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ASSESSMENT OF SOIL EROSION IMPACTS IN MUSANZE DISTRICT, RWANDA

Thesis submitted to the University of Rwanda: College of Science and Technology in partial fulfilment of the requirements for the award of the Degree of Master of Science in Geo-Information for Environment and Sustainable Development.

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October, 2024

DECLARATION

I, Odette DUSABIMANA, hereby declare that the work presented in this dissertation entitled "Assessment of Soil Erosion Impacts in Musanze District Rwanda" is my research. It has not been submitted for any degree in any other university or institution.

Signed:

Odette DUSABIMANA Date: … .. /… … …/ 2024

APPROVAL

It is hereby confirmed that this thesis entitled **“Assessment of soil erosion impacts in Musanze District, Rwanda”** submitted by Odette DUSABIMANA has been assessed and accepted by the post-graduate coordination team in the School of Architecture and Built Environment

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DEDICATION

To the almighty God

To my beloved parents

To my dear brothers and sisters

To my friends, colleagues and relatives

ACKNOWLEDGMENTS

Firstly, I present my deepest gratitude to the almighty God for the great gift of life he has blessed me and protected me throughout my life. The achievement of my dissertation work has resulted from the combined physical and moral effort of several people and institutions, to which I hereby express my sincere appreciation and recognition. I am highly thankful to the Greater Virunga Landscape (GVL) for the financial support that allowed this study's completion. Many thanks are addressed to the University of Rwanda (UR) staff and the College of Sciences and Technology (KIST) for their remarkable assistance in supporting me in my studies for a Master’s Degree in Geo-Information Sciences for Environment and Sustainable Development. I profoundly thank my Supervisors, Dr. Fabien RIZINJIRABAKE and Dr. Elias NYANDWI for their guidance and support of this dissertation. I would like to express my extremely grateful to my beloved husband, parents, brothers, and sisters for their encouragement and financial support. Furthermore, I am grateful to my classmates for their moral support during my entire academic journey.

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Odette DUSABIMANA

ABSTRACT

In Rwanda, soil erosion is one of the prevalent environmental issues. Soil erosion associated with agriculture practices in Rwanda leads to a decline the soil fertility, brings on a series of negative impacts of environmental problems, and has become a threat to sustainable agricultural production and water quality. As a case study, this study assesses soil erosion level and their impacts in the Kinigi, Nyange, and Shingiro sectors of Musanze District, Rwanda. Estimating soil erosion levels and assessing socio-economic and land degradation impacts were achieved using the Revised Universal Soil Loss Equation (RUSLE) based on five factors related to rainfall, soil characteristics, topography, support practice, and land use land cover management. Field surveys and interviews with local communities of 385 households help gather data on the socio-economic impacts, focusing on changes in agricultural productivity and livelihood, environmental factors, infrastructures, and livelihood and community wellbeing. Based on interviewers' findings, contouring, planting trees, and terracing were taken as measures in soil protection from erosion; and land degradation impacts, specifically concerning soil nutrients fertilizer effectiveness due to soil erosion in the study area. The Nyange sector faces severe erosion (62.05 to 640 tons/ha/year), and Kinigi and parts of Shingiro experience moderate to high erosion (29.52 to 107.08 tons/ha/year). In comparison, areas near Virunga National Park have lower erosion (2 to 29.52 tons/ha/year). Erosion impacts include increased agricultural costs (40%), property damage (33%), and land degradation affecting soil nutrients, with nitrogen, phosphorus, and potassium levels varying significantly across erosion intensity levels.

Keywords: Soil erosion, RUSLE equation, land degradation, socio-economic impacts of soil erosion, and GIS

LIST OF ABBREVIATIONS AND ACRONYMS

AAS **:** Atomic Absorption Spectrometry

CROM **:** Catchment Restoration Opportunity Mapping

DEM **:** Digital Elevation Model

GIS **:** Geographical Information System

IC **:** Ion Chromatography

ICPS **:** Inductively Coupled Plasma Spectrometry

IDW **:** Inverse Distance Weighting

IWRM **:** Integrated Water and Resources Management

LS **:** Slope length and slope steepness factor

LULC **:** Land Use Land Cover

MIDIMAR **:** Ministry of Disaster Management and Refugee Affairs

MoE **:** Ministry of Environment

NDVI **:** Normalized Difference Vegetation Index

NGO **:** Non-Government Organization

RAB **:** Rwanda Agriculture Board

RUSLE **:** Revised Universal Soil Loss Equation

TOC **:** Total Organic Carbon

USGS **:** United States Geological Survey

VNP **:** Volcano National Park

IUCN **:** International Union for Conservation of Nature
UR **:** University of Rwanda

LIST OF CHEMICAL SYMBOLS AND MEASURING UNITS

N : Nitrogen

HCl : Hydrochloric acid

P : Phosphorus

HNO_3 : Nitric Acid

K : Potassium

AAS : Atomic Absorption Spectroscopy

NH_4^+ : Ammonium

IC : Inductively Coupled

NH_3^+ : Ammonia

ICP : Inductively Coupled Plasma

NO_2- : Nitrite

QC : Quality Control

NO_3^- : Nitrate

$NH_4CH_3COO^-$: Ammonium acetate

Ca : Calcium

$4H_2O$: Water molecules

PH : Hydrogen Potential

FD : Dilution factor

C : Carbon

FC : Collective factor

% : Percentage

Na_2SO_4 : Sodium sulfate

Cmol/ Kg : Centimol per kilogram

NaOH : Sodium hydroxide

Mm : Millimeter

0^0 : Degree

ppm : Parts per million

Cmol : Centimols

ml : milliliters

Kg : kilogram

H_2SO_4 : Sulphuric acid

LIST OF TABLES

LIST OF FIGURES

TABLE OF CONTENTS

CHAPTER I. GENERAL INTRODUCTION

1.1. Background

Rwanda is particularly prone to a variety of natural hazards such as erosion, floods, and droughts (Rugigana et al., 2013). In the past ten years, the frequency and severity of these hazards have markedly risen in Rwanda, leading to higher human casualties, and increased economic and environmental losses. Erosion control measures in Rwanda are very inadequate (UNDP, 2023). Natural causes of soil erosion include vegetation degradation, increased rainfall intensity and amount, the physical and chemical properties of soil, and the topography of the land. Furthermore, human activities have been largely blamed for contributing to soil erosion (Golubovic, 2022).

