of the mineral licensing right, exploration licensing, and mineral traceability scheme. In 2017, RMBPG was established with aims similar to the former RMB by the addition of mine inspections and environmental protection compliance (REMA, 2023).

## **2.7. Existing mining methods in Rwanda**

Rwanda's mining sector primarily employs a combination of artisanal, small-scale, and increasingly semi-mechanized and mechanized methods, reflecting the country's transition towards a more formalized and industrialized industry. Given that many of Rwanda's ore deposits, particularly for minerals like tin(cassiterite), tungsten(wolframite), tantalum(coltan), and gold, are found in narrow veins at steep and deep depths, underground mining methods are commonly used (Dusengemungu et al., 2023).

These include techniques like sublevel stopping, where ore is blasted from different elevations and extracted from a lower level, and square-set stooing, which involves the use of interlocking timber supports as extraction processes. Surface mining methods like open-pit mining are also employed where deposits are closer to the surface, as well as stripping mining for peat seams and quarrying for industrial minerals like limestone and granite (Muhire et al., 2021). Following extraction, mineral processing in processing in Rwanda largely relies on gravity separation techniques due to the characteristics of the ore bodies and available resources.

These methods leverage differences in mineral density separation techniques, including panning, ground sluicing, and the use of shaking tables (RMB, 2017). In instances where mixed ores like cassiterite and coltan are present, magnetic separation is also utilized, exploiting differences in magnetic susceptibility to achieve separation (Muhire et al., 2021). While artisanal methods remain prevalent, accounting for a significant portion of the country's mineral output, there is a growing emphasis on incorporating mechanized techniques and establishing value-addition facilities like gold refineries and tin smelters to increase the overall efficiency and economic contribution of the sector.

## **2.7. The existing policy frameworks in the Rwanda mining sector**

Rwanda's mining sector holds a pivotal position in the nation's economic landscape. It stands as the country's second-highest export income, following tea and coffee, and is explicitly identified as a high-growth potential sector within Rwanda's overarching national development strategies,

including the Vision 2050 and NST1 (MINICOFIN, 2024). The sector's substantial contribution to the gross domestic product (GDP), projected to reach 8.5% by 2024, alongside its significant role in job creation, especially in rural areas, underscores its strategic importance for poverty eradication and enhancing the well-being of the population (MINICOFIN, 2024).

### **2.7.1. Principal legal and regulatory framework**

Rwanda has meticulously constructed a robust and dynamic legal and regulatory framework for its mining sector, characterized by continuous reform and an unwavering commitment to sustainable development. The framework is designed to provide clarity and predictability for investors while safeguarding national interests and environmental integrity.

### **2.7.2. Primary legislation: the 2024 Mining Law**

The foundation pillar of Rwanda's mining legal framework is Law No.072/2024 of 26 June 2024 on mining and quarry operations. This comprehensive legislation replaced the previous Law No.58/2018 of 13 August 2018, marking a significant and decent legislative modernization. This swift legislative update highlights the Rwandan government's proactive and continuous efforts to strengthen its legal framework, aiming to enhance the second sector's efficiency, attractiveness, and alignment with evolving national development goals (Ntirenganya, 2024).

Under the 2024 Mining Law, all rights of ownership and control over minerals and quarry products located within Rwanda are exclusively vested in the state, a principle enshrined in article 4 of the law and further affirmed by article 43 of Law No 27/2021 of 10 June 2021 on governing land. This fundamental tenet ensures that the nation retains sovereign control over its natural resources. The RMB serves as the primary grantor and regulator of mining activities, responsible for issuing the necessary rights for exploration, mining, processing, trading, and export, contingent upon the payment of prescribed fees and fulfillment of statutory requirements (Ngabire & Aimery, 2025).

While the 2024 mining law does not mandate government joint ventures or participation in mining operations, it explicitly permits the government to acquire shares in mining or quarry operations based on mutually agreed terms with the license holder. A notable new provision in the 2024 law introduces the concept that a grant of a mining license may entitle the government to free carried interest, with the specific number and modalities for issuance to be determined by ministerial order (Ntirenganya, 2024). This dual strategy combining the imperative to attract

private investors and leverage external expertise with the state's sovereign right to control its natural resources, allows for strategic influence in key mining projects without imposing mandatory government participation, which could potentially deter investors (Ngabire & Aimery, 2025).

Further strengthening regulatory oversight, the 2024 mining law introduces a new requirement that a license holder can't transfer the license through the assignment of shares until at least 30% of the committed investment has been realized. This provision is designed to ensure genuine investment and deter speculative transfers of mineral rights. Additionally, the law clarifies land tenure related to mining upon the discovery of a mineral deposit, and fair compensation to the land owner, the affected land is registered to the state. For exploration or quarry operations, a written lease contract is concluded with the land owner, and the land is returned upon completion of operations. The law also introduces tougher penalties for offences such as operating without a license or possessing illegally extracted minerals with significant fines and potential imprisonment, signaling a stronger stance against illicit mining activities and a push for formalization within the sector (Ngabire & Aimery, 2025; Ntirenganya, 2024).

### **2.7.3. Complementary laws and regulations**

The 2024 mining law operates within a broader, comprehensive legal and regulatory ecosystem, complemented by a suite of existing presidential orders, ministerial orders, and regulations issued by the RMB. This extensive array of legal instruments demonstrates that Rwanda's approach to mining is holistic and integrated within its broader national development agenda, recognizing that the sector's impacts extend beyond mere extraction to encompass land use, environmental quality, labor rights and economic diversification (Ngabire & Aimery, 2025).

The supporting legislation includes land law, environmental law,...

- **Land Law**

Law No.37/2021 of 10 June 2021 specifically governs land, reinforcing the principle of state ownership of minerals despite private land ownership. Organic Law No.08/2005 also outlines provisions for land use and management.

- **Environmental law**

The organic law No.04/2005 mandates environmental protection, conservations, and promotion, requiring all projects, including mining, to undergo EIA. The environment Law 2018 further strengthens this framework. Rwanda has proactively revamped its environmental legal framework to effectively address climate change and protect the environment, aligning with its Vision 2050 aspiration to become a green, carbon-neutral, and climate-resilient country. This policy mandates that all socio-economic sectors, including mining, must integrate environmental and climate change considerations into their development and implementation of policies, strategies, and plans (AMALA, 2024).

#### **2.7.4. Institutional framework**

The effective implementation of Rwanda's mining policy framework relies on a well-defined institutional structure, led by a dedicated regulatory body and supported by cross-sectional collaboration. The Rwanda Mines, Petroleum and Gas Board (RMB) stands as the central regulatory and promotional entity for the mining sector. Its core mandate involves regulating, planning, coordinating, and conducting all activities related to geological studies and the evaluation of mineral resources. The RMB's primary functions encompass licensing, overseeing mineral exploration, and actively promoting lucrative mining investment opportunities within Rwanda. To enhance efficiency and transparency, the RMB also operates a suite of online services like the mineral certification information system (MCIS) for export certificates, the geological information and mining cadaster system (GIMCS) for license applications and permits, the RMB cloud for secure data sharing, and the environmental rehabilitation fees information system (ERFIS) for managing environmental rehabilitation fees. The clear designation of RMB as the central authority for mining demonstrates a commitment to streamlined governance and efficiency in licensing and oversight (Muhire et al., 2021).

**Table 1:** Legislation Governing Rwanda's Mining Sector (2024)

<b>Legislation</b>	<b>Year of Enactment/Revision</b>	<b>Key Provisions Relevant to Mining</b>
Law No 072/2024 on Mining and Quarry Operations	2024	Primary law governing all mining activities, state ownership of minerals, licensing, government participation, license transfer, land registration, and penalties.
Law No 056/2024 establishing Tax on Minerals	2024	Revised tax rates for various minerals, differentiated rates for processed vs. unprocessed minerals, and exemptions.
Law No 006/2021 on Investment Promotion and Facilitation	2021	Designates mining as a priority economic sector, offering various investment incentives.
Law No 27/2021 on Governing Land	2021	Confirms state ownership of minerals regardless of land ownership, dictates compensation for landowners upon mineral discovery.
Organic Law No. 04/2005 Determining Modalities of Protection, Conservation and Promotion of Environment	2005	Mandates Environmental Impact Assessments (EIA) for all projects, including mining, and promotes sustainable development.
Environment Law	2018	Further strengthens environmental protection and climate change considerations in all socio-economic sectors.
Law Regulating Labour in Rwanda	2018	Governs labor relations, occupational health, safety, and employee welfare in the workplace.
Law N° 17/2018 Governing Companies	2018	Sets out the requirements and framework for the registration and operation of companies in Rwanda.

Source: RMB (2024)

### 2.7.5. National development frameworks

The long-term strategic direction for Rwanda is articulated in Vision 2050, which aspires to elevate the nation to upper-middle-income status by 2035 and high-income status by 2050. This vision is underpinned by goals of sustainable economic growth, ensuring a high quality of life, and fostering a green carbon-neutral, and climate-resilient economy. Vision 2050 is implemented through a series of medium-term national development strategies, including the NST1 and

subsequent NST2. These strategies serve as critical bridges towards achieving the Vision 2050 goals, prioritizing sustainable development, climate resilience, and the development of high-growth potential sectors, with mining explicitly identified among them. The integral inclusion of mining within these national visions and strategies signifies that the sector is not merely an economic activity but a strategic pillar for Rwanda's long-term socio-economic transformation (MINICOFIN, 2024).

## **2.8. Mining activities in Rugendabari sector**

The Rugendabari sector is found in the former Gatumba concession. This concession was discovered in 1930 and holds pegmatites as the main deposit of this region. The deposits extracted by Belgian private companies until the establishment of SOMIRWA. Numerous researchers have investigated and documented the mineral resources of this area. By 1958, the total mineral production from the concession was estimated to be 17,661 tons of cassiterite-columbite, 622 tons of wolfram, 4000 tons of beryllium, 9000 tons of amblygonite, 3.4 tons of microlite, and an undetermined amount of bismuth (Dewaele S. et al., 2011).

Before the privatization of the Rwanda mining industry, Rugendabari was mined using artisanal, illegal, and small-scale methods by different subcontractors. From 2008 until 2014, the concession operated under GMC (Gatumba Mining Company), a private company. After the failure of GMC, the concession was divided into different blocks licensed to different stakeholders, such as Ngororero Mining Company, Daba suppliers, and CEAVMC. The rich pegmatite is extracted to recover tin and tantalum, which are enriched in. Nowadays, the Rugendabari sector holds different companies that operate their mining activities in the area, including Daba suppliers and CEAVMC.

## **2.9. Mining activities on soil erosion**

Mining operations can lead to significant environmental damage, including erosion, the formation of sinkholes, biodiversity degradation, and soil and water pollution. The erosion of unstable areas like exposed hillsides, mine dumps, and tailing dams can cause substantial siltation in nearby waterways, negatively affecting the surrounding environment (Yellishettya et al., 2013). The degree of soil erosion is influenced by several factors, such as climate, susceptibility of the soil to erosion, the steepness and length of slopes, existing ground cover, effectiveness of soil conservation measures, and the characteristics of the catchment drainage. Mining activities often

drastically alter these factors, leading to severe sediment runoff in areas such as topsoil stockpiles, spoils and waste dumps, bare land, ramps and haul roads (Ramli et al., 2020).

The major erosion issues in surface mining arise from extensive disturbed areas, ineffective drainage systems, and a lack of integrated sediment control. To combat this, a comprehensive approach is necessary: minimize the size of disturbed areas at any given time, establish a robust drainage system across the mine lease, and integrate erosion and sediment control measures into every phase of mining. It is crucial to develop a mining and rehabilitation plan before commencing operations and to construct drainage and erosion controls in advance of actual mining (Ramli et al., 2020). Furthermore, divert storm runoff away from highly erodible zones, implement measures to slow down runoff velocity, limit the handling of spoil and topsoil, rehabilitate disturbed areas promptly, and consistently maintain all drainage and erosion control infrastructure. GIS software and the RUSLE model are likely used to estimate erosion rates by creating a mine erosion hazard level map. That map must consist of various parameters of the RUSLE model, like Rainfall erosivity, soil erodibility, slope length and steepness, cover management, and support practice.

## **2.10. Types of erosion appeared in the Rugendabari Sector**

The approach to the mining sites of the Rugendabari sector reveals a stark landscape, where the processes of gully, rill, and sheet erosion are scarily evident. By approaching closer to the Mpinga, Nkegete, and Karama sites, you can see how the removal of vegetation for mining has left the soil exposed and vulnerable. The first observation is the head-cut, or the steep, vertical face at the start of each gully. It's clear that runoff from rainfall is a primary driver as the water channels over the exposed ground, gaining speed and carving these deep incisions. These gullies aren't just minor ruts; they are significant cuts in the earth that snake downhill, expanding and deepening with each rain event. The sides of the gullies show signs of slumping and collapse, indicating that the erosion is an ongoing and aggressive process.

When you move further, the scale of the problem becomes clearer. The multiple interconnected gullies are forming a complex network, funneling sediment and water from the sites. The gullies on these mining sites vary in depth and width, a clear indicator of different ages and intensities of erosion. Some are relatively narrow and shallow, suggesting a recent formation, while others are wide and deep, signifying a prolonged period of active erosion. This process not only removes the topsoil but also carries away valuable minerals and pollutes nearby waterways with sediment.

The entire landscape is being reshaped by this unchecked geological force, transforming what was once a vegetated area into a scarred and unstable terrain.

There are numerous small channels, or rills, carved into the exposed soil, particularly on the sloped terrain surrounding the mining pits and waste dumps. These channels are typically a few centimeters wide and deep, forming an intricate branching network that funnels runoff. The rills are most pronounced in areas with minimal vegetation, such as recently disturbed earth and compacted footpaths, where the soil lacks the protective cover and root systems to resist the force of flowing water. The consistent presence of these rills indicates that the mining activities have significantly altered the natural landscape, leaving the soil vulnerable to the erosive power of rainfall.

The process of rill erosion of these sites appears to be a direct consequence of both the steep topography and the absence of soil stabilization measures. The water, unobstructed by vegetation gains momentum and concentrates into these small channels, effectively moving a considerable amount of soil downhill. Over time, these rills likely deepen and widen, potentially evolving into larger gullies if the erosion is left unchecked. This ongoing soil loss not only degrades the immediate landscape but also poses a risk of sediment runoff into nearby water bodies, impacting water quality and local ecosystems.

The appearance of sheet erosion in Rugendabari sector was noticed by the extensive land clearing that took place for the mining operations. This removal of vegetation has left the soil bare and unprotected. The lack of roots to hold the soil together makes it highly vulnerable to erosion. Following a recent rainfall event, I can see a thin, uniform layer of topsoil being washed away across the land. This is a classic sign of sheet erosion where runoff water moves over the surface in a broad sheet, picking up and transporting loose soil particles. The reddish-brown color of water in the nearby gullies and streams is a clear indicator of the suspended sediment, a direct result of this process. This erosion is more pronounced on the steeper slopes where the velocity of the runoff is higher, giving it more energy to detach and carry soil.

The consequences of this observed sheet erosion are significant and widespread. The most immediate impact is the loss of the fertile topsoil, which is crucial for any potential future land use, such as agriculture. This loss of soil fertility is a major environmental concern. Downstream, the sediment-laden runoff is deposited in rivers and streams. This buildup of sediment can choke

waterways, harm aquatic ecosystems, and alter the flow of water. The mining sites themselves show visible signs of this loss with a hardened less, permeable surface layer left behind after the topsoil has been stripped. This reduces the soil's ability to absorb water, leading to more runoff and a cyclical process of continued erosion. The observations underscore the urgent need for erosion control strategies (Revegetation, drainage management).

### **2.11. Mining activities on the vegetation cover**

The mining process unfolds in 5 stages, including prospecting, exploration, development, mining or extraction, and reclamation. It starts with prospecting, which involves assessing the mineral reserves to determine the deposit's economic viability. The second stage is the exploration phase focuses on planning the mine's opening and extraction methods. The third stage involves development through the construction of infrastructures, open-pit facilities, roads, and other infrastructure. The fourth stage is the extraction process, where the mineral is removed from the earth. The final stage of mine life cycle is land reclamation from a disturbed mine site. This stage is crucial to prioritize land and vegetation restoration throughout mining operations to ensure the sustainable future development of the landscape, a consideration that also holds significant interest for ecological research (Hartman & Mutmansky, 2002).

Mining activities impact vegetation cover, leading to significant ecological changes. The process often necessitates the clear-cutting of forests and other plant communities to access mineral deposits, directly destroying existing ecosystems. This initial clearing not only removes established vegetation but also disrupts the delicate balance of the soil, making it vulnerable to erosion. Additionally, the construction of infrastructures like roads, processing plants, and waste dump dams further expands the footprint of disturbance, preventing natural revegetation (Shanmukha et al., 2024). Dust generated from mining operations can settle on remaining vegetation, impairing photosynthesis and growth, while the alteration of water tables and the introduction of pollutants into the soil can create conditions unsuitable for many plant species to survive or thrive. Consequently, mining often results in a drastic reduction in biomass, a loss of plant biodiversity, and a fragmented landscape that struggles to recover its original vegetative state (Ranjan et al., 2023).

Brock (2020) emphasized the importance of incorporating mine closure planning into every stage of a mine's life cycle. This begins even before mining commences, with the removal of topsoil

and the storage of vegetation in landfills. Ultimately, the successful reuse of land after mining benefits not only the mining company but more significantly the landowners and surrounding communities. The extractive industry fundamentally transforms the environment, making it essential to monitor the condition of both the landscape and vegetation to understand and assess potential impacts.

## 2.12. Soil conservation practices review in Rwanda

In Rwanda, several studies have validated the effectiveness of soil conservation practices, with terracing emerging as a particularly potent solution. Research by Rutebuka et al. (2021) in two contrasting agro-ecological zones of Rwanda provides critical data on the performance of different terracing techniques. The study compared traditional slope farming to two consecutive methods (bench terracing (BT) and progressive terracing (PT)).

The findings demonstrate that the bench terracing, a radical and well-engineered method, significantly outperformed all other techniques, leading to negligible soil loss. The study found that bench terracing achieved a high effectiveness in runoff reduction, ranging from 70% to 85% at the study sites. Similarly, the progressive terracing method, a farmer-developed technique, also showed substantial potential in achieving a 93% soil loss reduction in mountainous areas. The associated USLE p-factor values, which quantify the effectiveness of conservation practice, highlight this success: Bench terracing had an annual average P-factor of 0.001 to 0.02, while progressive terracing ranged from 0.07 to 0.55. The evidence from the study suggested that while both methods are effective, the success of progressive terracing is highly dependent on the quality of its installation.

**Table 2:**Comparative effectiveness of terracing techniques

<b>Terracing type</b>	<b>Runoff reduction (%)</b>	<b>Soil loss reduction (%)</b>	<b>Average USLE P-factor</b>
Bench Terracing (BT)	70-85	Negligible	0.001-0.02
Progressive Terracing (PT)	Up to 52%	Up to 93%	0.07-0.55

Source: Rutebuka et al. (2021)

Terracing remains one of the most effective soil conservation techniques in Rwanda. Rutebuka et al. (2021) demonstrated that both radical and progressive terraces substantially reduced water-driven soil erosion, especially on steep slopes. Their study confirmed terracing as a cornerstone of Rwanda's erosion control policies. Similarly, to Majoro et al. (2023) underscore terracing's contribution to long-term soil productivity and hydrological regulation in hilly landscapes.

Agroforestry integrates trees with crop/livestock on the same land. Hategekimana et al. (2025) emphasizes that smallholder farmers in Rwanda are increasingly adopting agroforestry due to its dual benefits in improving soil fertility and reducing erosion. Trees provide permanent cover, slow surface runoff, and enhance infiltration, thereby minimizing soil displacement. Nahayo et al. (2016) also identified agroforestry as one of the widely adopted conservation practices in Northern Rwanda, influenced by socioeconomic and institutional factors.

Afforestation or establishing forest cover on degraded or bare land, plays a key role in erosion control by increasing vegetation density and root stabilization. Karamage et al. (2016) highlighted that deforestation in the Nyabarongo River catchment significantly contributed to high erosion risks and restoring forest cover was essential in controlling soil loss. Majoro et al. (2023) further noted that afforestation in Sebeya watershed improved slope stability and long-term sustainability of soil conservation efforts.



### 3.1.1. Climate

This region's climate comprises four seasons: a short rainy season from October to December, a short dry season from January to March, a long rainy season from April to June, and a long dry season from July to August. The area has an annual precipitation of 232.02mm and steep topography. Its annual temperatures range from 13 to 20 °C. The average annual rainfall was provided by the stations of Meteo-Rwanda surrounding the study area.

**Table 3:** Annual rainfall in Rugendabari Sector from 2016 to 2025

Year	Latitude/Easting	Longitude/Northing	Total Precipitation(mm)
2016	-1.95	29.66	1307
2017	-1.95	29.66	1657
2018	-1.95	29.66	1382.7
2019	-1.95	29.66	1249.8
2020	-1.95	29.66	1699.3
2021	-1.95	29.66	2332.8
2022	-1.95	29.66	2213.3
2023	-1.95	29.66	1742.1
2024	-1.95	29.66	1177.8
2025	-1.95	29.66	1485.3

Source: Rwanda Meteorological Agency (2025)

### 3.1.2. Population density

Rugendabari sector has an average population of 406.2 inhabitants per square kilometer (NISR 2022), which is less than but closer to Rwanda's overall population density, estimated at 553 inhabitants/km<sup>2</sup>. So, this highest demographic will contribute to resource demands and hence accelerate soil erosion in the Rugendabari sector.

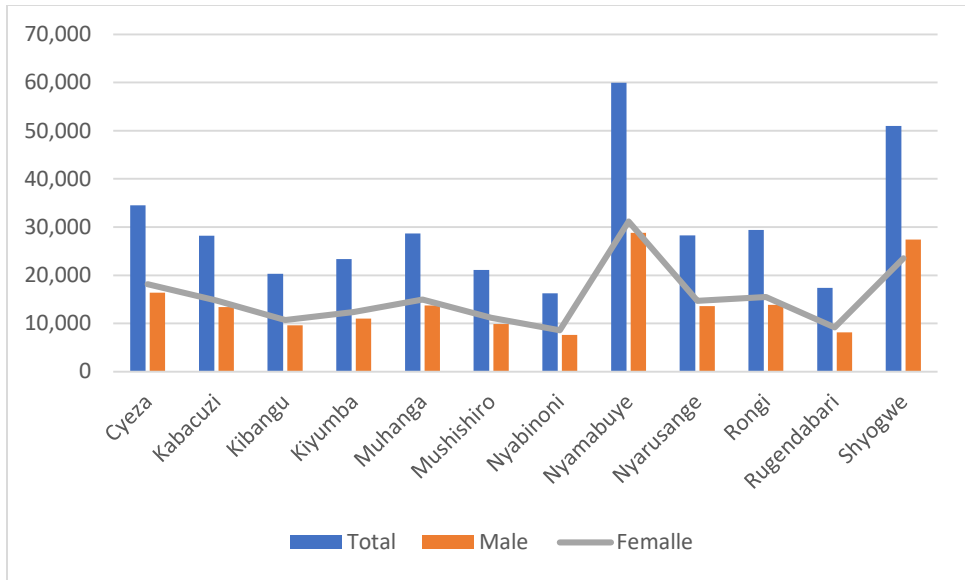
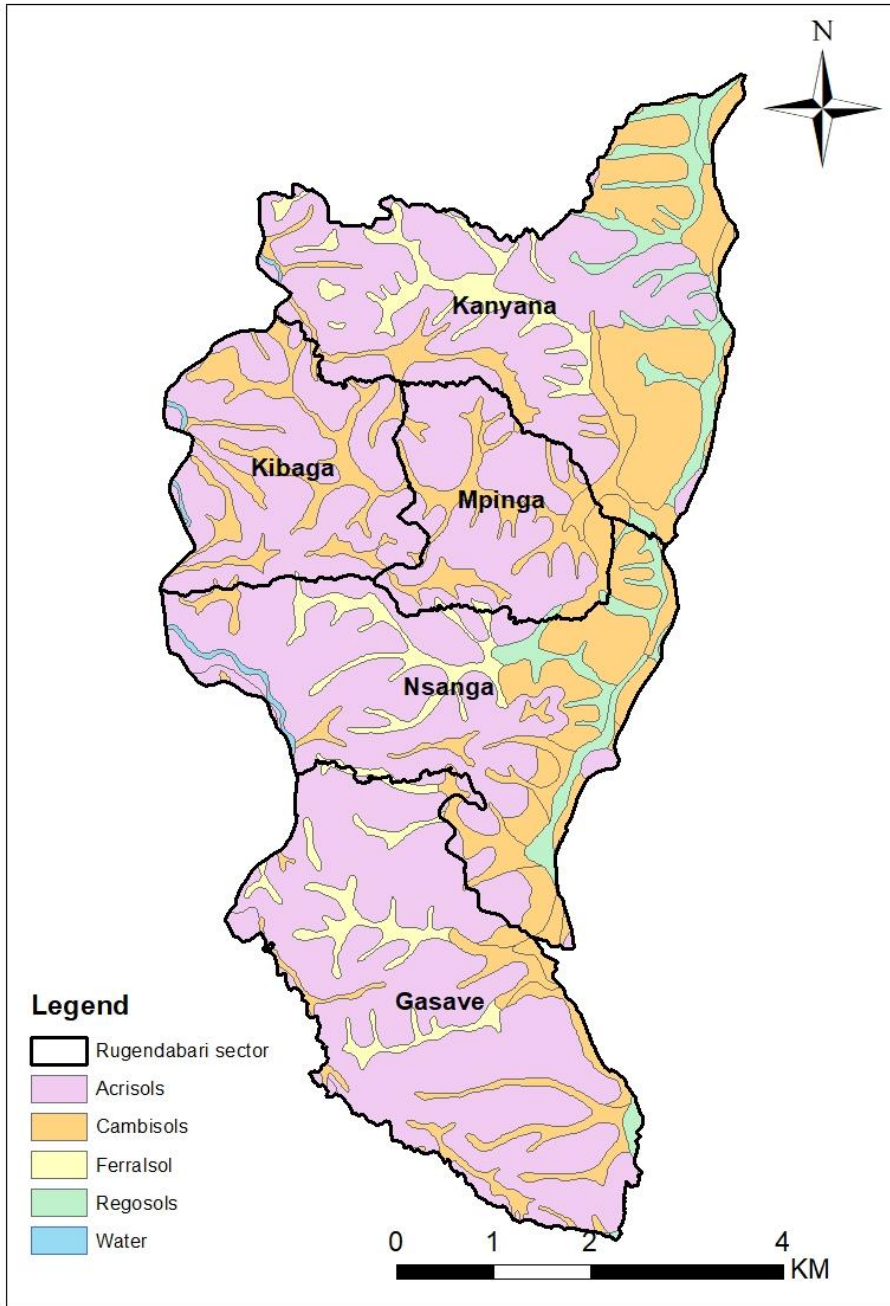


Figure 2: Population distribution of Muhanga district

Source: NISR (2022)

**3.1.3. Soil characteristics**

Most parts of the Muhanga district are composed of kaolisols. This type of soil was developed by weathering different parent materials, mainly clay, iron, and aluminium oxides. The presence of iron and aluminium oxides makes it reddish. The profile of kaolisols reveals an upper humus horizon of low humus, while the structure of the middle section differs for different subtypes, but it generally shifts gradually from the humus horizon to the parent rock. The Rugendabari sector mostly consisted of humic Kaoli soils derived from granitic rocks, weathered and mixed with iron and aluminium oxides, classified in five classes as shown in **Figure 3**: Acrisols, Combisols, Ferralsol, Regosols, and Water. The area is also composed of clay soils rich in silts, especially in their alluvial deposits (Muhanga, 2019).



**Figure 3:** Rugendabari soil map

Source: Muhanga District (2019)

### 3.3. Data analysis and interpretation

The data analysis and interpretation for this research primarily uses the Revised Universal Soil Loss Equation (RUSLE) model to model mining-induced soil erosion risks on vegetation cover spatially. The methodology integrates with Geographical Information System (GIS) and Remote

Sensing (RS) techniques to analyze key factors, including rainfall erosivity, soil erodibility, slope length and steepness, cover management, and conservation practices. The RUSLE parameters are computed using ArcGIS software and supported by satellite imagery (Landsat 8, ESRI LULC) and other spatial data. The analysis also incorporates field measurements, such as determining the total suspended solids (TSS) in one stream found in Rugendabari sector (Birikana stream) to assess sediment yield and its contribution from mining activities. Furthermore, a comparison of Normalized Difference Vegetation Index (NDVI) maps from 2014 and 2025 was used to analyze the impact of soil erosion on vegetation cover. The findings from these models and measurements were cross-referenced with primary data from interviews with local farmers, miners, and local leaders to validate the results and provide a comprehensive understanding of the environmental impacts.

### **3.3.1. Revised Universal Soil Erosion Equation (RUSLE)**

By calculating soil loss due to erosion, the universal soil loss equation (USLE) was one of the most commonly used methods to estimate soil erosion loss rate (Wischmeier & Smith, 1978). The limitations of this model it predicts the soil loss on low erosion plots with low erosion rates. USLE determines the sheet erosion that has small rills and can't differentiate between sheet and rill erosion (Evans & Boardman., 2016).

The USLE has often been criticized in past soil erosion research due to its restricted applicability and its failure to identify the specific cause-and-effect connection leading to erosion. Furthermore, its use in complex terrain has been questioned because the strength-length factor doesn't account for the shape of the upslope area. Despite its global acceptance, the key limitation of this model is its inability to quantify the process of soil deposition (Alewell, 2019). The USLE model faces the problem of failing to differentiate individual factors influencing soil erosion, such as plant growth, decomposition, water infiltration, runoff detachment, or sediment transport. Its performance is inadequate at the regional scale because runoff exerts a greater influence on soil erosion estimates than the kinetic energy of raindrops. Additionally, the model is incapable of calculating sediment yield from a single storm event (Alewell, 2019).

The original USLE model was developed into the revised universal soil loss equation (RUSLE) (Renard. et al., 1997); hence, it considers different parameters like topography, soil, rainfall, and land use. The RUSLE model was selected due to its different advantages related to existing

known data, assisted by GIS software. Different authors documented that RUSLE, combined with GIS, estimates accurate soil loss based on cell small part to determine soil erosion, then combines different cells to get the total loss of the study area (Byizigiro et al., 2020).

The amount of soil loss due to erosion is expressed as follows:

$$A = R \times K \times LS \times C \times P \quad (\text{Equ 1}) \quad (\text{Byizigiro et al., 2020})$$

Where A = Average annual soil loss in tons/ ha/ year

R = Rainfall-runoff erosivity factor (MJ mm ha/h<sup>1</sup>/ year)

K = Soil erodibility factor (tons ha h /ha/ MJ/mm)

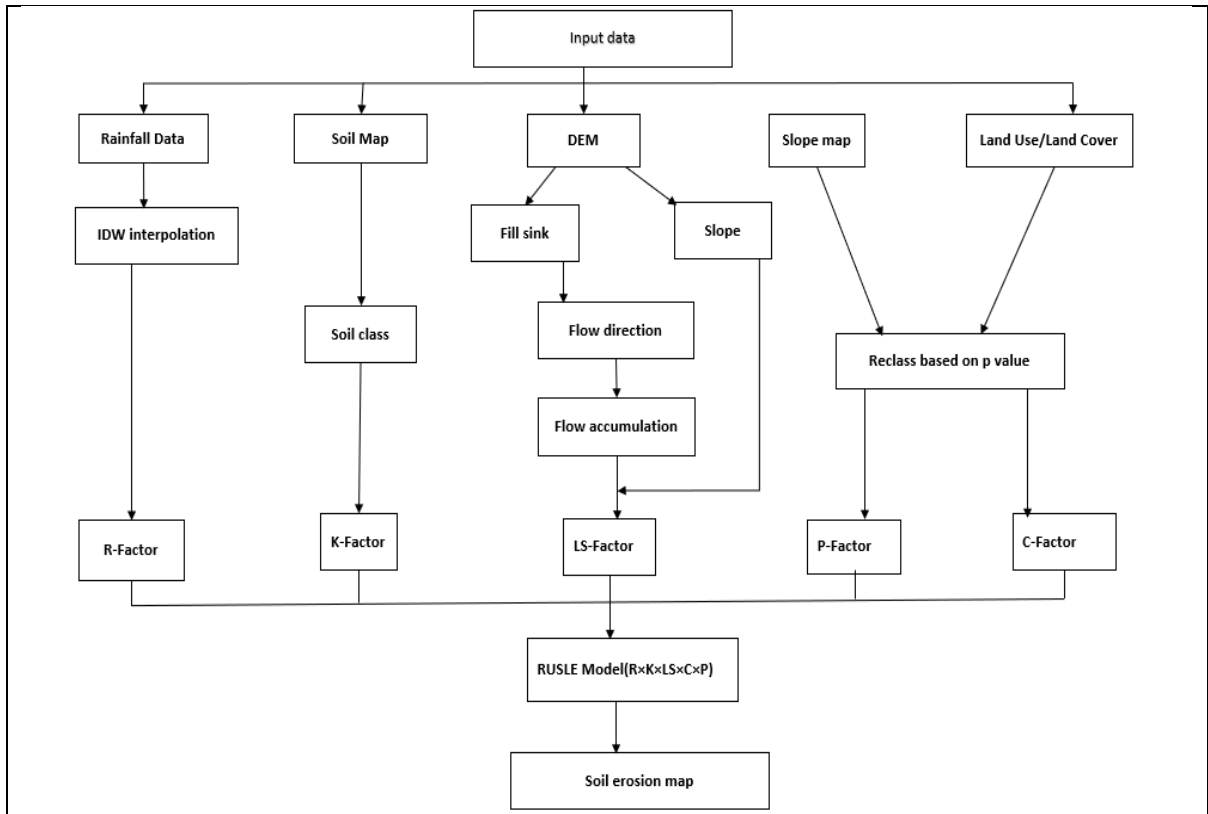
LS = Slope length and steepness factor (dimensionless)

C = Cover management factor (dimensionless, ranges from zero to one)

P = Conservation practice factor (dimensionless, ranges from zero to one)

These factors are utilized in the RUSLE model. The land cover management factor is derived from land use and land cover data that is generated from the Landsat images. The rainfall data from 2015 to 2025, generated by the Rwanda Meteorological Agency, data used to estimate rainfall erosivity(R). The existing digital elevation model (DEM-10m) of Rwanda was processed to generate the topographic factor (LS). The reclassification of slope produces the support practice factor (P). While the soil erodibility factor (K) was generated based on the Vital Sign project (<http://www.vitalsigns.org>), which is a soil database project implemented in African countries, including Rwanda (Byizigiro et al., 2020).