The Rwandan biophysical environment is predominantly characterized by steep slopes, especially from the Eastern to Western regions. This mountainous terrain makes soil vulnerable to water erosion, especially in the northern and western highlands of Rwanda. The erosion risk is most significant on slopes ranging from 5% to 55%, which cover about 48% of the total arable land (Rutebuka, 2021). Soil erosion on arable land can lead to land degradation and decrease in agricultural productivity, damage property, and infrastructure, and displace people and water pollution due to pollutants from roads, roofs, and other surfaces. Lack of proper rainwater drainage systems and other mitigation strategies may cause problems in different sectors in both rural and urban areas (Bizimungu, 2017). According to the same author, deforestation and the transformation of natural grasslands for urban development and intensified agriculture, driven by rapid population growth, have escalated soil erosion. Urbanization leads to more impervious surfaces, reducing the soil's infiltration capacity. This leads to downstream and stream bank erosion, higher water turbidity, habitat destruction, combined sewer overflows, infrastructure damage, polluted streams, and a loss of biodiversity (Prakash, 2005). These regions need urgent runoff control measures, such as terracing in agricultural lands and implementing rainwater harvesting systems like dams, reservoirs, percolation tanks, and storage tanks (Mupenzi et al., 2011).

In Rwanda, deforestation and the clearing of vegetation for unsuitable land use have led to significant localized soil erosion. It was noted that the percentage of land at risk of erosion that is currently protected in each district is very low (IUCN, 2022). Unplanned settlements lacking stormwater management systems and proper waterways in developed areas have led to significant runoff. It is important to recognize that unsustainable human activities and insufficient knowledge of land use and management significantly amplify people's vulnerabilities to erosion (Kunene et al., 2021). Extensive soil exhaustion occurs due to continuous farming, degradation, and erosion, with insufficient fertilizer use to replace nutrients lost from soil depletion and overexploitation. Approximately 11 percent of the country faces an extremely high or very high risk of soil erosion (REMA, 2021). Soil erosion in Rwanda severely threatens soil fertility, water resources, the national economy, and overall well-being. Soil losses are linked to increased acidity, reduced nutrients, and low organic carbon content, resulting in decreased fertility and diminished ability to support plant growth (Kabirigi et al., 2017)

1.2. Problem Statement

Climate change, as an emerging threat, can worsen existing environmental degradation, increasing vulnerability to erosion (Segura et al., 2014). The Northern Province has relatively abundant rainfall with high intensity, causing soil erosion. All rainwater is not able to infiltrate the soil quickly enough, and so it runs off the surface, carrying with it soil, rocks, and other debris therefore it is necessary to estimate soil loss from erosion and pinpoint areas with high erosion deposits to improve land management. Water runoffs have been an outstanding challenge in Musanze District for a long time (Karamage et al., 2017). Community members living around Virunga National Park (VNP) report that Musanze District authorities cannot establish a reliable water management system for proper rainwater harvesting and utilization due to the hilly landscape. As a result, water runoff, soil erosion, and poor harvests are rampant. The District of Musanze predominantly experiences rill erosion, except for the Kinigi Sector, which also suffers from severe gully erosion (MoE, 2020).

Musanze District is prone to high erosion due to steep topography, high rainfall, and seasonal agriculture its geology underlies volcanic rocks and ash, and rainwater from the Volcanoes National Park (VNP). Musanze district has areas with steeper slopes that are more susceptible to erosion because water and wind have more energy to move soil particles, and land that has been cleared of vegetation or is used for intensive agriculture is more susceptible to erosion. The vegetation helps to hold soil particles in place and the agricultural practices can disturb the soil surface and around rivers and streams, where the banks are less stable and more easily eroded. Around the Volcano National Park (VNP), soil erosion occurs due to poor land management and overcultivation caused by high rainfall, vulnerable soils, and insufficient agroforestry trees in agricultural lands (Karamage, 2017).

Kinigi, Nyange, and Shingiro sectors are the most affected areas by erosion in Musanze district, Rwanda (Uzamukunda, 2015). The sectors were located in the foothills of the Virunga Mountains, and are characterized by steep slopes and heavy rainfall (Rutagengwa et al., 2020). This combination of factors makes the area susceptible to erosion. Soil erosion is further intensified by deforestation and overgrazing, which expose the soil (Chaplot & Mutema, 2022). The region receives an annual average rainfall of 1,600 mm, much higher than the national average of 1,200 mm, the steep slopes and underlying geology hinder proper water drainage, heightening the risk of soil erosion. The inappropriate land use factor like the construction of roads can also contribute to soil erosion. The rainwater that falls on the steep slopes of those three sectors cannot infiltrate the soil quickly enough, so it runs off the surface, carrying soil, rocks, and other debris. This runoff can cause erosion, resulting in the loss of agricultural land, infrastructure damage, and loss of life (Hitimana, 2006). An assessment of annual soil erosion in the study area is necessary to develop effective erosion prevention measures and sustainable land management practices.

The Revised Universal Soil Loss Equation (RUSLE) and Catchment Restoration Opportunity Mapping (CROM) offer distinct approaches to estimating soil erosion, each with unique advantages. RUSLE is a well-established model that quantifies soil erosion by incorporating factors such as rainfall, soil type, topography, crop management, and erosion control practices (Renard et al., 1997). RUSLE lies in its empirical foundation and wide applicability across different environments, providing detailed estimates of soil loss and helping to identify critical areas for erosion control. CROM model focuses on identifying and prioritizing areas within a catchment where restoration interventions could be most effective, based on landscape attributes, land use, and ecological potential (Simmons et al., 2017). While the RUSLE model provides quantitative erosion estimates and supports erosion control measures, CROM is innovative in its spatial planning approach, emphasizing strategic restoration efforts to enhance ecological resilience and manage soil erosion in a broader catchment context.

In 2020, Potential soil erosion risk areas were identified and mapped using the Catchment Restoration Opportunity Mapping (CROM) methodology. Potential soil erosion risk areas were pinpointed and mapped using the Catchment Restoration Opportunity Mapping (CROM) at the district level. In small-scale erosion risk estimation is still lacking, and there is no universal model that fits all situations, particularly in highly heterogeneous environments. The CROM model categorized erosion risk into six levels: no risk, low risk, moderate risk, high risk, very high risk, and extremely high risk. The CROM model has not been applied in the study area; instead, the study relied on the output of the Revised Universal Soil Loss Equation (RUSLE) model (Oh & Jung, 2005).

1.3. Objectives

1.3.1. General objective

The primary objective of this research is to assess soil erosion impacts in Musanze District using the RUSLE model to inform decision-makers about a balanced approach to land management, set a series of mitigation measures, and minimize potential conflicts over land resources.

1.3.2. Specific objectives

- ✓ To estimate soil erosion levels in the Kinigi, Nyange, and Shingiro sectors using the RUSLE model.
- ✓ To evaluate the impacts of soil erosion on agriculture and soil nutrients in the Kinigi, Nyange, and Shingiro sectors.
- ✓ To evaluate the impacts of soil erosion on infrastructure in the Kinigi, Nyange, and Shingiro sectors.
- ✓ To assess the impact of soil erosion on the overall well-being of the community and propose recommendations.

1.4. Research questions

- ✓ What are the soil erosion levels in the Kinigi, Nyange, and Shingiro sectors?
- ✓ How does soil erosion impact crop productivity and soil nutrient levels in the Kinigi, Nyange, and Shingiro sectors?
- ✓ What are the effects of soil erosion on infrastructure durability and maintenance costs in the Kinigi, Nyange, and Shingiro sectors?
- ✓ How does soil erosion affect the overall well-being of communities in the Kinigi, Nyange, and Shingiro sectors, and what recommendations can be made to mitigate these impacts?

1.5. Justification of the study

I am personally interested in this study as it allows me to improve my skills in assessing soil erosion levels using the Revised Universal Soil Loss Equation (RUSLE) model. It also helps me develop expertise in evaluating the impacts of soil erosion on people's livelihoods and environmental land degradation. Most importantly, this study is a mandatory academic requirement for obtaining a Master's degree in Geo-information Science and Environment for Sustainable Development. Furthermore, it will significantly contribute to the academic community, providing a valuable resource for students and researchers interested in this field. It will expand the available reference materials in the library and serve as a guiding reference for future research endeavors. Also, the study assesses soil erosion and its impacts including socio-economic ones in Musanze District. The study holds profound social interest by addressing critical issues that affect the well-being of the local population. This assessment is vital for sustaining agricultural productivity, preserving livelihoods, and ensuring food security. It directly contributes to enhancing the socio-economic conditions of the community, fostering environmental sustainability, and fostering a more prosperous and ecologically resilient future for the district's residents.

1.6. The study's scope and limitations

This research is enclosed in space, time, and content. First of all, the study is limited in space since it is carried out this research is done in the Kinigi, Nyange, and Shingiro sectors of

Musanze district Rwanda around Virunga National Park. Secondly, the study is limited in time as it was completely done in a short time and the study is limited in as it focuses on identifying the Revised Universal Soil Loss Equation (RUSLE model) for examining soil erosion levels and its effects on socio-economic aspects such as livelihoods, environmental effects, and soil fertility within the study area. For obtaining the socio-economic impact surveys of soil erosion in the study area, especially when collecting data from households. This approval ensures that participants' rights and well-being are protected and that the data collected is handled with integrity and confidentiality.

CHAPTER 2: LITERATURE REVIEW

2.0 General introduction

Globally, soil erosion is a significant environmental issue, leading to the loss of fertile land, reduced agricultural productivity, and increased sedimentation in waterways. This problem is particularly acute in Rwanda, where steep slopes, heavy rainfall, and unsustainable land use practices exacerbate the rate of soil erosion. In Rwanda, soil erosion poses serious threats to soil fertility, water quality, and the overall economy, necessitating urgent and effective mitigation measures (MoE, 2020).

Soil erosion rates are critically high, with approximately 24 billion tons of fertile soil lost each year due to erosion. This loss of topsoil not only diminishes soil fertility but also leads to sedimentation of water bodies, degradation of ecosystems, and increased greenhouse gas emissions. Deforestation, unsustainable agricultural practices, urbanization, and climate change all contribute to the increasing rates of soil erosion in various regions (FAO, 2019). For instance, regions with intensive agriculture or deforestation experience higher erosion rates, exacerbating soil degradation and compromising local food production. Efforts to address soil erosion at both global and regional levels are crucial for preserving soil fertility, mitigating environmental degradation, and ensuring sustainable land management practices for future generations (Montgomery, 2007).

2.1. Soil erosion types and causes

Rwandan soils are inherently fragile and prone to erosion, especially in combination with cultivated lands, rivers, and water reservoirs downstream. This also raises the risk of crop destruction and siltation of marshes and plains (MIDIMAR, 2012). A recent survey of 25,144 plots nationwide revealed that 88% experienced low levels of soil erosion (splash and wind erosion), followed by moderate erosion (diffuse overland flow), and severe soil loss (rill erosion, gully erosion, mass movement, and landslides). Large areas of Rwanda's soil are exhausted due to continuous farming, soil degradation, and erosion, with minimal use of fertilizers to compensate for the nutrient loss (IWRM, 2022).

There are four major types of soil erosion: Splash erosion, which is the initial stage involving the detachment and airborne movement of small soil particles caused by raindrop impact; Sheet erosion, where soil particles are detached by raindrop impact and removed downslope by water flowing overland as a sheet rather than in defined channels or rills; Rill erosion, where concentrated water creates tiny channels a few centimeters deep by running through small streamlets or head cuts; and Gully erosion, which involves the removal of topsoil along drainage channels by surface water runoff, resulting in open, incised, and unstable channels typically more than 30 cm deep (Marzen & Iserloh, 2021). This happens when water creates several small channels, each a few centimeters deep, on a piece of land. Gully erosion occurs when the topsoil is removed along drainage channels by surface water runoff, resulting in an open, incised, and unstable channel generally more than 30 cm deep.

Soil erosion is the natural process by which soil is displaced or worn away by environmental factors such as wind, water, and human activities. Deforestation, typically for agricultural expansion and fuelwood collection, exposes soil to erosion by removing the protective vegetation cover. Additionally, inadequate soil conservation measures, such as terracing and agroforestry, further exacerbate erosion rates. Population growth and associated land use changes intensify pressure on land resources, leading to increased erosion (Grepperud, 1996). Combating soil erosion in Rwanda necessitates comprehensive strategies, including sustainable land management practices, reforestation efforts, and policies that promote conservation and land use planning.

Soil erosion is a natural process where soil is displaced or worn away by environmental factors like wind, water, and human activities. It involves the detachment and movement of soil particles from one place to another, gradually degrading fertile topsoil. The main agents of this process are wind and water, with rainfall, surface runoff, and windstorms being key contributors. Erosion can be exacerbated by deforestation, improper agricultural practices, and urbanization, which remove protective vegetation cover and disturb the soil structure. The consequences of soil erosion are far-reaching, including reduced soil fertility, compromised water quality, and increased vulnerability to extreme weather events. Effective soil conservation practices and sustainable land management are vital for reducing the impacts of soil erosion and protecting the productivity and resilience of ecosystems (Lal, 2001).

Rwandan soils are naturally fragile and erosive. The combination of solid and downstream cultivated lands, rivers, and water reservoirs is caused by soil degradation and soil erosion (Nimusima et al., 2018). It also increases the risk of crop destruction and siltation of marshes and plains. Large shares of Rwanda’s soils are exhausted due to continuous farming, soil degradation, and soil erosion, and little use of fertilizers that can compensate for the loss of nutrients caused by soil loss. Erosion is the gradual process of wearing away or moving soil, rock, or other materials on the Earth's surface through natural forces such as wind, water, ice, and human activities. It's a natural geological process, but human activities can significantly accelerate erosion rates, leading to severe environmental and societal impacts (MIDIMAR, 2012).

Rwanda has faced increased soil erosion due to unsustainable human activities and shifts in land use. The primary factors influencing soil erosion are land use, vegetation cover, topography, soil properties, and climate. Approximately 90 percent of the country is on slopes, leading to a high risk of soil erosion and reduced fertility. Extensive areas of soil are depleted due to continuous farming, soil degradation, and erosion, with minimal use of fertilizers to offset nutrient loss from soil depletion and overexploitation. Approximately 11 percent of the country faces an extremely high or very high risk of soil erosion (REMA, 2021).