All data collected from different sources are uploaded into the software manual for modeling. The polygons merged with the designed code, then formed a vector map that was converted into a raster of the same references and a DEM of 10m resolution. The data collected was combined in ArcGIS to form grid cells, each of which must hold the true location in space and show the orientation and size. Then the cell sizes will be measured and computed using the statistical tool in ArcMap.



**Figure 4:** RUSLE model flowchart

Source: Kebede et al. (2021)

The following factors are calculated as follows:

**a) Rainfall erosivity (R)**

The rainfall erosivity factor explains the impacts of raindrops on soil. It also explains and shows the extent of runoff that is likely to be due to rainfall intensity. To estimate this factor, we need the continuous rainfall data (Fayas et al., 2019). This factor is obtained from a combination of intensity, magnitude, and duration of each recorded rainfall. Previously, the R-factor was calculated as the product of the total kinetic energy of a rainstorm (E) and its maximum 30-minute intensity (I30).

For a single year, the R factor is the total of all individual rainstorm erosion index values (Benavidez et al., 2018), and over the n-year timeframe, the R factor is calculated as follows:

$$x = \sum_{i=1}^{12} \frac{p_i}{pn} \quad (\text{Equ 2})(\text{Mohamadi \& Kavian, 2015})$$

$$R = 4.17x - 152 \quad (\text{Equ 3})(\text{Mohamadi \& Kavian, 2015})$$

Where  $p_i$  is the mean monthly precipitation (mm),  $p_n$  is the mean annual precipitation (mm), and  $x$  is the ratio of precipitation variation.

The rise of intensity and rainfall will increase the R factor; the estimation of the average R factor depends on analyzing annual rainfall data gathered over a long period. For every storm, its erosion index will be the product of its kinetic energy (E) generated by raindrops with the highest intensity recorded in 30 minutes of the storm (Renard et al., 1997a).

So, the R-factor is calculated as follows:

$$R = \frac{\sum_i^j EI_{30}}{n} \quad (\text{Equ 4})(\text{Mohamadi \& Kavian, 2015})$$

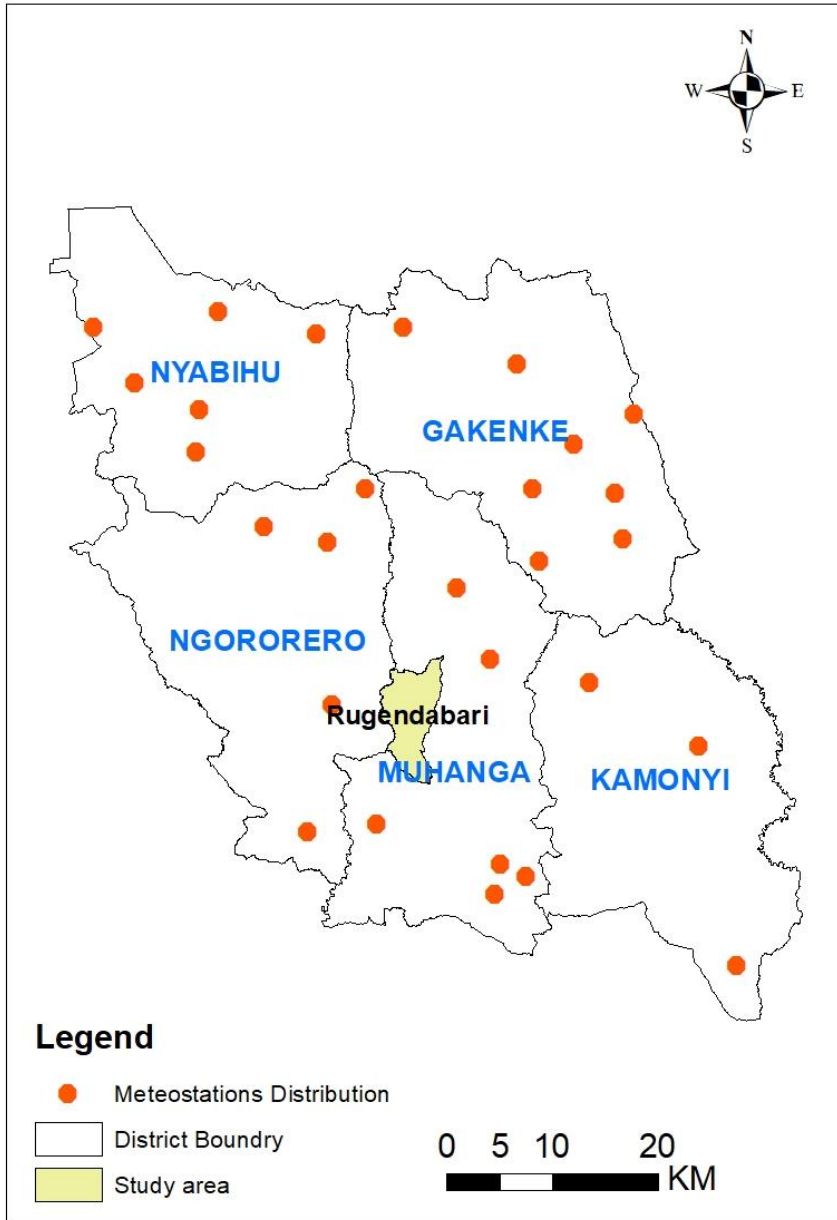
Where  $EI_{30}$  is the erosion index (MJ/mm/ha/h) for the storm,

$I$  and  $J$  are the number of storms in the  $n$ -year period,

$E$  is the total storm kinetic energy (MJ/ha/mm),

$I_{30}$  (mm/h) is the maximum 30-minute rainfall intensity.

However, the data were poor to provide the true results, thus impacting in creation of different models to handle that problem (Panagos et al., 2017). Different equations shall be used in determining the erosivity using the RUSLE model of any study area, but the erosivity dataset produced by Panagos et al. (2017) is more recommended for areas with low rainfall or no rainfall station measurements because its raster dataset is available freely. Then, rainfall variability and erosivity will be calculated using the inverse distance weighted method (IDW for interpolation).



**Figure 5:** Meteo-stations used to estimate precipitation in study area using the IDW method

Source: Rwanda Meteorological Agency (2025)

The data from Meteo Rwanda recorded from different stations surrounding the study area are computed and create the R raster map of Rugendabari sector. Thus, the final R map will be produced by the following formula:

$$R = (0.526 * P) - 8.12 \text{ (Equ 5) (Julien et al., 2024)}$$

R: Rainfall erosivity factor (MJ mm ha<sup>-1</sup> h<sup>-1</sup> per year)

P: Average annual rainfall (mm).

### b) Soil erodibility (K)

The soil erodibility factor (K) depends on the ability of the soil to erode. It depends on soil properties such as soil texture, soil structure, organic matter of the soil, and soil permeability. Soil erodibility comes from the interaction of rainfall effects, runoff, and the infiltration capacity of soil. Soil erodibility factor (K) depends on the influence of soil surface and soil loss properties that appear during rainfall events, especially in upland areas.

Soil susceptibility to erosion depends on a wide range of interconnected physical, chemical, and mineralogical properties, including its texture, cohesion between soil particles, infiltration capacities, and organic content. Due to complex influence, it's difficult to accurately determine these values for every type of soil using just the limited set of soil properties. The soil erodibility nomograph is the recognized tool for determining K values. This tool uses 5 soil characteristics, including but not limited to modified silt percentage, modified sand percentage, organic matter percentage, structural class, and permeability class. According to Wischmeier and Smith (1965), the K values can be calculated using this nomograph for soils with a silt content below 70percent, provided all influencing factor data are accessible.

However, during practical time, especially at the scale, acquiring this comprehensive data is often challenging, and it may not be reliable to apply data from one area to another. This factor is defined as the rate of soil loss per unit of erosive energy created by the rainfall, calculated under the condition that the plot of land consists of clean bare soil with a slope of 9% and 22.6m long (Fayas et al., 2019). The soil map is digitized, and soil erosivity is calculated due to the type of soil.

Soil erodibility (K) describes how vulnerable a particular soil is to being washed away by rain and runoff. This vulnerability depends on the physical and chemical makeup of the soil itself. Factors like soil texture, structure, organic matter content, how well water drains through it, and even the concentration of iron, aluminum, and salts all play a role in how easily the soil particles are detached and carried away. The Rugendabari soil contents include sand, clay, silt, and loam. Then, to get the K factor, we will use the following formula:

$$f_{sand} = 0.2 + 0.3e^{(-0.256 \times ms \times (1 - \frac{msilt}{100}))} \text{ (Equ 6) (Wischmeier \& Smith, 1965)}$$

$$f_{cl - si} = \frac{msilt}{mc + msilt} \text{ (Equ 7) (Wischmeier \& Smith, 1965)}$$

$$f_{org} = 1 - \frac{0.256 \times Org C}{Org C + \exp(3.27 - (2.95 \times org C))} \text{ (Equ 8) (Wischmeier \& Smith, 1965)}$$

$$f_{hisand} = 1 - \frac{0.7 \times (1 - \frac{msilt}{100})}{(1 - \frac{ms}{100}) + \exp(-5.51 + 22.9 \times (1 - \frac{ms}{100}))} \text{ (Equ 9) (Wischmeier \& Smith, 1965)}$$

Where;

*fsand*: Factor of low soil erodibility due to coarse-grained sand particles in the soil

*fcl-si*: Factor for low soil erodibility due to high clay-silt ratios

*forge*: Factor for reduced soil erodibility due to high carbon content

*fhisand*: Factor for reduced soil erodibility due to very high sand content

*ms*: Percentage of sand with grain sizes of 0.05–2 mm

*msilt*: Percentage of silt with grain sizes of 0.002–0.05 mm

*mc*: percentage of clay with grain sizes of <0.0002mm

*orgC*: Percentage of organic carbon (Mamvunja, 2020).

Hence, soil erosivity calculation follows the equation below:

$$K = f_{sand} \times f_{cl - si} \times f_{org} \times f_{hisand} \text{ (Equ 10) (Wischmeier \& Smith, 1965)}$$

The computation of the K factor is done using the following formula:

$$\text{Fraction of organic carbon (F\_OrgC)} = (1 - ((0.0256 * [OC topsol]) / ([OC topsol] + \exp(3.72 - (2.95 * [OC topsol]))))) \text{ (Julien et al., 2024)}$$

$$\text{Fraction of Silt (F\_silt)} = (1 - ((0.7 * (1 - [SAND] / 100)) / ((1 - [SAND] / 100) + \exp(-5.51 + 22.9 * (1 - [SAND] / 100))))) \text{ (Julien et al., 2024)}$$

$$\text{Fraction of Clay (F\_clay)} = ([silt top] / [clay top] + ([Silt top]))^{0.3} \text{ (Julien et al., 2024)}$$

$$\text{Fraction of Sand (F\_sand)} = (0.2 + (0.3 * \exp((-0.256 * [sand top] * (1 - [silt top] / 100)))) \text{ (Julien et al., 2024)}$$

$$K \text{ Fcator: } [F\_orgC] * [F\_sand] * [F\_silt] * [F\_clay] * 0.1317. \text{ (Julien et al., 2024)}$$

The soil erodibility factor will be classified according to Table 2 below;

**Table 4:** Soil features and the corresponding k factor

<b>Textural class</b>	<b>K Factor (ton/Hectare)</b>
Clay	0.49
Clay loam	0.60
Loam	0.67
Loamy sand	0.09
Sand	0.04
Sand clay	0.45
Silty clay	0.58

Source: Allafta & Opp (2022)

**c) Land surface cover management factor (C)**

Land cover management factor explains how vegetation cover affects the rainfall energy, overflows, and infiltration capacity of soil (Nearing et al., 2005). When the cover management value is equal to 1 means that no vegetation is found on the land; however, when the vegetation cover tends to be zero, it means that all soil is covered by vegetation (Oliveira et al., 2015). Calculating the C-factor perfectly requires expensive and time-consuming field experiments under natural rain.

Many countries have never conducted field studies, and they lack their own data that resulting in the adaptation of C-factor values from the United States and using them within GIS to map erosion in their regions (Ganasri & Ramesh, 2016). To determine the C-factor using remote sensing data, we use two methods. Both methods use the Normalized Difference Vegetation Index (NDVI) because the data is readily available and simple to work on it. NDVI is a widely used indicator that measures how long green and healthy vegetation is by analyzing satellite imagery from -1 to 1, which indicates increased vegetation (Almagro et al., 2019).

$$NDVI = \frac{NIR-RED}{NIR+RED} \text{ (Equ 11) (Oliveira et al., 2015)}$$

Where;

NIR is the surface spectral reflectance in the near-infrared band

RED is the surface spectral reflectance in the red band

The first proposed method to determine the C-factor was generated by (Durigon et al., 2014), and adapted by (Colman, 2018) ( $C_rA$ ), and the second method was developed by ( $C_vK$ ). These C-factors ( $C_rA$  &  $C_vK$ ) were calculated through below equations:

$$CrA = 0.1 \frac{(-NDVI+1)}{2} \text{ (Equ 12) (Oliveira et al., 2015)}$$

$$Cvk = \exp\left(-\alpha \frac{NDVI}{(\beta-NDVI)}\right) \text{ (Equ 13) (Oliveira et al., 2015)}$$

Where;

$C_rA$  and  $C_vK$  are the estimated C-factors,  $\alpha$  and  $\beta$  parameters are related to the shape of the curve that associates NDVI with the C-factor. The adjusted C-factor method for this research depends on the original method.  $C_rA$  was found to have significant errors by Colman (2018), who suggested an adjustment factor of 0.1 to improve its accuracy. Since another study by Sone et al. (2019) confirmed this adjustment works well and then we decided to use it.

The c-factor quantifies how different land use and land cover (LULC) types influence soil loss rates. Determining this factor requires details on soil management practices, the role of crop and canopy residues as soil loss cover, soil moisture levels, and the irregularity of the soil surface. For my study, Esri Rwanda's LULC classification was used to derive the c factor (Roslee & Sharir, 2019). The Rugendabari sector land was categorized into relevant LULC types from which the C parameter was extracted to create a C factor map. This raster map was then converted to vector format to assign a corresponding C factor value to each LULC type as presented in the accompanying Table 6 (Thakuri et al., 2019).

**Table 5:** Land Use-Land Cover type, and C factor

No	LULC type	C Factor
1	Shrubland	0.03
2	Built-Up	0.00
3	Forest	0.03
4	Grassland	0.01
5	Agriculture land	0.21
6	Barren land	0.45
4	Wetland	0.24
5	Waterbody	0.00
	Snow glacier	0.00

Source: Thakuri et al. (2019)

#### d) Slope length steepness factor (SL)

The LS-factor is the product of slope length(L) and slope steepness factor (S). The slope length factor (SL-factor) is expressed as a ratio, and it compares the real soil loss observed on a specific slope to the soil loss that occurs on the standardized plot within a length of 22.23m (Schmidt et al., 2019).

$$L = \left( \frac{\lambda}{22.13} \right)^m \text{ (Equ 14) (Fayas et al., 2019)}$$

Where  $\lambda$  represents the length of the slope in meters, and m is the slope steepness. There is also the new approach developed and adapted by the RUSLE model to describe soil loss within increasing slope steepness from equation 15 below.

$$L_{i,j} = \frac{(A_{i,j-in} + D^2)^{m+1} - A_{i,j-in}^{m+1}}{D^{m+2} \times X_{i,j}^m \times 22.13^m} \text{ (Equ 15) (Schmidt et al., 2019)}$$

Where,  $A_{i,j-in}$  the flow accumulation in  $m^2$  at the inlet of the grid cell (i,j)

D is the grid cell in m

$X_{i,j}$  is the  $\sin a_{i,j} + \cos a_{i,j}$  where  $a_{i,j}$  is the aspect of the grid cell(i,j).

m is the coefficient that represents the ratio of rill and interrill erosion and is calculated by the beta value ( $\beta$ ), which ranges between 0 and 1.

$$m = \frac{\beta}{\beta+1} \text{ (Equ 16) (Schmidt et al., 2019)}$$

$$\beta = \frac{\sin \theta / 0.0896}{0.56 + 3 \times (\sin \theta)^{0.8}} \text{ (Equ 17) (Schmidt et al., 2019)}$$

Where  $\theta$  is the slope angle in degrees. S-factor is calculated by the empirical formula proposed by McCool et al. (1987) and is used to calculate the slope steepness factor in RUSLE. McCool et al. (1987) developed the two relations between soil loss and slope steepness in radians; one with inclination less than 6% and the other with a value equal to or greater than 9%. These two relations are described as follows:

$$S = 10.8s + 0.03 \text{ (Equ 18) for slope steepness in percent } < 9\% \text{ (Schmidt et al., 2019)}$$

$$S = 16.8s - 0.50 \text{ (Equ 19) for slope steepness in percent } \geq 9\% \text{ (Schmidt et al., 2019)}$$

The S-factor proposed by McCool et al. (1987) is recommended for areas with low rainfall; however, there are also other different S-factors developed since the 1940s, but all of them have

in common that empirical evidence and thus validity is limited to slope gradients less than 50% (Schmidt et al., 2019). Then the SL-factor is calculated as:

$$SL = \left( \text{Flow accumulation} \times \frac{\text{Cell size}}{22.13} \right)^{0.4} \times \left( \frac{\sin \theta}{0.0896} \right)^{1.3} \quad (\text{Equ 20})(\text{Julien et al., 2024})$$

The SL-factor shows the effect of topography behavior affected by soil erosion. Here, as the slope gradient and slope length increased, the soil erosion increased, thus increasing of SL factor. The higher slope length and high slope gradient result in an increase in overland flow. Both slope length and slope gradient will be calculated through the following relation Fayas (2019). The SL is calculated by computing as follows:

$$SL = \text{Power}(\text{FlowAcc\_Flow3} * 30.82971254 / 22.13, 0.4) * \text{Power}(\sin(\text{Slope\_Extra24}) * 0.0174 / 0.0896, 1.3) \quad (\text{Equ 21.}) \quad (\text{Julien et al., 2024})$$

Where **LS**: Slope length and Steepness factor

**FlowAcc\_flow3**: Flow Accumulation.

#### e) **Support practice factor (P)**

Under the European Union's common agricultural policy (CAP), farmers receive incentives for meeting the standards. The reason for this is to implement good agricultural and environmental condition regulations, which require them to manage their land to prevent soil erosion and maintain soil quality/health (GAEC, 2009). To measure how these policies reduce soil erosion, the government uses risk models based on the universal soil loss equation (USLE) that became the most common model choice at the national level (Panagos et al., 2014). The P values delivered from image classification using remote sensing technique or from previous research or known experts (Karydas et al., 2009).

Among the six RUSLE/USLE input factors, the support practice P-factor is the most considerable factor. The P-factor explains how specific land management practices minimize soil erosion (Ebabu et al., 2022). This factor quantifies how conservation practices such as strip cropping, terracing, and subsurface drainage protect soil by controlling the pattern, velocity, and erosive force of water runoff (Morgan & Nearing, 2011).

The lower the P-factor value, the better the practice is for controlling soil erosion. The P-factor ranged from 0 to 1, where a zero value stands for a good anthropogenic erosion resistance facility and a value of 1 indicates a non-anthropogenic erosion resistance facility (Byizigiro et

al., 2020). Contour farming, terracing, and strip cropping are commonly indexed and documented control measures and are presented in Table 7 below.

**Table 6:** Support practice factor values as per soil conservation practice

Slope %	Strip cropping (P)	Contour Cropping (P)	Terrace Cropping (P)	
			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

Source: Byizigiro et al. (2020)

### 3.1.4. Land use in the Rugendabari sector

Two types of land use and land cover maps were used with a resolution of 10m. The global land use and land cover map published in 2024 by ESRI shows that the Rugendabari sector is dominated by agriculture, which accounts for around 35.7%, forestry, 24.3%, built-up area 4.2%, grassland 30.4%, and mining activity, which accounts for 4.3%. Below is a summarized table of the land use and land cover of the Rugendabari sector.

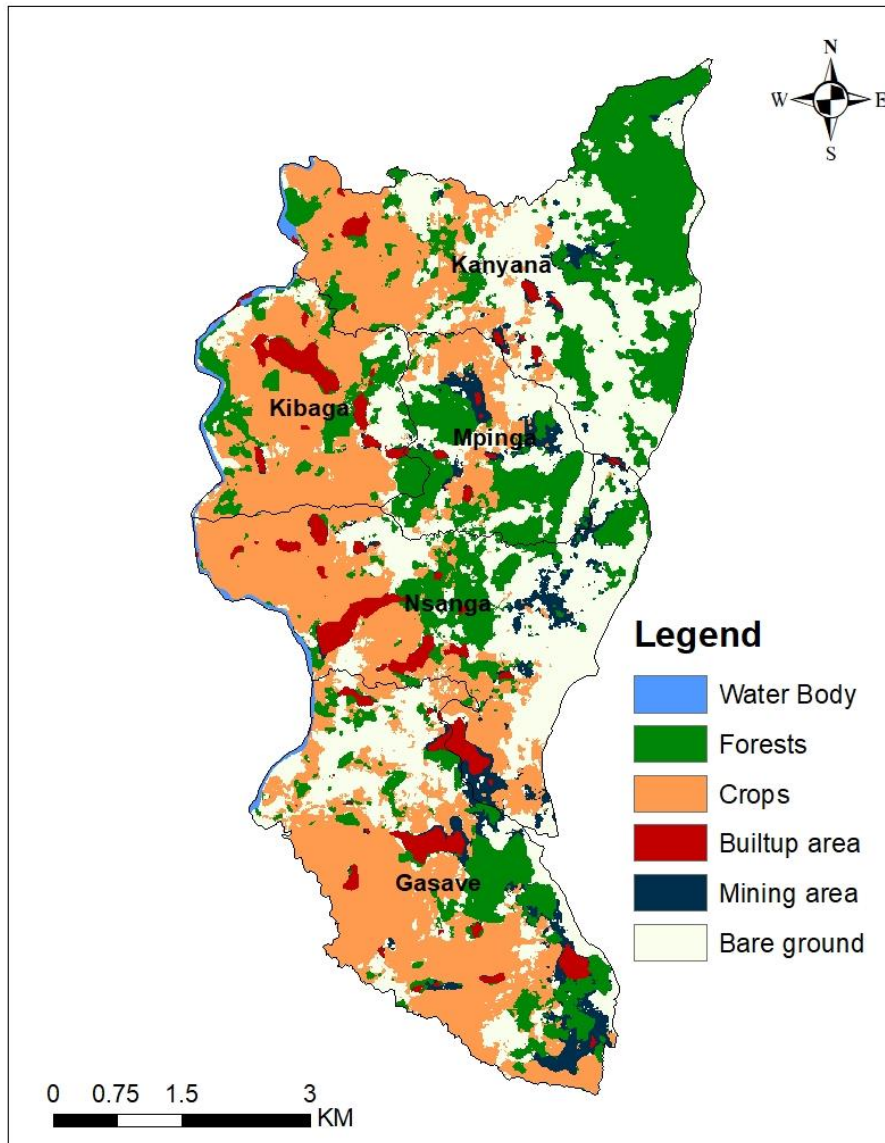
**Table 7:** The LULC of Rugendabari sector in 2025

Land Use	Count	Percentage
Water Bodies	4508	1.1
Forests	103991	24.3
Crops	152733	35.7
Built-up Area	18310	4.2
Mining area	18424	4.3
Grassland	130117	30.4
	428083	100

Source: Source: ESRI (2024)

In different sectors, decision makers consider different parameters to determine the reality of land cover data, including high resolution, accuracy, duration, and comparison with the latest data. The maps exported from the previous parameters can be the greatest solution for different projects related to human health, land use planning, and different modeling. The updated land use land cover was downloaded from the ESRI web with a variable land use land cover of 2024

in Universal Transverse Mercator (UTM), Mosaic projection is WGS84, and the source of image is Sentinel 2 with a cell size of 10m.



**Figure 6:** The LULC of Rugendabari sector in 2025

source: ESRI (2025)

### **3.2. Data collection methods and techniques**

The research was built on a comprehensive approach, integrating both primary and secondary data to ensure a robust and experienced analysis. Primary data are gathered directly through observations, sampling, and interviews, which provide firsthand insights and unique perspectives from participants. This was complemented by a thorough review of secondary data, including existing academic literature, statistical reports, online platforms, online databases, science bureaus or agencies, and archival documents. By triangulating these two sources to validate the findings.

#### **i. Primary data**

Primary data was collected directly from the study area through field measurements and interviews. The researcher conducted field measurements to determine the total suspended solids (TSS) in Birikana stream. This involved using a plastic bottle to collect water samples from the stream. Additionally, the researcher conducted interviews with 15 local farmers, 15 miners, 3 stakeholders, and 3 local leaders across three cells in the Rugendabari sector to gather actual information. The responses from these interviews were collected using the Kobo tool and used for comparison with the field and the computed results. The study also utilized rainfall data from the Rwanda Meteorological Agency from 2016 to 2025, which was used to estimate rainfall erosivity.

#### **ii. Secondary data**

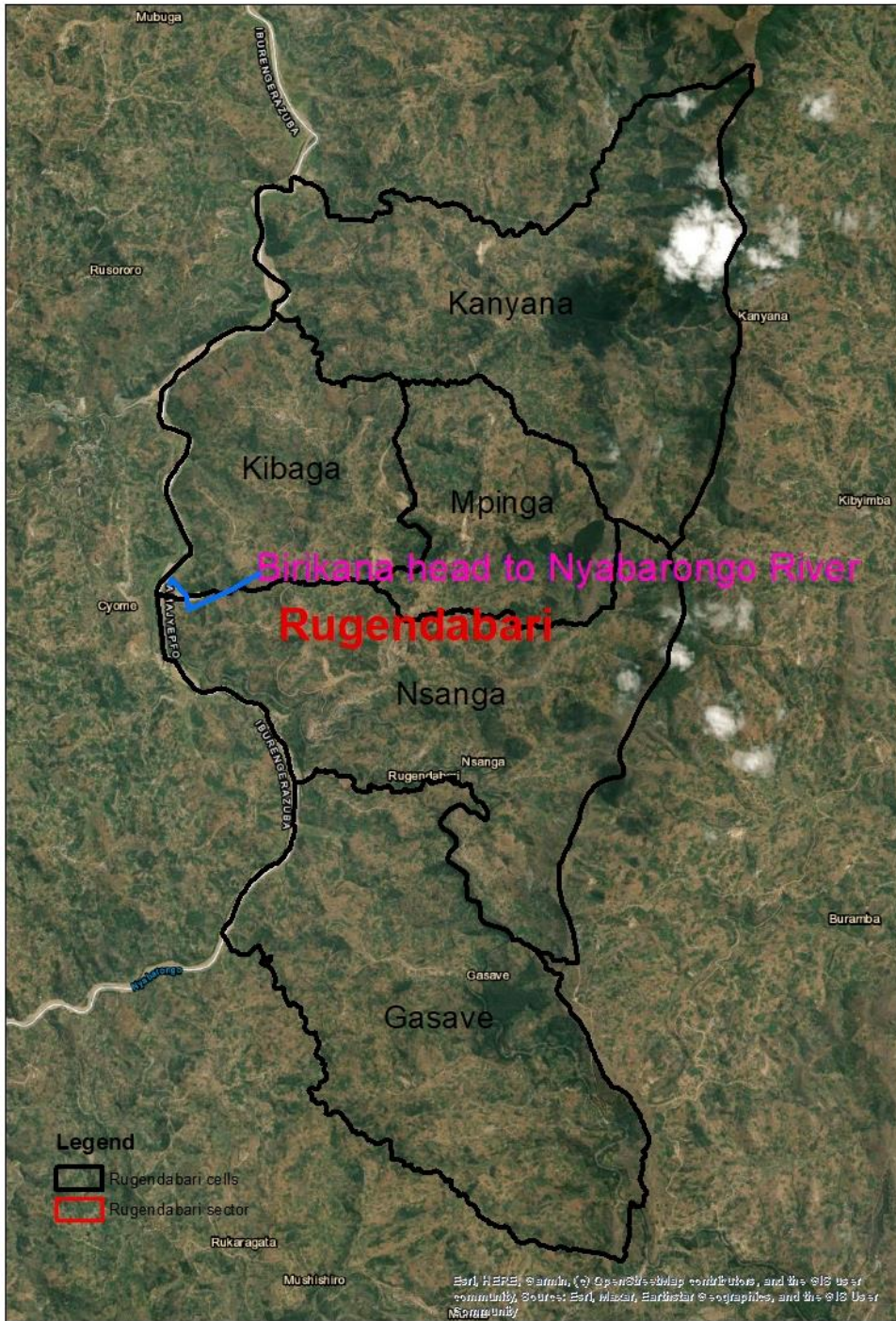
Secondary data for this research were gathered from a variety of sources, including existing spatial data and scholarly publications. The study used Geographical Information Systems (GIS) and remote sensing techniques, incorporating satellite imagery from Landsat 8 and ESRI LULC (Land Use Land Cover) to model soil loss and analyze factors like vegetation cover. The researchers also drew on data from the National Institute of Statistics of Rwanda (NISR 2022) to understand population density. Furthermore, the methodology was informed by a review of literature on soil erosion, mining impacts on soil, and existing research on soil erosion models in Rwanda. The documents include a comprehensive reference list of peer-reviewed articles and reports to support the background and methodology.

### **3.4. Soil loss determination**

During soil loss calculation, the study depends on stream flow and suspended solids in Birikana stream, Rugendabari sector

#### **a) Stream flow**

The discharge of the Birikana stream was measured using the cross-section area velocity method or the current meter method. This method measured the stream flow within a 1m depth and a 5m wide section of the Birikana stream, which is divided into 5 sections of 1m each. The stream flow of the Birikana stream was measured manually by bubbling a plastic bottle and recording the velocity from the starting point to the ending point. The following figure illustrates the Birikana stream outlet to the Nyabarongo River near Cyome bridge.



**Figure 7:** Birikana stream and which heads to the Nyabarongo River

Source: ESRI (2025)

The discharge of Birikana stream is calculated using the continuity formula.  $Q=V*A$  (Equ 22), where Q stands for Discharge (Amount of water passing a whole cross-section in stream) of stream expressed in cubic meters per second ( $m^3$ ), V is average stream velocity expressed in meters per second(m/s), and A stands for cross-section area of the stream expressed in square meters ( $m^2$ ).

Cross-sectional area will be determined by multiplying the width of the stream by its height,  $A=W*H$  (Equ 23) expressed in square meters ( $m^2$ ), while stream velocity (V) will be determined through measuring the displacement of flowing water corresponding to the froth material placed on the water.



**Figure 8:** Birikana stream measurement (Cross-section area and Velocity)

Source: Field survey (May,2025)

### **b) Total Suspended Solids**

The process of extracting minerals can increase the amount of TSS that flows into nearby bodies of water. Specific mining activities that contribute to TSS production include preparing the mine site, sorting and crushing materials, washing resources, and storing materials in areas exposed to rainfall. According to the American Public Health Association (APHA) standard method (Rice et al., 2012), total suspended solids are the organic and inorganic materials in a given water sample

that are captured by a filter with a pore size of 2 micrometers ( $\mu\text{m}$ ) or even less. The quantity of TSS is determined by weighing the residue on the filter after it has been dried (Rice et al., 2012).

TSS consists of a mixture of sand, silt, clay, biological matter, and mineral precipitates, with its formation being primarily driven by the physical forces of water. TSS is generated and introduced into the stream through several hydrological processes, including the erosion of soil from adjacent land and stream banks, the scouring and resuspension of sediment from the stream bed, and the deposition of solid particles directly within the water column as dissolved organic matter clumps together or inorganic solids precipitate (Butler & Ford, 2018). However, total dissolved solids (TDS) are defined as the portion of organic and inorganic solids that are small enough to pass through a standard 2- $\mu\text{m}$  filter. The most direct method involves taking a known volume of the filtered water, evaporating it completely, and then weighing the solid residue left behind.

### c) Sampling

A 1L plastic bottle was used to collect the sample from the Birikana stream for analysis of sediment content. The samples were collected from undisturbed water inside the stream upstream.



**Figure 9:** Birikana stream water sampling

Source: Field survey (May,2025)

### d) Calculation of TSS concentration

Step 1: Take one bottle of 1 L, weigh the sample before the experiment to know the initial quantity of the sample.

Step 2: Shake the bottle before you pour the sampled water into the evaporation pan.

Step 3: Pour the sample into the evaporation pan.

Step 4: Heat the sample above 110 degrees Celsius to evaporate all the water.

Step 5: Measure the final product that persists to evaporate.

Step 6: Calculate the total suspended solids of the sample using the formula (*Equ 24*).

The total suspended solids are calculated by the following equation:  $TSS = \frac{F_s}{V_s}$  (*Equ 24*) expressed in milligrams per liter (mg/l). where TSS is total suspended solids,  $F_s$  is the dried solids left after evaporating water content, and  $V_s$  is the total volume of sampled material.



**Figure 10:** TSS concentration measurement

Source: Field survey (Jully,2025)

The experiment calculating TSS was conducted using the evaporation process, as shown in Figure 10(A), which includes the apparatus used: a weight balance, a Sample bottle, and an evaporating pan. In Figure 10 (B), we weighted the sample taken from the field, and the last picture, Figure 10 (C), shows the final mass of TSS found in sampled water from Birikana stream.