2.2. Estimation of soil erosion

Soil erosion levels can be estimated using various methods that consider factors such as land use, soil type, topography, and climate conditions. Commonly used techniques include the Revised Universal Soil Loss Equation (RUSLE) which calculates erosion rates based on factors like rainfall erosivity, soil erodibility, slope length, slope steepness, and land cover management practices. Additionally, geographic information systems (GIS) technologies are increasingly employed to assess erosion dynamics over larger spatial scales (Lal, 2001), other commonly used methods for estimating soil erosion include the Water Erosion Prediction Project (WEPP) model and the Soil and Water Assessment Tool (SWAT). WEPP offers detailed simulations of soil erosion and sediment transport using physical processes and is highly adaptable to varying land conditions (Flanagan & Nearing, 1995). SWAT integrates hydrology and erosion processes to predict water quality and quantity impacts at the watershed scale (Arnold et al.,

1998) and provide detailed insights into the impacts of erosion on soil productivity, biodiversity loss, and downstream sedimentation, highlighting the importance of sustainable land management practices in mitigating erosion risks and preserving soil health (Montgomery 2007).

2.3. Effects of soil erosion

Areas affected by soil erosion experience significant soil fertility loss and reduced crop yields, as erosion depletes essential nutrients. This diminishes the soil's economic value, often leading to famine among local populations in severely eroded regions. Additionally, eroded materials can block river flow, causing river valley over-flooding, and resulting in the destruction of natural vegetation and environmental degradation (Montgomery, 2007).

Soil erosion has numerous effects, such as migration, invasion, violence, defense, and functionality. In terms of migration, significant soil loss results in the dispersal and mixing of a vast diversity and abundance of soil organisms. As a result, erosion directly affects soil population dynamics. The invasion effect involves soil runoff transporting organisms over significant distances. For instance, soil-dwelling organisms can be carried into river systems by erosion events, allowing them to reach and colonize new aquatic habitats (Asuoha et al., 2019).

The violence effect refers to the intensity of erosive events that can significantly alter or even destroy entire communities of soil organisms, potentially contributing to extinction processes. Regarding the defense effect, erosion acts as a stressor, and soil organisms have evolved mechanisms to mitigate or eliminate related damage, thereby aiding in ecosystem restoration and soil conservation. The function effect of erosion enables soil organisms to support various ecosystem functions and services, including decomposition, plant productivity, nutrient cycling, and the regulation of greenhouse gas emissions (Orgiazzi and Panagos, 2018).

Soil erosion poses significant socio-economic challenges in Musanze District, Rwanda, primarily impacting agricultural productivity, food security, and livelihoods. Agriculture is vital to the region's economy, but the loss of fertile topsoil due to erosion leads to lower crop yields and reduced crop diversity. This, in turn, decreases farmers' incomes and exacerbates poverty levels (Bizuru et al., 2018). Moreover, erosion-induced infrastructure damage, such as roads and buildings, disrupts access to essential services and hampers economic development (Mukashema, 2015). The deterioration of water quality from sedimentation in rivers and streams worsens the problem, impacting human health and biodiversity (Ndayisaba et al, 2018). Efforts to address soil erosion in Musanze District are crucial for sustaining agricultural production, improving livelihoods, and enhancing overall socio-economic resilience in the region.

Food security and agricultural sustainability by depleting fertile topsoil essential for crop growth, thereby reducing yields and compromising the livelihoods of millions worldwide, it undermines water supply systems and reservoir storage capacity as eroded sedimentation fills up water bodies, diminishing their capacity to store freshwater, exacerbating drought vulnerability, and impairing water quality. Additionally, soil erosion contributes to the loss of biodiversity, disrupting ecosystems and diminishing the services they provide, such as pollination and soil fertility maintenance (Montgomery, 2007)

2.4. Soil erosion and its impacts

Erosion is a global environmental challenge with wide-ranging impacts. Environmentally, erosion causes soil degradation, loss of topsoil, and ecosystem disruption, significantly affecting biodiversity by destroying habitats and threatening numerous plant and animal species. Economically, erosion translates to substantial financial losses due to reduced agricultural productivity, infrastructure damage, and increased healthcare costs. Livelihoods, especially in rural areas, are deeply impacted as erosion disrupts traditional practices, affecting income and exacerbating poverty. Public health is compromised through waterborne diseases, air pollution, and compromised sanitation resulting from erosion (Kaiser, 2023).

Erosion in Rwanda has pervasive impacts across multiple domains. Environmentally, erosion impacts soil degradation and loss of fertility by stripping away the topsoil, habitat destruction, biodiversity loss and ecosystem disruption, sedimentation in water bodies due to siltation, and water quality and life., Economically, erosion impacts agriculture productivity by degrading arable land, resulting in lower crop yields, infrastructure damage, leading to increased maintenance and repair costs for roads, buildings, and other structures, livelihood disruption, and poverty particularly for those dependent on agriculture (Ndagijimana, 2017). This can lead to increased poverty and vulnerability among affected communities, displacement, and migration. Erosion-induced disasters such as landslides can displace communities, forcing them to migrate and impacting their traditional livelihoods (Barbier and Hochard, 2018). In Public health, erosion can increase diseases such as waterborne diseases by contaminating water sources with sediments and pollutants. Erosion can impact biodiversity through habitat loss and fragmentation pushing species towards extinction, and threats to endemic and rare species by disrupting their habitats and reducing their available living space (Isik, 2011).

2.5. Impact of soil erosion on socio-economic factors

Erosion impacts both rural and urban areas by isolating communities, and cutting off roads, drinking water supplies, and other essential socio-economic infrastructure. It is often triggered by unsustainable agricultural practices, mismanagement, climate change, sloppy driving, and sediment disasters. Although these factors worsen soil erosion, they do not fully explain the varying severity of erosion in regions plagued by poverty (Igwe and Fukuoka, 2010).

Soil erosion in Musanze District, Rwanda, has profound socio-economic implications, significantly affecting the livelihoods and well-being of local communities. The district's rugged terrain and heavy rainfall intensify erosion rates, resulting in the loss of fertile topsoil essential for agricultural productivity. As a result, crop yields diminish, posing threats to food security and farmers' incomes. Reduced agricultural output contributes to increased poverty levels and exacerbates vulnerability to food insecurity and malnutrition among residents. Furthermore, soil erosion can lead to environmental degradation, affecting water quality, biodiversity, and ecosystem services, which are essential for sustaining livelihoods and local economies (Bizuru et al., 2018).

Soil erosion can be addressed by implementing erosion control systems, which are influenced by both the physical characteristics of farmland (such as slope, soil type, and location) and socio-economic factors (including non-farm and farm income, household size, education, extension services, and land tenure).