### **3.5. Sediment yield in Birikana stream**

The total amount of TSS of the stream within twenty-four hours is the sediment yield of that stream. It is calculated within 24 hours, and the calculation involves both discharge and TSS data. The TSS yield = Discharge/Day\* TSS (*Equ 25*), expressed in kg/day.



**Figure 11:** Sedimentation in Birikana stream

Source: Field survey (May,2025)

### **3.6. Assessing the contribution of mining activities to sediment yield**

Evaluating the precise contribution of mining works to the overall sediment yields of water bodies is a critical environmental management task. The suspended solids yield of Birikana, Gikumba, and Gisumo streams under natural conditions without anthropogenic activities is governed by a baseline of factors inherent to the region's climate and geography. Generally, natural sediment load is the product of the area's steep topography, the specific geology of the mining area, and the erosive factor of seasonal rainfall events acting upon the landscape. Moreover, in the Rugendabari

sector, this baseline equilibrium was disrupted by mining operations performed upstream. The activities, such as open-cast mining, mineral washing, stockpile creation, and tailings production, create unconsolidated materials in the area. These practices strip the land of its protective vegetation cover and expose loose-finely soils that become easily moved by runoff, leading to erosion creation and the sediment load far exceeding the stream's natural carrying capacity.



**Figure 12:** Sediments from an active mine polluting Rugendabari streams

Source: Field survey (May,2025)

In this research, the difference between the TSS yield of Rugendabari streams in their natural state versus their yields under the influence of various mining activities conducted upstream in this sector. By observation, there are differences. To establish a robust, data-driven assessment of the mining-impacted sediment loads are contrasted with a baseline, meticulously calculated to represent the stream's condition before the commencement of these works.

The quantitative understanding is paramount for local environmental stewardship, as elevated sediment yields have severe downstream consequences. These include the degradation of water quality for communities reliant on streams, the smothering of aquatic habitats, which harms biodiversity, and the increased risk of siltation that can damage critical infrastructure like water intake points. By isolating and measuring the sediment contribution directly attributed to mining, stakeholders must ensure that the laws and regulations for protecting the environment.

### **3.7. Soil erosion initiated by mining activities on the vegetation cover**

Rugendabari sector is one among the sectors of Muhanga district that holds a high amount of ore reserve, as described by different authors. This sector has around 20 mine sites that are exploited every day to recover the Tin, Tantalum, Tungsten (3Ts), and Lithium, which are concentrated in probable and proven ore deposits in this sector. The Mpinga mine site for Daba suppliers' Ltd extracts resources and processes them from one main open pit. The continuous mining operations and the disposal of solid waste from these large pits have led to considerable environmental damage and the destruction of vegetation in the area. Open-pit mining, which extracts ore by removing overlying rock and soil, inherently damages existing vegetation as the pit expands.

Furthermore, this method generates substantial solid waste, necessitating the construction of tailing dams. These dams occupy large land areas, thereby causing additional harm to the vegetation originally present on that land. Mining operations directly lead to a decrease in vegetation around the mine sites; typically, the reduction in vegetation cover signals an expansion of mining activities, including larger pits and the creation of tailing dams. This decline in vegetation is a direct consequence of mining processes like expansion and waste disposal.

The normalized different vegetation index (NDVI), which ranges from 0 to 1 effectively measures vegetation cover at a given area, with values closer to 1 indicating dense vegetation. Consequently, researchers such as Yu et al. (2023) have suggested using NDVI to monitor the progression of mine expansion and the success of reclamation efforts (Kuzevic et al., 2022).

The GIS software, combined with remote sensing data, effectively assesses and monitors vegetation conditions in mining areas by leveraging specific features. Landsat imagery has been used in mapping the footprint of surface mining and its ecological effects. Overall, shifts in vegetation serve as a key indicator for environmental change, with vegetation indices offering a powerful method to evaluate various environmental impacts at different scales.

This study utilized satellite imagery of the Rugendabari sector from 2017 and 2025, specifically Landsat 8 data for both years. All imagery employed had a 30m resolution and had undergone both geometric and atmospheric corrections. Additionally, the cloud cover for all satellite data was kept below 10%. Land sat 8 carries 2 sensors. One operational land imager sensor is built by Ball Aerospace, and another by Technological Corporation, and the thermal infrared sensor is

built by NASA Goddard Space Flight Center. Nine bands were produced with a resolution of 30m.

**Table 8:** Band types provided by Landsat 8

Band	Name	Range (µm)
Band 1	Coastal aerosol	0.43-0.45
Band 2	Blue	0.45-0.51
Band 3	Green	0.53-0.59
Band 4	Red	0.64-0.67
Band 5	Near-Infrared	0.85-0.88
Band 6	SWIR1	1.57-1.65
Band 7	SWIR2	2.11-2.29
Band 8	Panchromatic (PAN)	0.50-0.68 (15m resolution)
Band 9	Cirrus	1.36-1.38

Source: Kuzevic et al. (2022)

The infrared light waves reflected by the surface transformed into vegetation indices. This vegetation index is an indicator that describes the greenness relative to the density and health of vegetation from the pixel. These indices are used in NDVI, where NDVI ranges from -1 to 1. So, the classification depends on the amount of NDVI, where NDVI below 0.1 describes the barren rock/sand, and NDVI ranging between 0.2 and 0.5 shows the presence of shrubs and grassland. While NDVI above 0.6 describes an intensive forest.

$$NDVI = \frac{NIR-RED}{NIR+RED} \text{ (Equ 11) (Kuzevic et al., 2022)}$$

### 3.8. Influences that make conservation practice be adopted

A successful conservation strategy cannot be limited to technical recommendations alone. The adaptation of soil conservation practices, such as terracing and agroforestry, is significantly influenced by a complex mix of socioeconomic and institutional factors, as highlighted by multiple studies on smallholder farmers in Rwanda (Uwiringiyimana & Choi, 2022).

The major barrier to adoption is the limited awareness and training among the stakeholders regarding effective soil conservation techniques and their long-term maintenance. This points to a need for enhanced extension services and bottom-up support programs to improve stakeholders' technical capacity. However, financial and socio-economic factors play a critical role. The high cost of establishing and maintaining conservation technologies, coupled with limited access to credit, acts as a significant deterrent. This suggests that a successful framework

must include financial mechanisms, such as tailored micro credit products, to ease the financial burden on farmers and miners (Mukuralinda et al., 2020).

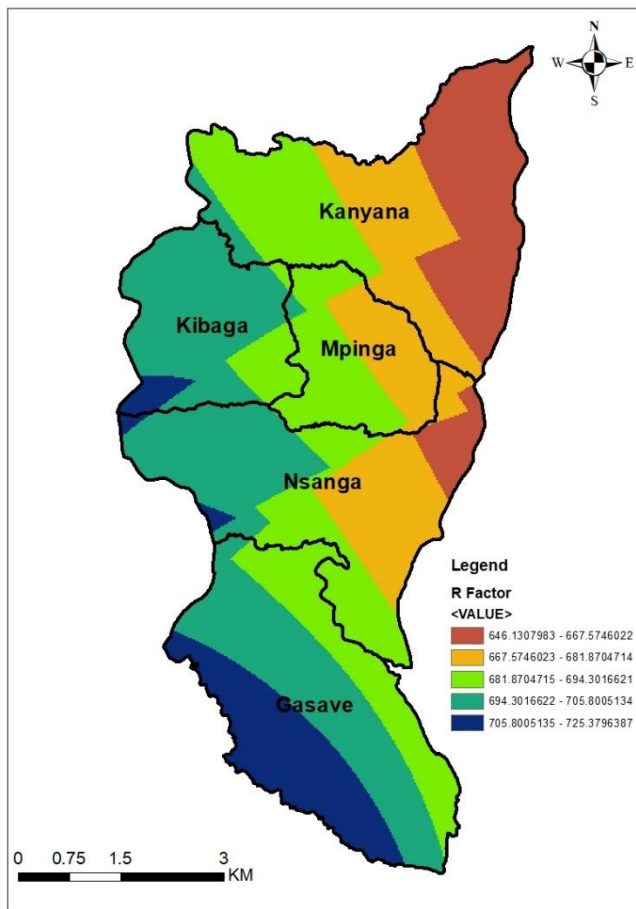
The issue of land tenure security is also a powerful determinant of adoption. Farmers who have secure land ownership, like those who inherited or purchased their plots, are more likely to invest in durable conservation measures because they have a long-term sense of land use rights and expect to benefit from improved land productivity over time. Conversely, those with insecure tenure are less likely to make such long-term investments (Nishimwe et al., 2021). Finally, institutional support, particularly from agricultural cooperatives and extension services, has a positive and significant influence on the adoption and intensity of conservation practices. These findings demonstrate that the problem is not a simple technical deficit but a holistic challenge involving environmental, technical, socio-economic, and institutional dimensions. A conservation framework that ignores these underlying factors must be ineffective in achieving widespread and sustainable change (Nabahungu & Visser, 2011).

## Chapter Four: Results

### 4.0. RUSLE model parameters

#### 4.1. Rainfall erosivity

The rainfall erosivity(R-Factor) was determined based on average rainfall from Rugendabari Sector, which varies between 307mm and 2332.8mm. The R-Factor values calculated range from 646 MJ mm/ha/h to 725 MJ mm/ha/h. The patterns of average rainfall in the Rugendabari sector show the distribution of high values in Gasave cell and low values in Kibaga cell. However, these R-Factor variations impact the soil loss amount because of anthropogenic activities, especially the most intensive activities of mining.

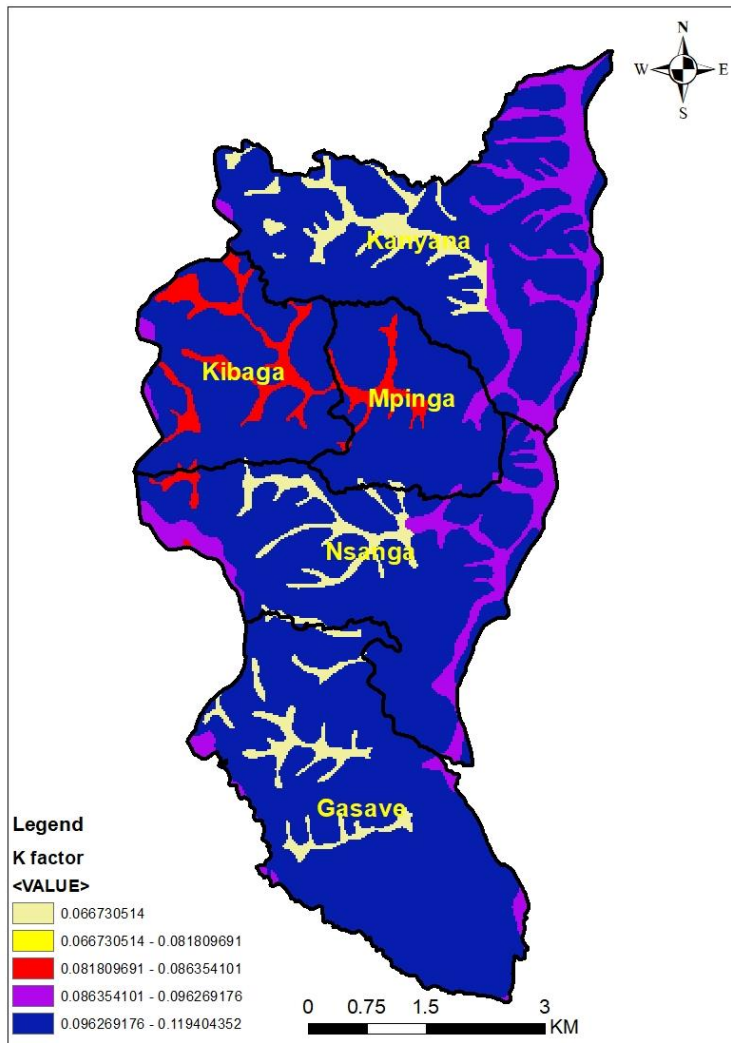


**Figure 13:** Rainfall erosivity (R-Factor)

Source: Rwanda Meteorological Agency (2025)

## 4.2. Soil erodibility (K)

Soil erodibility in Rugendabari sector depends on soil content, which refers to the amount of sand, coarse grain, clay-silt content, and carbon content. The high amount of coarse-grain sand reduces soil erodibility, the high clay-silt ratio reduces soil erodibility, and high carbon content also reduces soil erodibility. The high K factor is the tendency of soil erosion to occur. The Rugendabari erodibility ranges from 0.067 to 0.119 hahr/ha/MJ/mm. K is measured in Metric tons hectare hour per hectare per megajoule per millimeter.

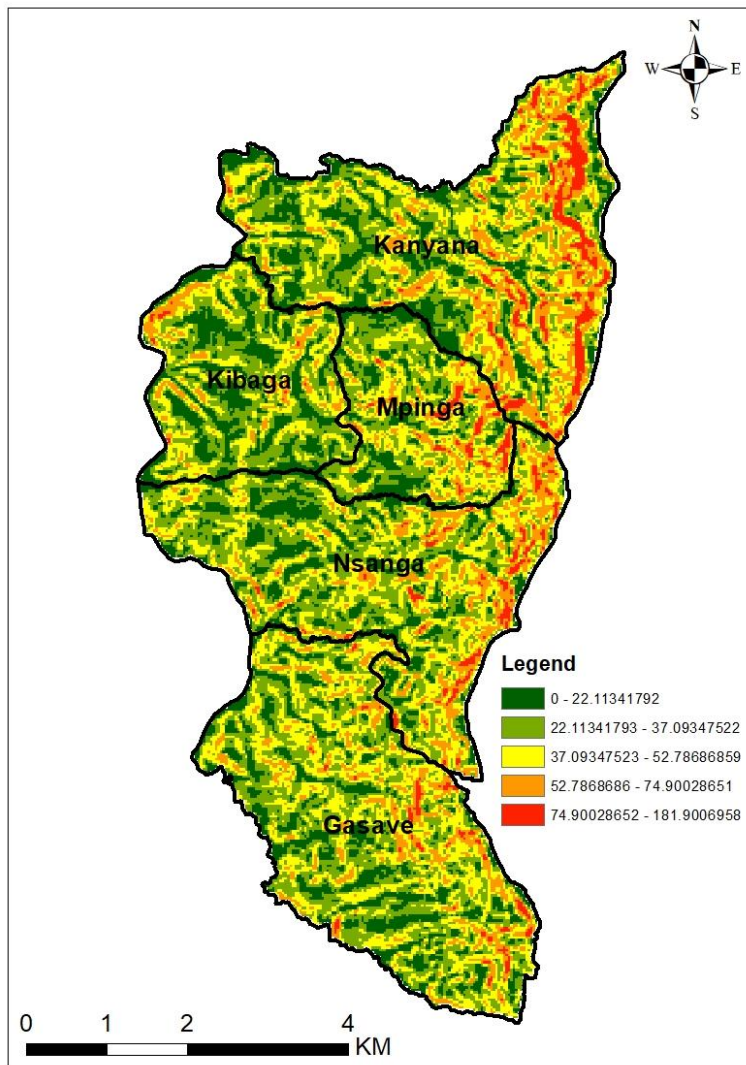


**Figure 14:** Soil erodibility (K-Factor)

Source: MINAGRI (2025)

### 4.3. Slope Length steepness factor (SL)

Slope length is the distance from the origin of overland flow to the point where either the slope decreases enough that deposition occurs, or the runoff water enters a well-defined channel. So, the greater the slope, the greater the velocity of runoff and erosion increases. The SL-factor is computed in ArcGIS software using the equation (*Equ 26*) developed by Moore and Burch (1986). The computation of this factor needs factors like flow accumulation, flow direction, slope steepness, and a digital elevation model, as well as tools like the spatial analyst in GIS software.



**Figure 15:** Slope length steepness factor (SL-factor)

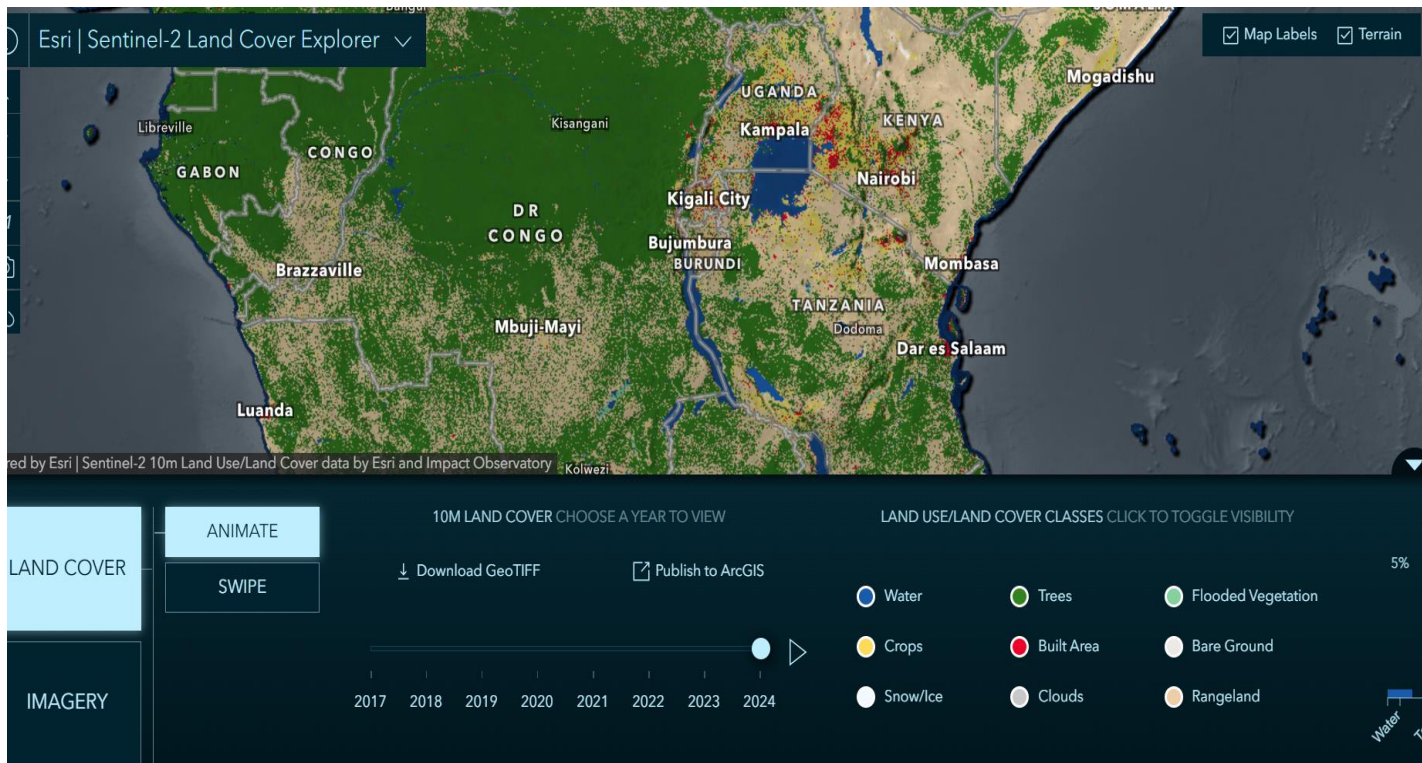
Source: MINAGRI (2025)

$$SL = \text{Power}(\text{FlowAcc\_Flow3} * 30.82971254 / 22.13, 0.4) * \text{Power}(\text{Sin}(\text{Slope\_Extra24}) * 0.01745 / 0.0896, 1.3) \text{ (Equ 26)}$$

Where LS = combined slope length and slope steepness factor; cell size from DEM of 10m resolution, and sin slope = slope degree value in sin. The LS factor value in the study area varies from 0.00 to 182. The computation shows that the majority of the study area has an SL-Factor value less than 37, and some specific areas only show values higher than 100.

#### 4.4. Cover management factor (C)

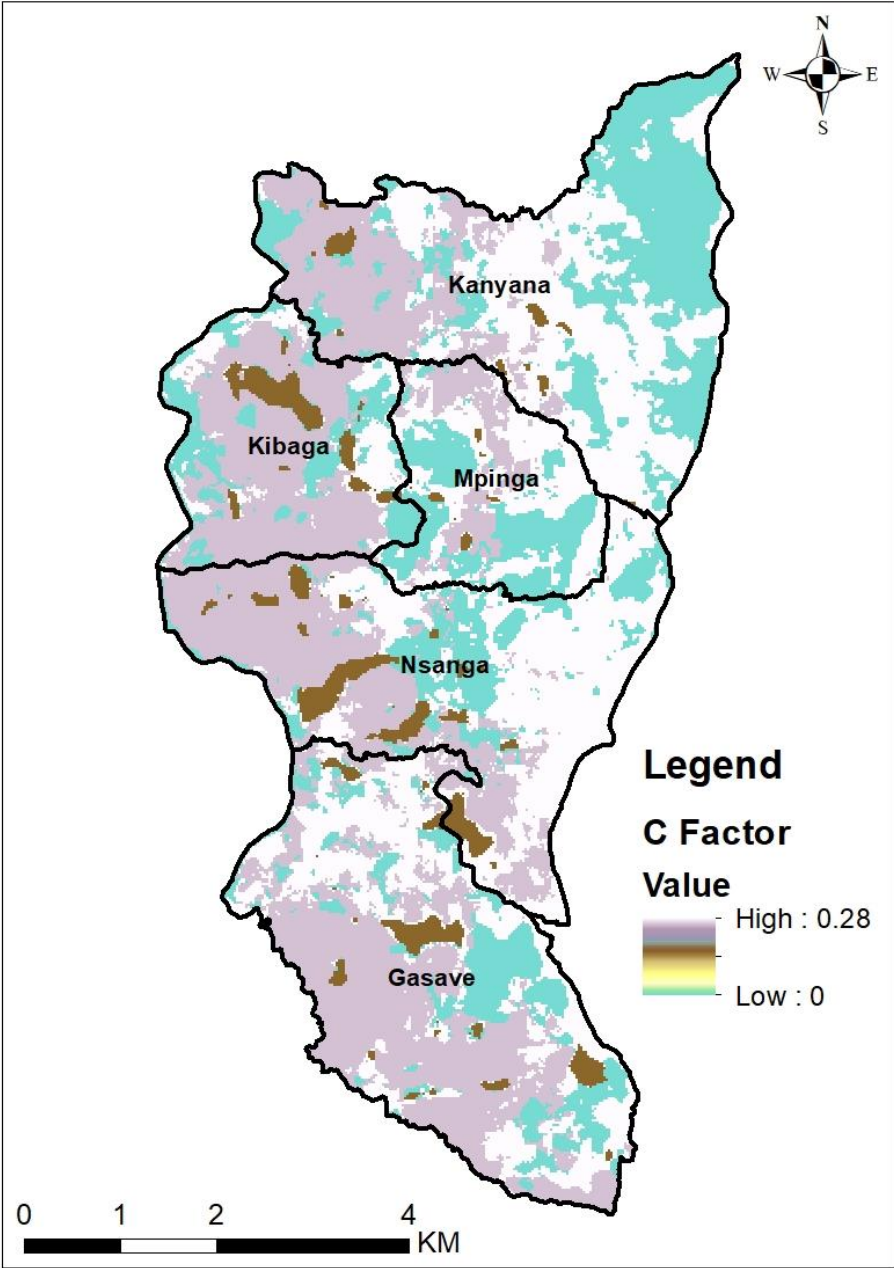
The cover management factor describes the vegetation destruction, vegetation management, and erosion control practices through erosion modeling. The RUSLE model determines different factors, including the cover factor (C), calculated based on the comparison of the present conditions of the site with the standard conditions. Based on the Environmental Systems Research Institute (ESRI), they classified land covers into water, crops, trees, Built-up area, flooded vegetation, and bare land (Figure 13).



**Figure 16:** ESRI vegetation cover classifications

Source: ESRI (2025)

Then the cover management factor of Rugendabari sector ranges from 0 to 0.28 means that there are parts with low soil loss and those disturbed land whose C factor is near 0.28, and this area tends to erosion risks. Figure 14 below.

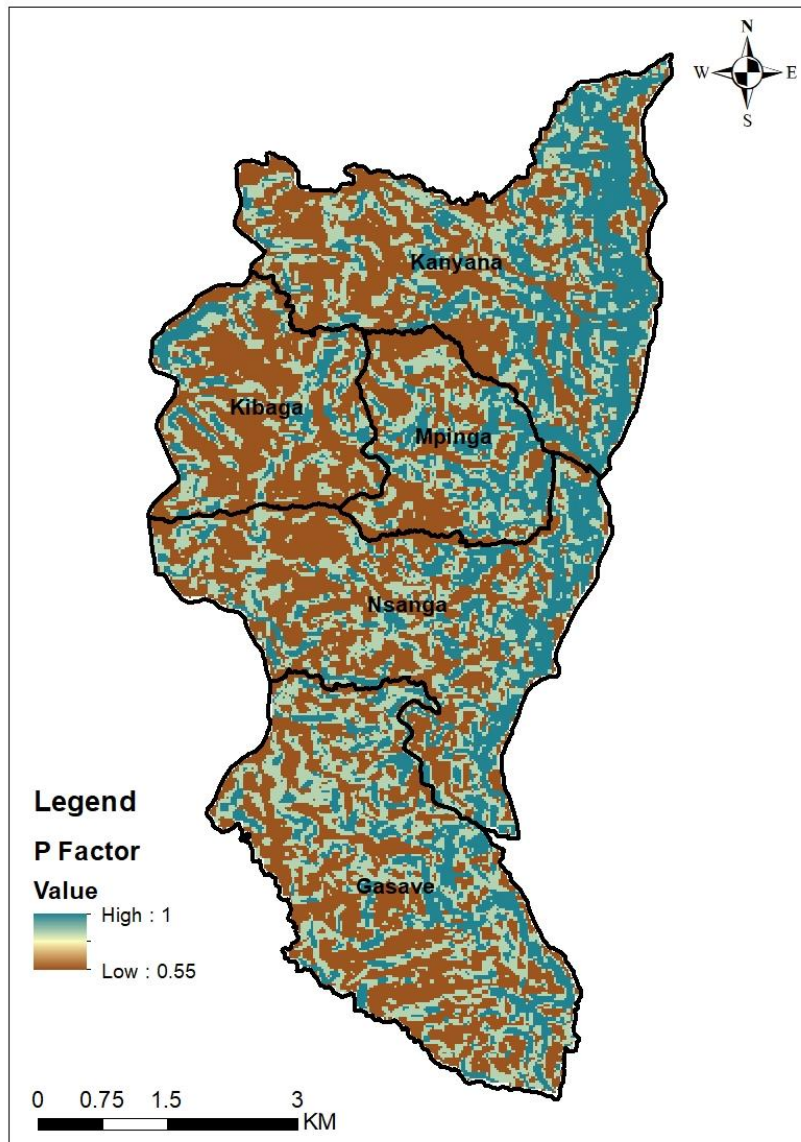


**Figure 17:** Cover management factor (C-factor)

Source: MINAGRI (2025)

#### 4.5. Conservation support practice factor (P)

The P-Factor (figure 18) represented below shows how the Rugendabari sector reacted to environmental damage factors over time. From the Rwanda Water Resource Board, different conservation practices were implemented, including terracing, agroforestry, afforestation, buffer zone creation from rivers/streams, channeling, and greenspace creation.



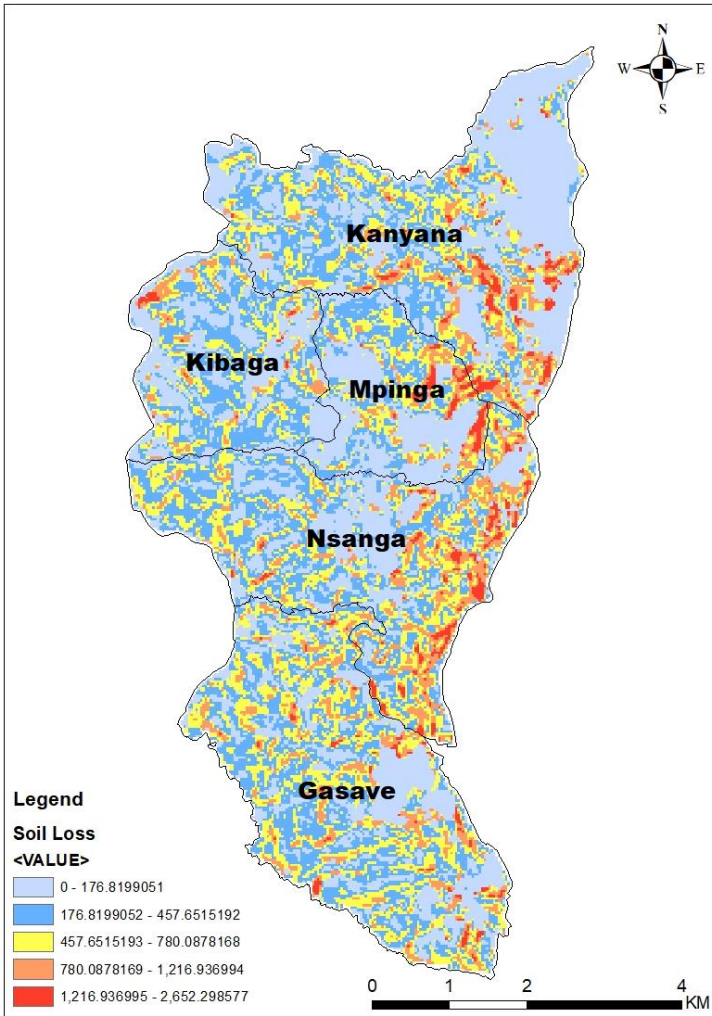
**Figure 18:** Conservation support practice factor (P-factor)

Source: MINAGRI (2025)

Renard et al. (1997b) classified the support practices according to the slope of the study area. From figure 15 above, p equal to 1 corresponds to the Rugendabari slope greater than 40%, allowing afforestation as best conservation practices, p factor less than 1 corresponds to the slope less than 40%, and this should be part with no conservation practices and should be the region for agriculture, grazing, and built-up area.

#### **4.6. Soil loss**

The soil loss in the Rugendabari sector is estimated by the RUSLE model by considering different parameters such as soil types, topography, vegetation cover, rainfall pattern, and soil erosion management practices. The RUSLE parameters are computed in the ArcGIS software and generate a distribution of soil loss across the Rugendabari sector. Then the amount of soil loss across the Rugendabari was determined by an empirical formula that combined rainfall erosivity factor, soil erodibility factor, slope length factor, cover management factor, and supportive practices (R, K, C, SL, P). So, the average soil loss in the Rugendabari sector is estimated in the range from 0 to 2652 tons/ha/year.



**Figure 19:** Annual soil lost in Rugendabari sector

Source: MINAGRI (2025)

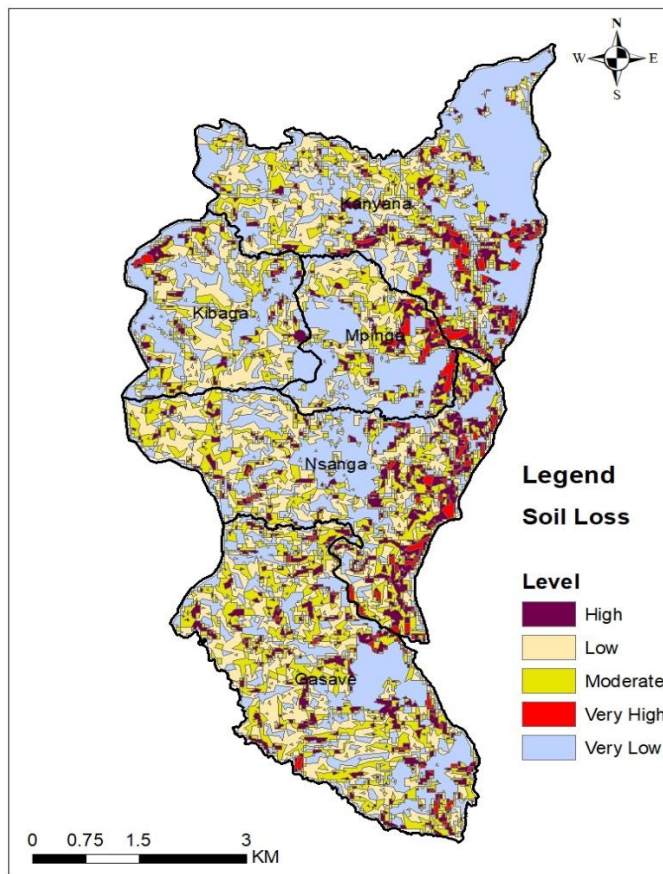
By analyzing statistically, the soil loss value between 0-177tons/ha/year affected the 36.9% of total area with 1532.2 ha found in very low soil loss, soil loss between 177-458tons/ha/year affected the 28.9% of total area with 1198.4 ha found in low soil loss, soil loss between 458-780tons/ha/year affected the 21% of the total area with 870.7ha found in moderate soil loss, soil loss between 780-1217 tons/ha/year affected the 10.8% of the total area found in high soil loss and the soil loss range between 1217-2652 tons/ha/year affected 2.4% of the total area with 101.3 ha found in very high soil loss, table 9 below.

**Table 9:** The Rugendabari sector affected area by soil erosion level

Erosion level	Area in Ha	Percentage
High	449.9	10.8
Low	1198.4	28.9
Moderate	870.7	21
Very High	101.3	2.4
Very Low	1532.2	36.9
Total	4152.5	100

Source: MINAGRI (2025)

Figure 20 shows the classification levels of soil loss in Rugendabari sector. It highlights the area's most susceptible to erosion, allowing for targeted conservation efforts and providing a basis for evaluating the effectiveness of erosion control strategies and understanding broader environmental implications.