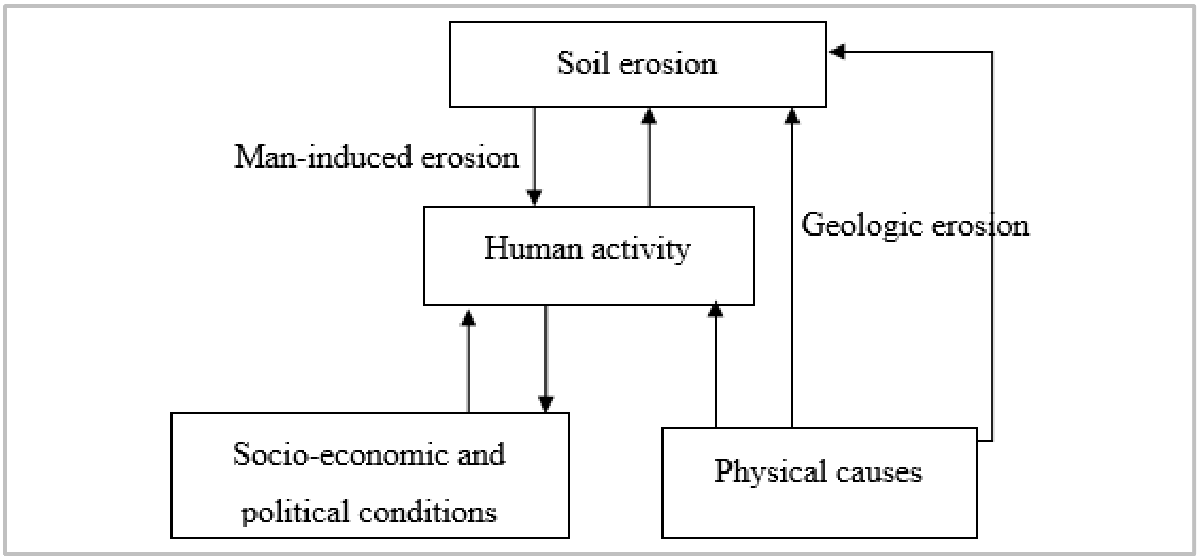

Figure 1: Soil erosion accelerated by the interaction of physical, socio-economic, and political (Mandal & Giri, 2021)

The figure above illustrates how the interplay of physical, socioeconomic, and political factors accelerates erosion within an integrated system. Consequently, while the physical environment is significant, the sustainable implementation of soil erosion control systems heavily relies on socioeconomic conditions, including farmers' perceptions of soil erosion and control possibilities, as well as their impacts on livelihoods (Green & Heffernan, 1987).

2.6. Effects of Soil Erosion on Soil Nutrients

Soil erosion in Rwanda significantly reduces the effectiveness of soil fertilizers, thereby undermining agricultural productivity and food security. The country's hilly terrain and heavy rainfall exacerbate erosion, leading to the loss of topsoil and essential nutrients crucial for plant growth and nutrient uptake. As a consequence, the retention and availability of applied fertilizers diminish, reducing their effectiveness in supporting optimal crop yields. Moreover, erosion-induced soil degradation results in increased nutrient runoff and leaching, further depleting soil fertility and exacerbating nutrient deficiencies in agricultural lands. Musanze district's rugged topography and heavy precipitation intensify erosion rates, resulting in the loss of fertile topsoil and essential nutrients crucial for plant growth. Soil's ability to retain and utilize applied fertilizers decreases, leading to reduced nutrient availability for crops. Moreover, erosion-induced soil degradation exacerbates nutrient runoff and leaching, further depleting soil fertility and hindering agricultural productivity (Arriaga & Lowery, 2007)

Soil erosion can significantly impact various soil nutrients through physical displacement, nutrient loss, and alterations in soil properties. Erosion processes, like water runoff, can strip away the topsoil layer reducing crop nutrient availability that is rich in organic matter and essential nutrients, resulting in decreased soil fertility. Additionally, erosion can result in the loss of nutrient-rich sediment, exacerbating nutrient depletion in affected areas. Moreover, soil erosion can alter soil pH, texture, and structure, affecting nutrient availability, uptake, and cycling processes. These changes can disrupt the balance of essential nutrients like nitrogen, phosphorus, and potassium, ultimately affecting soil productivity and agricultural yields (Medhi et al., 2021).

Phosphorus is essential for energy transfer in plants and is a vital component of DNA and RNA. Soil erosion can lead to the loss of phosphorus-rich soil particles, particularly those attached to sediment. This reduction can decrease phosphorus availability in the soil, hindering plant growth and productivity.

Potassium plays a role in numerous physiological processes in plants, such as enzyme activation and water regulation. Soil erosion can transport potassium-rich soil particles away from the topsoil, reducing the availability of potassium for plant uptake (Chu, 1990). Nitrogen is vital for plant growth and crucial for chlorophyll formation and protein synthesis. Soil erosion can lead to the loss of nitrogen through runoff, especially in the form of nitrate ions, which are water-soluble and can be easily transported away from the soil.

CHAPTER 3: METHODOLOGY

3.1. Description of the Study Area

This study is conducted in the Kinigi, Nyange, and Shingiro sectors of Musanze District in Rwanda's Northern Province. The geographical coordinates of the study area range from approximately 1.3833° S to 1.7167° S latitude and 29.5667° E to 29.7500° E longitude (NISR, 2012). This area is renowned for its beautiful landscape and its proximity to Volcanoes National Park, which is home to the endangered mountain gorillas.

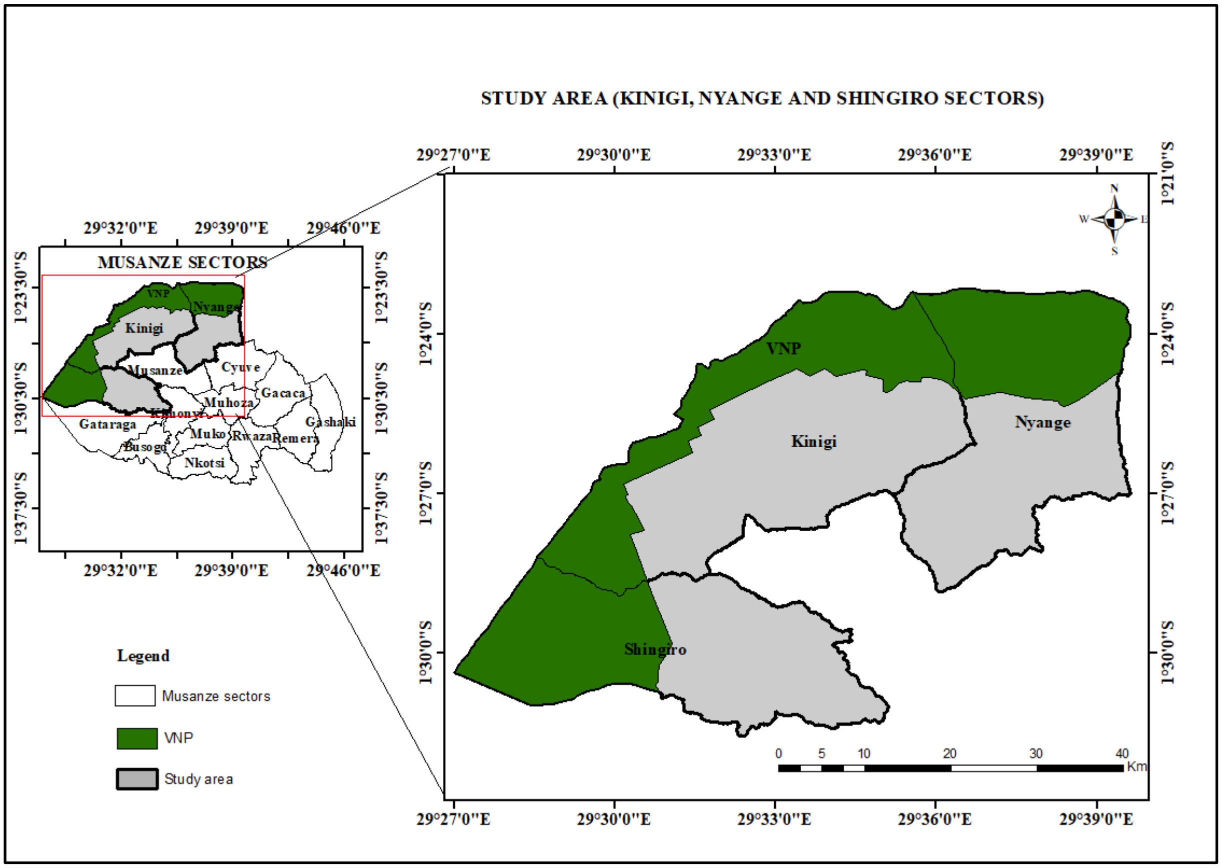

Figure 2: Location of the study area sectors around VNP (DUSABIMANA,2024)

Musanze District is bordered by the districts of Rubavu to the west, Nyabihu to the southwest, Burera to the northeast, and Gakenke to the southeast. Kinigi, Shingiro, and Nyange sectors are located around the VNP and are especially prone to erosion because of their steep terrain and significant rainfall. The area is also densely populated, which exacerbates the issue of land scarcity, intense competition for the available land, and unsustainable land use practices like overgrazing and deforestation. These practices further contribute to soil erosion and land degradation, reducing land productivity and worsening food insecurity (Nyirigira, 2019).

According to JICA (2020 the area has a typical tropical climate, with high annual rainfall reaching up to 1,500 mm. Rainfall amounts vary between 2,000 and 3,000 mm per year (Nahayo et al 2013). The average maximum temperature ranges from 22-26°C, while the average minimum temperature ranges from 10-15°C. The climate is divided into four main seasons: a short dry season from January to March, a long rainy season from March to May with torrential rainfall, a long dry season from June to August, and another rainy season from September to December (Ngarukiyimana et al., 2021).

3.2. Methods of Data Collection

The study utilized data including rainfall, soil, digital elevation models, and the Normalized Difference Vegetation Index (NDVI). These data types are integral to RUSLE because they directly influence the erosion processes it models. Rainfall data provides insight into the intensity and frequency of precipitation, which affects the erosive power of rain. Soil data informs the model about soil erodibility and its susceptibility to erosion. Digital elevation models (DEMs) are used to determine slope steepness and length, which influence erosion rates. The Normalized Difference Vegetation Index (NDVI) reflects vegetation cover, which impacts soil protection and erosion control. Rainfall data (mm) were sourced from Meteo Rwanda. The later collected rainfall data utilizing tipping bucket rain gauges positioned in the Kinigi sector in Bisoke and Kampanga cells, and in the Shingiro sector (one rain gauge) (See Figure 4). Rainfall data were utilized to estimate the R-factor.

Soil data comprise varying percentages of sand, clay, silt, and total organic carbon (TOC), nitrogen, phosphorus, and potassium. The samples were collected from the topsoil at five (5) points, with the total sampling points obtained from the Rwanda Agriculture Board (RAB). Four soil sampling points were located in the Kinigi sector within four cells (Bisoke, Nyonirima, Kampanga, and Nyabigoma), and an additional point was sampled in the Nyange sector, each with their respective geographical coordinates. Soil samples were collected at a consistent depth of 0-30 cm to ensure comparability, as soil properties can vary significantly with depth. The selection of these sample points was based on a stratified sampling approach to capture the variability in soil erosion across different topographical and land use conditions.

Additionally, socio-economic data were collected from 385 households within these areas to understand the human impact and perceptions regarding soil erosion. The sample size for the socio-economic surveys was calculated using statistical methods (see Equation 1) to ensure a high level of confidence and precision in the results, providing the interactions between soil erosion and community livelihoods (see Figure 3). Soil data were collected and analyzed in the laboratory to determine soil texture elements, TOC, nitrogen, phosphorus, and potassium. These data were used to calculate the K-factor and assess the impact of soil erosion on nutrient levels. Potassium (K) and nitrogen (N) are vital for plant growth, each contributing to different physiological processes. Potassium is crucial for water regulation, enzyme activation, photosynthesis, and nutrient transport, contributing to plant strength and disease resistance (Kumar et al., 2020). Nitrogen is a fundamental component of chlorophyll necessary for photosynthesis and is integral to amino acids and nucleic acids, essential for protein synthesis and genetic material (Dubey et al., 2014). Potassium deficiencies can lead to yellowing leaf edges, weak stems, and poor root development, while nitrogen deficiencies often cause yellowing of older leaves and stunted growth.

Soil parameters including sand, clay, silt, and total organic carbon (TOC) are typically analyzed in a laboratory using various techniques such as hydrometer, pipette, sieve, laser diffraction, and dry and wet combustion. Particle size analysis methods, such as the hydrometer and pipette methods, are commonly used to determine the percentages of sand, silt, and clay in soil samples. These methods involve the sedimentation of soil particles in water, with particle size determined by their settling rates. Total Organic Carbon analysis involves the quantification of carbon content in the soil sample using techniques such as field surveys would involve on-the-ground observations and measurements of erosion features such as gullies, sediment deposition, and soil loss.