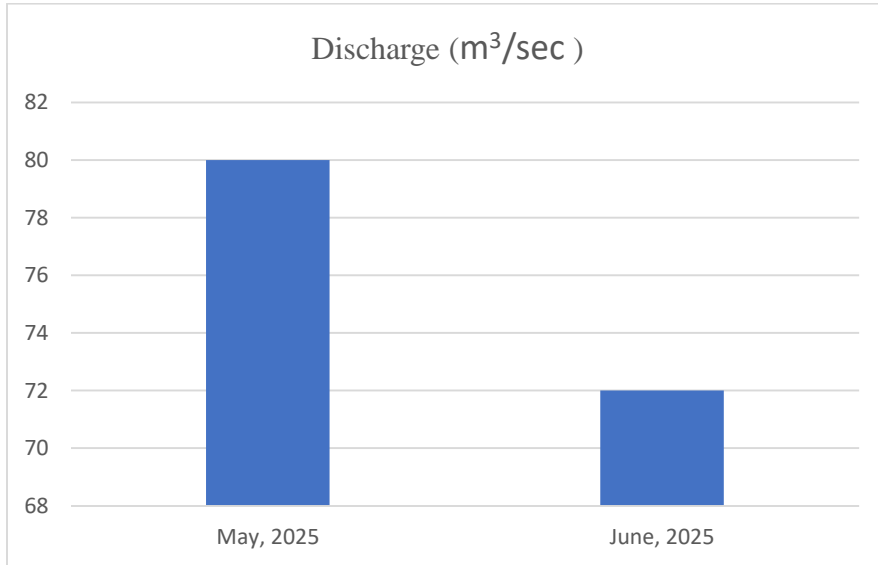
**Figure 20:** Rugendabari soil erosion classification

Source: MINAGRI (2025)

## 4.7. Soil loss estimation by field measurement

### 4.7.1. Stream flow

Through measuring the main streams from the study area, Birikana stream was measured twice in May and June 2025. The outlet of the Birikana stream represents the product of upstream feeds. The result from the measurement represents the discharge of 80 m<sup>3</sup>/sec in May and 72 m<sup>3</sup>/sec in June.



**Figure 21:** Birikana stream discharge in m<sup>3</sup>/sec

Source: Field survey (May,2025)

### 4.7.2. The amount of suspended soil

The sampled water in May at Birikana stream outlet headed to Nyabarongo stream resulted in 112 mg/l of concentration and 86 mg/l in June. Then the average concentration is estimated as 99 mg/l of suspended soil discharged in the Nyabarongo River every year. Then the sediment load for the Birikana stream is calculated using stream concentration and flow, resulting in 19,502.208 tons/month and 234,026.5 tons/year.

**Table 10:** The TSS amount in Birikana stream

Average TSS (mg/L)	Concentration in Kg/L	Average flow(m3/sec)	Flow L/sec	TSS per flow (kg/sec)	Average load per day (kg/day)	Average load per month(ton/month)	Load per year(ton/year)
99	0.289	76	76,000	7.524	650,073.6	19,502.208	234,026.5

Source: Field survey (Jully,2025)

#### **4.8. Contribution of mining activities to the sediment load from Rugendabari streams**

The result above shows that mining activities in Rugendabari are a significant driver of soil erosion through altering the landscape and accelerating the degradation of land. The mining operations from exploration to extraction involve extensive excavation, deforestation, and the creation of pits, all of which leave the soil exposed and unstable. The major issue in this sector is the improper management and abandonment of mine waste, including rock debris and tailings. The unconsolidated materials are dumped in piles, often on steep slopes, where they are easily eroded by the area with heavy rainfall. The failure to restore mined sites and revegetate abandoned ones has exacerbated topsoil loss in unprotected areas, and they have been repeatedly damaged. This situation is worsened by a lack of adequate oversight, which has allowed for detrimental practices and illegal artisanal mining to flourish, further contributing to environmental degradation and pollution.



**Figure 22:** One of the mining sites prone to soil erosion in Rugendabari Sector

Source: Field survey (May,2025)

The combination of steep topography, high rainfall, and intensive mining works creates a scenario where the soil is highly vulnerable to erosion. The extensive soil loss from the mining area in Rugendabari has a direct and severe impact on the sediment load of local water bodies, particularly the Birikana stream and subsequently the Nyabarongo river.

Mining operations introduce large quantities of waste like soil, rock debris, and tailings, which readily flow into rivers, increasing the severe erosion already occurring on steep slopes. This runoff, laden with sediment, clogs waterways, reduces water storage capacity, and elevates flood

risks downstream. The field measurements confirm the scale of the problem; the discharge from the Birikana stream was measured at 80 m<sup>3</sup>/s in May and 72 m<sup>3</sup>/s in June 2025.

Analysis of water samples from the stream's outlet revealed an average annual total suspended solid (TSS) concentration of 99 mg/l. this translates to a staggering estimated sediment load of 234,026.5 tons per year being discharged from the Birikana stream into the Nyabarongo river, highlighting the profound contribution of upstream mining activities to river sedimentation and water pollution. This massive sediment yield not only degrades water quality for communities but also smothers aquatic habitats, harms biodiversity, and increases the risk of siltation damaging critical infrastructure.



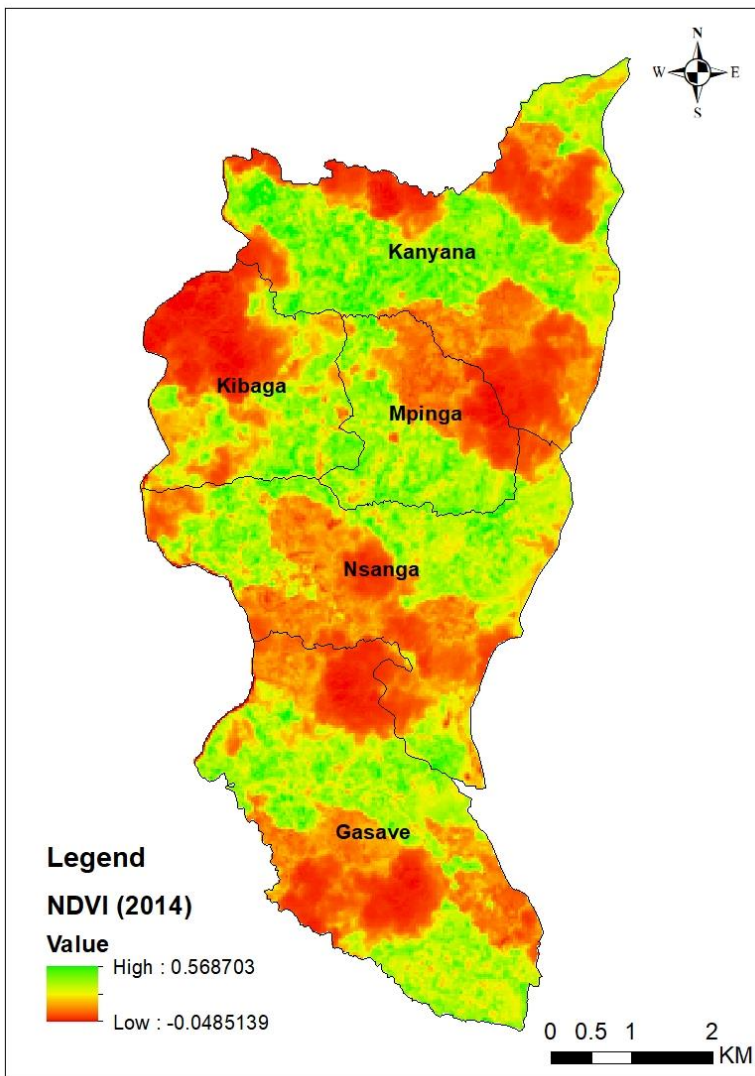
**Figure 23:** Birikana stream erosion feeds into Nyabarongo River

Source: Google Earth (2025)

The results from baseline representing natural condition through RUSLE model measuring showed that the annual soil loss in Rugendabari range between 0 to 2,652tons per year, however by calculation using field measurement the soil suspended in one among the streams found in this sector sampled and analyzed to get the TSS that results into soil loss of 234,026.5 tons discharged by Birikana stream head to Nyabarongo river as reservoir. The contribution of mining activities to soil erosion in the Rugendabari sector became 88 times that of the natural erosion conditions.

#### 4.9. Impacts of soil erosion initiated by mining on vegetation cover

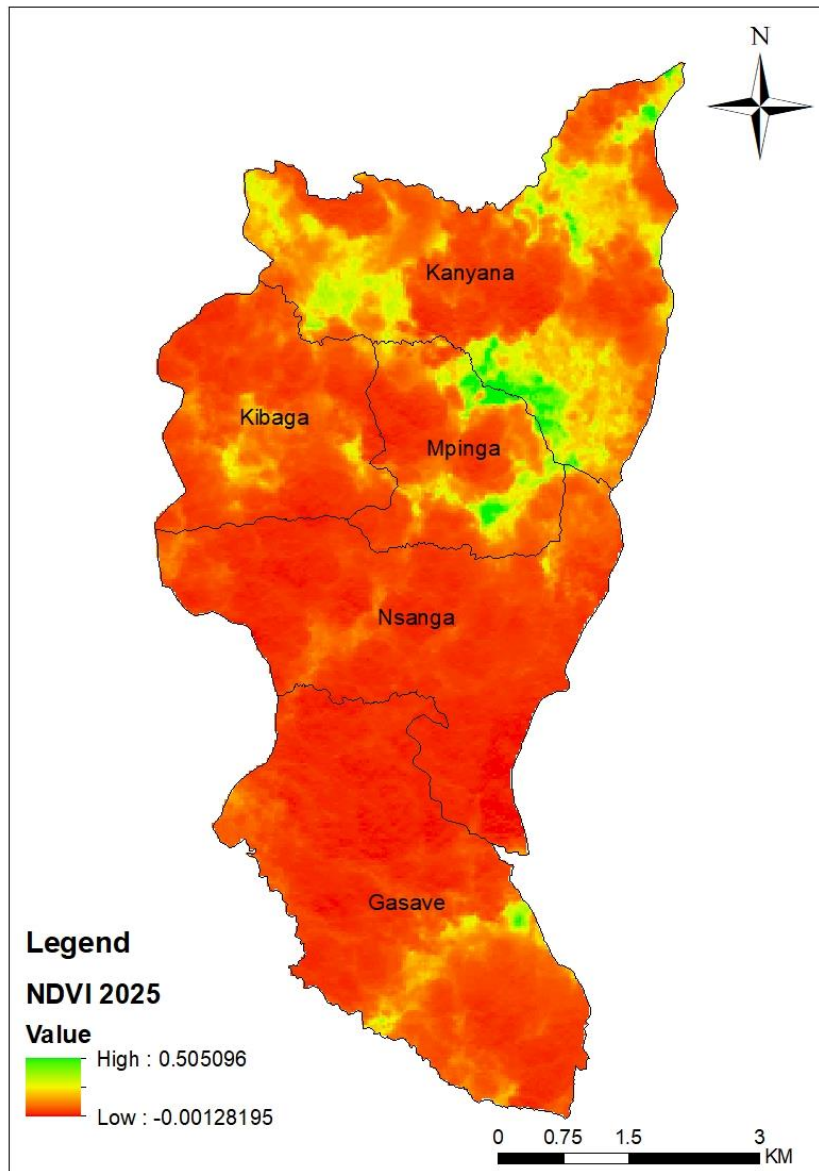
By checking the NDVI maps for the Rugendabari sector from 2014 to 2024, there is a discernible trend of a decrease in vegetation cover over the decade. In 2014, **Figure 24** displays areas with high NDVI values up to 0.56 that indicating healthier vegetation. However, the 2025 maps show a general shift towards lower NDVI values with more widespread presence of red and orange colors, signifying the reduction of vegetation across the area.



**Figure 24:** Vegetation behavior of Rugendabari sector in 2014

Source: NDVI (2014)

This reduction is particularly evident in areas like Mpinga, Kanyana, and Nsanga, which are known for their intensive mining activities. The decline in vegetation directly correlates with the expansion of mining activities, as open-pit mining involves stripping overlying rock and soil, creation of tailing dams and water disposal dams, occupying significant land, all leading to vegetation destruction and increased exposed areas.



**Figure 25:** Vegetation behavior of Rugendabari sector in 2025

Source: NDVI (2025)

## **Chapter Five: 5. Discussions**

The findings of the study on mining-induced soil erosion in the Rugendabari sector offer a distinct contribution to soil erosion research in Rwanda by highlighting the role of unregulated, small-scale mining on soil erosion and vegetation reduction. The following discussion synthesizes the data to explain the significant disparities between this research and previous studies.

### **a. The Order of Magnitude Disparity; Comparison of mining and agriculture erosion status**

The data presented in this study reveals a fundamental difference in the severity of erosion between mining and agricultural landscapes. While previous studies focused on agriculture dominated catchments reported average annual soil loss rate ranging from 30 to 65 tons/ha/year, this study found erosion rates in mining area reaching up to 2652 tons/ha/year. this is the order of magnitude difference in severity, highlighting that mining intensifies erosion well beyond what is seen in traditional agricultural zones.

This disparity is not simply a matter of scale; it is a reflection of a fundamental difference in physical mechanisms of erosion. Agricultural erosion is primarily characterized by the detachment and transport of topsoil through sheet and rill erosion. In contrast to open pit mining involves the wholesale removal of vegetation and the topsoil horizon, creating an entirely new, unstable landscape of exposed, unconsolidated subsoil, waste rock, and artificial, steep slopes. This creates conditions where catastrophic gully erosion and mass movement become the dominant mechanisms, leading to the extreme soil loss rates observed.

### **b. Methodological contribution and validation**

Most soil erosion research in this region relies on predictive models like RUSLE, which provide estimates but are rarely confirmed with actual data from the same area. The current study bridges this critical gap by combining high-resolution RUSLE-GIS modeling with direct field measurements of total suspended solids (TSS) in the Birikana stream. This two-pronged approach provides an unprecedented level of empirical validation. The high RUSLE numbers are not merely theoretical predictions; they are corroborated by the massive measured sediment load of 234,026.5 tons/year, which serves as a tangible metric of the on the ground reality. This

methodological innovation provides a new, more robust standard for future studies in the region, grounding theoretical models in empirical observation.

### **c. On-site degradation and regional pollution**

The study's findings demonstrate that the immense sediment load entering the Nyabarongo River from the Birikana stream is a direct consequence of the onsite land degradation in the Rugendabari sector. The link between the exposed and unstable mining sites and the polluted waterways is undeniable. This localized environmental crisis has a significant ripple effect. The high sediment yield degrades water quality for communities reliant on the river, smothers aquatic habitats, and harms biodiversity. It also poses a long-term risk to critical infrastructure, such as water intake points and hydropower facilities, due to siltation. The problem, therefore, extends beyond a single mining site to become a regional hydrological and ecological crisis that demands a basin-level response.

### **d. Governance and social challenges**

The impact on vegetation cover observed through NDVI analysis between 2014 and 2025 confirms that mining sites suffer a greater reduction in biomass and plant health than agricultural regions, reinforcing the destructive footprint of mining on ecosystems. The severe environmental outcomes observed in Rugendabari sector point to an underlying problem of governance and institutional support. The study notes the improper management of mining waste and the lack of adequate oversight of mining operations. The presence of unregulated artisanal mining suggests that harmful practices continue, contributing to the problem. The study highlights that the issue is not merely a technical deficit in conservation practices but a holistic challenge involving environmental, technical, socio-economic, and institutional dimensions.

## **Chapter Six: Conclusion and Recommendation**

### **6. 1. Conclusion**

Based on the spatial modeling and field analysis conducted in the Rugendabari sector, this research concludes that mining activities are the primary driver of the severe soil erosion and subsequent high sediment loads impacting the local watershed. The study successfully utilized the Revised Universal Soil Loss Equation (RUSLE) model integrated with GIS to map the spatial distribution of soil erosion, revealing an average annual soil loss ranging from 0 to 2,652 tons/ha/year. The area with high erosion is strongly correlated with intensive mining operations, where the area of high soil loss occupies 10.8%, and very high erosion risk covers 2.4% of the total study area.

The study confirms that the mechanisms behind this erosion are extensive excavation, deforestation, and particularly the improper management of mining waste. The unconsolidated rock debris and tailings are left in piles on steep slopes, which, combined with the region's heavy rainfall and high topographic relief, become major sources of sediment. The failure to restore and revegetate abandoned pits and waste sites aggravates this issue, allowing for continuous erosion. This is compounded by a lack of sufficient oversight, which has enabled detrimental and illegal artisanal mining practices to continue further polluting and destroying the environment.

The direct consequences of this extensive soil loss are a dramatic increase in the sediment load of Birikana Stream, which ultimately pollutes the Nyabarongo River. Field measurements substantiate the model's findings, showing a significant discharge from the Birikana stream and the average annual total suspended solids (TSS) concentration of 99 mg/l at its outlet. This culminates in an estimated 234026.5 tons of sediment being discharged in the Nyabarongo River annually from this single stream. This massive sediment yield not only degrades water quality for downstream communities and damages critical infrastructure but also damages aquatic habitats, leading to a loss of biodiversity. The findings provide a robust, data-driven assessment that highlights the urgent need for targeted soil conservation strategies, responsible mining practices, and enforced environmental regulations to mitigate the severe environmental damage in the Rugendabari sector.