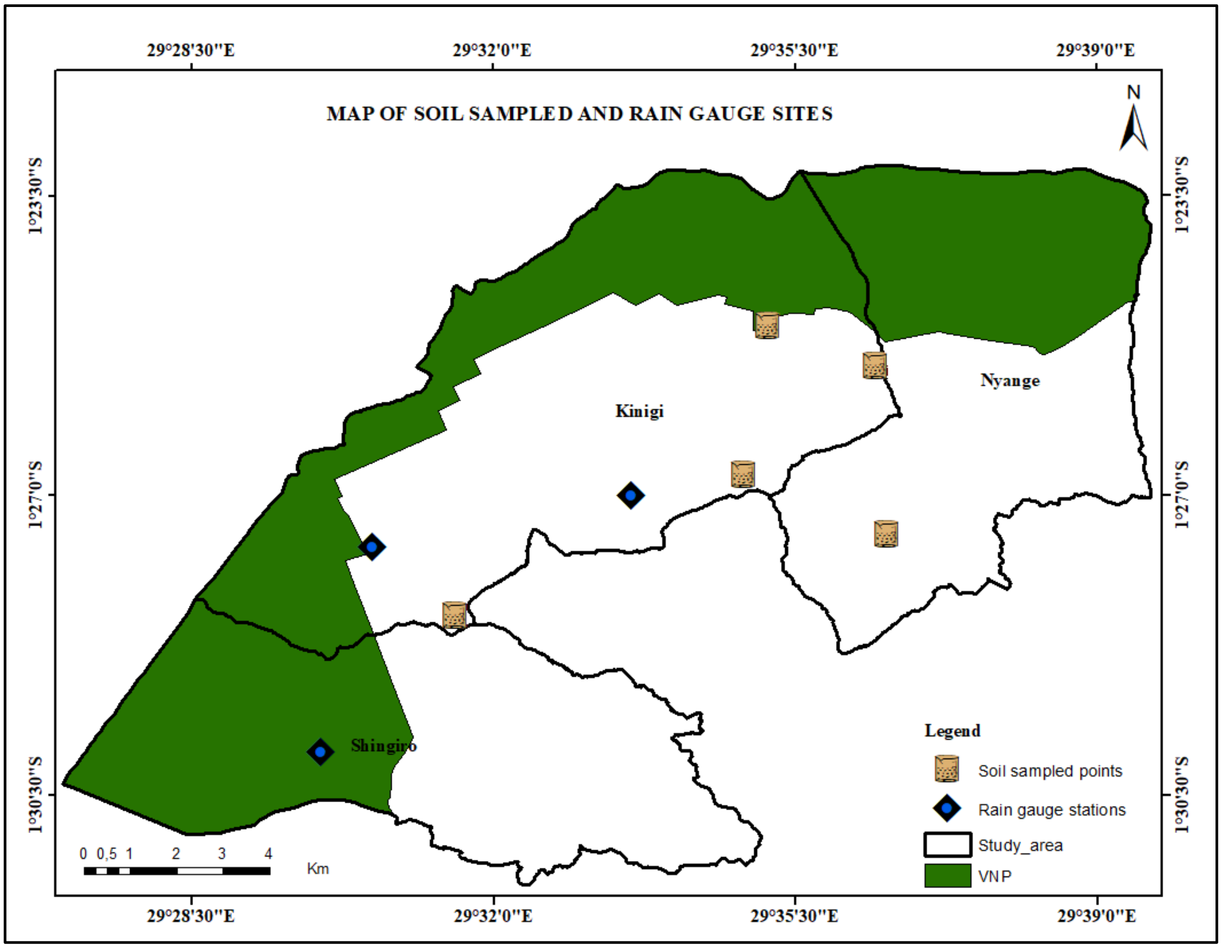

Figure 3: Soil sampling sites and rain gauge locations in the study area (DUSABIMANA,2024)

Figure 3 indicates soil sampled and Rain Gauge Sites" within the Kinigi, Nyange, and Shingiro sectors, which are located adjacent to the Volcanoes National Park (VNP). The map highlights areas where soil samples have been collected (marked by brown squares) and locations of rain gauge stations (indicated by blue diamonds). The green area indicates the VNP, while the grey area outlines the broader study area. Both soil sampling points are included and rain gauge stations suggest that the study could be focused on understanding how rainfall patterns affect soil properties and erosion within these sectors, possibly about conservation efforts and agricultural practices near the protected environment of the national park.

3.2.1 Soil erosion rates in the study area

The Digital Elevation Model (DEM) data, obtained from USGS Earth Explorer, had a 30 m resolution (x, y). This data was used to calculate slopes and slope gradients for assessing the conservation practice factor (P-factor) and factors related to slope, including slope length (L factor) and slope steepness (S factor), collectively known as the LS factor.

The Normalized Difference Vegetation Index (NDVI) was utilized as a proxy for land cover data. NDVI data for the study area were derived from Landsat 8, which includes eight bands. The imagery was acquired from Earth Explorer and analyzed in ArcGIS. The NDVI was used to estimate the C-factor, reflecting the impact of cropping and management practices on soil erosion within the study area

3.2.2 Economic and social effects of soil erosion in the study area

Socio-economic data on the impacts of soil erosion, including expenses related to erosion control measures, rehabilitation initiatives, and healthcare costs arising from erosion-related health issues were collected using household semi-interviews. Determining the sample size for a household survey involves statistical calculations that ensure the results are both accurate and representative of the population being studied. Here are different steps to determine the sample size for household surveys: Define survey parameters, including population size (N), which represents the total number of households, and specify the confidence level and margin of error, confidence level (typically set at 95% for surveys, corresponding to Z=1.96 for a normal distribution), but can vary based on the study's requirements), the margin of Error (E) was decided on an acceptable margin of error, often set at 5% (E = 0.05), Estimate proportion (p) or Standard Deviation (σ) i.e.Estimate of Proportion (p): If estimating a proportion (e.g., the percentage of households with a specific characteristic), estimate p based on prior knowledge or assumptions and estimate of standard deviation (σ**)** estimating a mean (e.g., average household income), estimate the standard deviation of the variable of interest (Cochran, W.G. 1977)

$$n = \frac{Z^2\, p(p-1)}{E^2} \qquad \text{(Equation 1)}$$

Where: n is the required sample size, Z is the Z-value corresponding to the desired confidence level, p is the estimated proportion of households with the characteristic, and E is the margin of error

3.2.3 Effects of soil erosion on soil nutrients in the study area

The effects of soil erosion on nutrient levels in the Kinigi, Nyange, and Shingiro sectors were measured by collecting soil samples from various points within these areas. These points were categorized based on erosion severity, with a specific focus on regions experiencing high to severe erosion, as well as areas with low to moderate erosion. The soil samples were subsequently analyzed for their Nitrogen (N), Phosphorus (P), and Potassium (K) content.