## **6.2. Recommendation**

Based on the research findings, the following recommendations are proposed to mitigate soil erosion and its environmental impacts in the Rugendabari sector:

### **a. Site restoration and erosion control guidelines**

The study's soil loss map, which identifies areas with erosion rates up to 2652 tons/ha/year, should be used to prioritize conservation efforts. Interventions must be tailored specifically to the unique challenges of mining sites, distinguishing them from traditional agricultural practices. Stakeholders should be mandated to implement progressive and post-closure restoration of mined sites. This includes the stabilization of waste piles and the systematic revegetation of cleared land using native species to reduce erosion. The construction of integrated sediment control basins or check dams at the headwaters of the Birikana stream and other tributaries is also critical to trap sediment at the source, thereby protecting the downstream Nyabarongo River.

### **b. Regulatory and institutional reforms**

There is a critical need for enhanced oversight and enforcement of existing environmental and mining laws. This includes implementing a system of progressive site rehabilitation, where companies are required to restore sections of the mine as they are exhausted, rather than waiting until the end of the mine life. Policies should also be developed to provide clearer guidelines and support for the formalization of artisanal and small-scale miners, bringing them under regulatory control to ensure environmental protection compliance.

### **c. Integrated land-use planning**

The high-resolution soil erosion maps generated by the study should be used to inform land-use planning decisions for the study area/Rugendabari sector. Target high-risk zones with soil conservation measures; using the soil loss map generated by the RUSLE model, which identifies areas with soil loss up to 2,652 tons/ha/year, authorities and land managers should prioritize conservation efforts. Interventions such as the construction of terraces, contour cropping, and afforestation should be implemented in the areas identified as having High and very high erosion risk to effectively reduce sediment runoff.

The areas identified as having high and very high erosion risk should be designated as no-go zones for future mining projects or be subjected to exceptionally strict environmental safeguards. This proactive approach will help balance the economic benefits of mining with long-term environmental protection.

**d. Stakeholders' collaboration and knowledge transfer**

Achieving sustainable change requires collaboration between the parties involved. The research should serve as a basis for fostering collaboration between government bodies, private mining companies, local farmers, and community leaders. This involves developing and implementing sustainable management practices that are not only technically sound but also consider the socio-economic realities of the community, safeguarding the long-term ecological health of the Rugendabari ecosystem.

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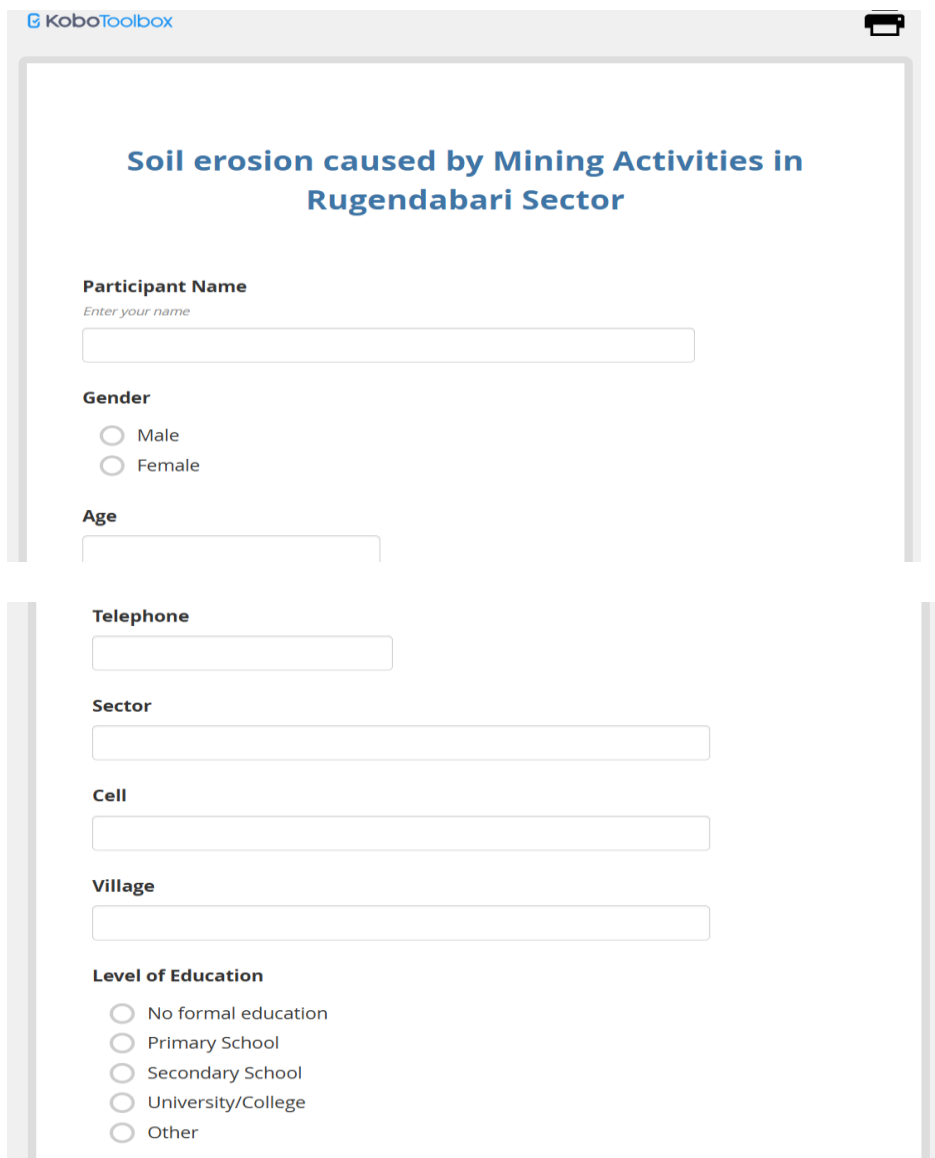
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## ANNEX

### I. Interview

During the interview, the sample size must be neither small nor large according to the population size; a sample should not be less than 36 respondents. In this study, I interviewed 15 local farmers, 15 miners, 3 stakeholders, and 3 local leaders in 3 cells of the Rugendabari sector. The tool contained 26 questions asked of the sampled persons. The responses from the interviewees were collected using the Kobo tool, then used in comparison with the computed and field results.

The tool: <https://ee.kobotoolbox.org/x/bved9o9W>



The image shows a screenshot of a KoboToolbox survey form. The form is titled "Soil erosion caused by Mining Activities in Rugendabari Sector". It contains several sections with input fields and radio buttons:

- Participant Name**: A text input field with the placeholder "Enter your name".
- Gender**: Two radio button options: "Male" and "Female".
- Age**: A text input field.
- Telephone**: A text input field.
- Sector**: A text input field.
- Cell**: A text input field.
- Village**: A text input field.
- Level of Education**: Five radio button options: "No formal education", "Primary School", "Secondary School", "University/College", and "Other".

**Main Occupation**

- Farming
- Mining
- Trading
- self employed
- Unemployed
- Student

**How long have you lived in this sector (in years)?**

Years

**Is there any mining activities carried in this sector?**

- Yes
- No

**If yes, what is the distance range from your residence to the nearest mining site (Ugereranye)?**

- 0km-1km
- 1km-2km
- 2km-3km

**Are you aware of what soil erosion is?**

- Yes
- No

**In your opinion, is soil erosion a problem in this area?**

- Major problem
- Minor problem
- Not problem
- I don't Know

**What signs of soil erosion have you observed in this area?**

- Gullies
- Loss of topsoil
- Exposed tree roots
- Muddy water in rivers/streams after rain
- Landslides

**Over the past years (10years ago), how has the problem of soil erosion in this area changed?**

- Significantly increased
- Slightly increased
- Remained the same
- Slightly decreased
- Significantly decreased
- I don't know

**What do you believe are the main causes of soil erosion in this area?**

- Heavy rainfall
- Deforestation
- Mining activities
- Poor farming practices
- Construction activities
- Natural landscape

**Are there mining activities currently happening/have happened in last 10 years near your community?**

- Yes, currently active
- Yes, happened in the past but not active now

**If yes, what types of mining activities are present?**

- Open pit mining
- Underground mining
- Insitu leaching
- Sand, stone or gravel quarrying
- Solution mining

**Do you believe that these mining activities have contributed to soil erosion in the area?**

- Yes, alot
- Yes, somehow
- No

**If yes, how these mining activities contributed to soil erosion in this area?**

- Vegetation and topsoil removal during site preparation
- Creation of pits, tunnels, trenches and dams.
- Improper waste/soil dumping
- Increased runoff from the mine
- Infrastructure constructions like roads

**Have you noticed any changes in vegetation cover (trees, shrubs, grasses) of this area?**

*Haba kwiyongera cyangwa kugabanuka kw'ibimera?*

- Yes, significant decrease in vegetation
- Yes, slight decrease in vegetation
- No change
- Yes, slight increase in vegetation
- Yes, significant increase in vegetation
- I don't know

**If there has been a decrease, what do you think are the main reasons for the decrease?**

- Agriculture activities
- Mining activities
- Cutting trees for firewood
- Overgrazing
- Climate change

**Do you believe that soil erosion caused by mining has affected the vegetation cover in this area?**


- Yes, significantly
- Yes, moderately
- Yes, slightly
- No
- I don't know

**In your opinion, who should be primarily responsible for addressing the problems of soil erosion in this area?**

- Individual land users
- Local community leaders
- Mining companies
- Government
- NGOs
- Everyone has a role

**What suggestions do you have for mining companies to reduce their impact on soil erosion and vegetation cover?**

**Do you have any other comments or observations you would like to share regarding soil erosion, mining activities, and the vegetation cover in this area?**

 Save Draft



 Submit

## II. Rugendabari rainfall data from 2016 to 2025 (Meteo-Rwanda)

station_Name	Lat	Lon	Elev	YY	MM	PRECIP
RUGENDABARI	-1.95	29.66	1546	2016	5	11.3
RUGENDABARI	-1.95	29.66	1546	2016	6	0
RUGENDABARI	-1.95	29.66	1546	2016	7	0
RUGENDABARI	-1.95	29.66	1546	2016	8	50.3
RUGENDABARI	-1.95	29.66	1546	2016	9	84
RUGENDABARI	-1.95	29.66	1546	2016	10	40.4
RUGENDABARI	-1.95	29.66	1546	2016	11	93.3
RUGENDABARI	-1.95	29.66	1546	2016	12	27.7
RUGENDABARI	-1.95	29.66	1546	2017	1	27.4
RUGENDABARI	-1.95	29.66	1546	2017	4	117.5
RUGENDABARI	-1.95	29.66	1546	2017	5	94.3
RUGENDABARI	-1.95	29.66	1546	2017	6	0
RUGENDABARI	-1.95	29.66	1546	2017	7	0
RUGENDABARI	-1.95	29.66	1546	2017	8	18.9
RUGENDABARI	-1.95	29.66	1546	2017	9	48.2
RUGENDABARI	-1.95	29.66	1546	2017	10	131
RUGENDABARI	-1.95	29.66	1546	2017	11	145.8
RUGENDABARI	-1.95	29.66	1546	2017	12	73.9
RUGENDABARI	-1.95	29.66	1546	2018	1	156.8
RUGENDABARI	-1.95	29.66	1546	2018	2	85.3
RUGENDABARI	-1.95	29.66	1546	2018	3	187.9
RUGENDABARI	-1.95	29.66	1546	2018	4	454.8
RUGENDABARI	-1.95	29.66	1546	2018	5	182.5
RUGENDABARI	-1.95	29.66	1546	2018	6	0
RUGENDABARI	-1.95	29.66	1546	2018	7	8.2
RUGENDABARI	-1.95	29.66	1546	2018	8	20.3
RUGENDABARI	-1.95	29.66	1546	2018	9	18.1
RUGENDABARI	-1.95	29.66	1546	2018	10	115.2
RUGENDABARI	-1.95	29.66	1546	2018	11	83.8
RUGENDABARI	-1.95	29.66	1546	2018	12	69.8
RUGENDABARI	-1.95	29.66	1546	2019	1	198.4
RUGENDABARI	-1.95	29.66	1546	2019	2	51.6
RUGENDABARI	-1.95	29.66	1546	2019	3	81.9
RUGENDABARI	-1.95	29.66	1546	2019	4	111.5
RUGENDABARI	-1.95	29.66	1546	2019	5	115.1
RUGENDABARI	-1.95	29.66	1546	2019	6	60.1
RUGENDABARI	-1.95	29.66	1546	2019	7	33
RUGENDABARI	-1.95	29.66	1546	2019	8	46.9
RUGENDABARI	-1.95	29.66	1546	2019	9	103.4
RUGENDABARI	-1.95	29.66	1546	2019	10	195.2

RUGENDABARI	-1.95	29.66	1546	2019	12	252.7
RUGENDABARI	-1.95	29.66	1546	2020	1	230.1
RUGENDABARI	-1.95	29.66	1546	2020	2	84.3
RUGENDABARI	-1.95	29.66	1546	2020	3	339
RUGENDABARI	-1.95	29.66	1546	2020	4	271.2
RUGENDABARI	-1.95	29.66	1546	2020	5	181.4
RUGENDABARI	-1.95	29.66	1546	2020	6	38.1
RUGENDABARI	-1.95	29.66	1546	2020	7	6.1
RUGENDABARI	-1.95	29.66	1546	2020	8	4.3
RUGENDABARI	-1.95	29.66	1546	2020	9	52.4
RUGENDABARI	-1.95	29.66	1546	2020	10	195.8
RUGENDABARI	-1.95	29.66	1546	2020	11	197.6
RUGENDABARI	-1.95	29.66	1546	2020	12	99
RUGENDABARI	-1.95	29.66	1546	2021	1	162.1
RUGENDABARI	-1.95	29.66	1546	2021	2	209.5
RUGENDABARI	-1.95	29.66	1546	2021	3	291.6
RUGENDABARI	-1.95	29.66	1546	2021	4	307.4
RUGENDABARI	-1.95	29.66	1546	2021	5	365.3
RUGENDABARI	-1.95	29.66	1546	2021	6	3.6
RUGENDABARI	-1.95	29.66	1546	2021	7	38.8
RUGENDABARI	-1.95	29.66	1546	2021	8	263.8
RUGENDABARI	-1.95	29.66	1546	2021	9	137.3
RUGENDABARI	-1.95	29.66	1546	2021	10	136
RUGENDABARI	-1.95	29.66	1546	2021	11	153.6
RUGENDABARI	-1.95	29.66	1546	2021	12	263.8
RUGENDABARI	-1.95	29.66	1546	2022	1	374.8
RUGENDABARI	-1.95	29.66	1546	2022	2	628.8
RUGENDABARI	-1.95	29.66	1546	2022	3	199.1
RUGENDABARI	-1.95	29.66	1546	2022	4	165.6
RUGENDABARI	-1.95	29.66	1546	2022	5	145.8
RUGENDABARI	-1.95	29.66	1546	2022	6	2.2
RUGENDABARI	-1.95	29.66	1546	2022	7	7.4
RUGENDABARI	-1.95	29.66	1546	2022	8	111.5
RUGENDABARI	-1.95	29.66	1546	2022	9	102.8
RUGENDABARI	-1.95	29.66	1546	2022	10	34.4
RUGENDABARI	-1.95	29.66	1546	2022	11	238.4
RUGENDABARI	-1.95	29.66	1546	2022	12	202.5
RUGENDABARI	-1.95	29.66	1546	2023	1	135.6
RUGENDABARI	-1.95	29.66	1546	2023	2	122.3
RUGENDABARI	-1.95	29.66	1546	2023	3	297.6
RUGENDABARI	-1.95	29.66	1546	2023	4	525.5
RUGENDABARI	-1.95	29.66	1546	2023	7	0
RUGENDABARI	-1.95	29.66	1546	2023	9	279.4

RUGENDABARI	-1.95	29.66	1546	2023	10	74.6
RUGENDABARI	-1.95	29.66	1546	2023	11	105.4
RUGENDABARI	-1.95	29.66	1546	2023	12	201.7
RUGENDABARI	-1.95	29.66	1546	2024	2	91.4
RUGENDABARI	-1.95	29.66	1546	2024	3	137.9
RUGENDABARI	-1.95	29.66	1546	2024	4	231.8
RUGENDABARI	-1.95	29.66	1546	2024	5	91.6
RUGENDABARI	-1.95	29.66	1546	2024	6	0
RUGENDABARI	-1.95	29.66	1546	2024	7	0
RUGENDABARI	-1.95	29.66	1546	2024	8	37.4
RUGENDABARI	-1.95	29.66	1546	2024	9	48.7
RUGENDABARI	-1.95	29.66	1546	2024	10	98
RUGENDABARI	-1.95	29.66	1546	2024	11	209.2
RUGENDABARI	-1.95	29.66	1546	2025	2	41.4
RUGENDABARI	-1.95	29.66	1546	2025	3	179.6
RUGENDABARI	-1.95	29.66	1546	2025	4	159
RUGENDABARI	-1.95	29.66	1546	2025	5	105.3