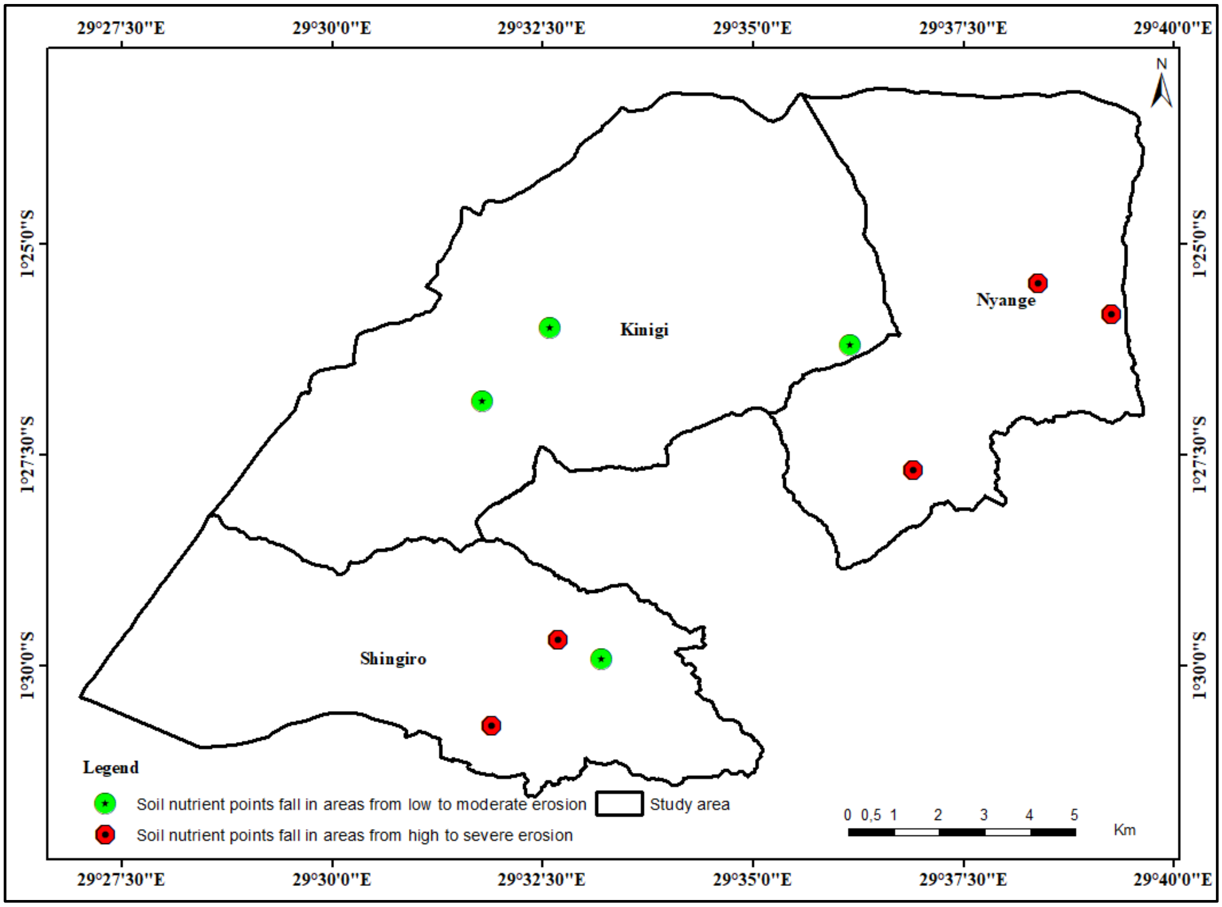

Figure 4: Soil sampling points location (DUSABIMANA,2024)

The corresponding soil loss was also assessed to determine the relationship between erosion severity and nutrient depletion. The data was mapped to visually represent the distribution of nutrient levels across different erosion zones, enabling a comprehensive understanding of soil degradation patterns within the study area.

Soil erosion can alter the concentration of soil nutrients in eroded soils compared to unaffected soils. This change can be quantified by measuring soil nutrients in soil samples collected from eroded areas within the field. The amount of nitrogen lost due to erosion can be estimated by measuring the difference in nitrogen content between eroded soils and multiplying it by the volume or weight of eroded soil. By collecting three soil samples from each sector, Soil samples were analyzed in a laboratory to determine nitrogen, phosphorus, and potassium levels.

Analysis of soil samples to assess nitrogen, phosphorus, and potassium (NPK) begins with a series of preparatory steps that include removing debris, air-drying, grinding to a fine powder, and filtration to remove particles and solids. After preparation, nutrients are analyzed using various techniques, including spectrometry, Atomic Absorption Spectroscopy (AAS), Ion Chromatography (IC), and Inductively Coupled Plasma (ICP).

Soil nitrogen content was analyzed using the (Keeney et al. 1982) method as follows:

$$\text{N (\%)} = (T - bl) * 0.2 * FC * FD * 100 * 1000 \qquad \text{(Equation 2)}$$

Where FC collective factor of H_2SO_4 N/70, FD dilution factor (=10), 0.2 means 1 ml of H_2SO_4 N/70 is equivalent to 0.2 mgr of n, T-bl: blank titration.

Soil erosion can impact potassium (K) analysis in various ways, affecting the distribution, availability, and concentration of potassium in eroded soils and sediment transported to other locations. Soil erosion results in the loss of topsoil, which often contains potassium-rich minerals and organic matter. The amount of potassium lost due to erosion can be estimated by measuring potassium concentrations in eroded soils and calculating the total mass or volume of potassium lost.

$$\text{K concentration (cmol (+)/Kg)} = \frac{\text{Volume of soil extract (L) X Potassium concentration from the instrument } (\frac{\text{mg}}{\text{L}})}{\text{Weight of soil sample}} \qquad \text{(Equation 3)}$$

K concentration (cmol (+)/Kg) indicates the amount of potassium in the soil sample, measured in milligrams per kilogram or parts per million, representing the potassium content per unit weight of soil.

The volume of soil extract (L) denotes the volume of the soil extract used for analysis, typically measured in liters. The soil extract is a solution obtained by mixing a known amount of soil with a specific volume of extracting solution, such as water or chemical extraction, to release the soluble potassium from the soil matrix.

The potassium concentration from the instrument (mg/L) represents the amount of potassium in the soil extract as measured by the analytical instrument, such as a spectrophotometer or a flame photometer, typically reported in milligrams per liter (mg/L). This measurement provides the potassium concentration in the soil extract solution after analysis.

The weight of the soil sample, typically measured in kilograms, refers to the amount of soil used for extraction. The soil sample weight is crucial for calculating the concentration of potassium in the soil on a weight basis (mg/kg). The K-factor measures the soil's susceptibility to detachment and transport by rainfall and runoff.

Soil erosion can significantly impact phosphorus (P) analysis due to the redistribution of phosphorus-rich sediments. Erosion processes, particularly in agricultural landscapes, can lead to the loss of topsoil, which often contains high concentrations of phosphorus due to fertilization practices. This redistribution alters the spatial distribution of phosphorus within the landscape, making it challenging to accurately assess phosphorus levels in soil samples collected for analysis. Erosion can transport phosphorus-laden sediments into water bodies, contributing to eutrophication and further complicating phosphorus monitoring efforts (Hansen et al., 2002).

$$P\ (ppm) = \mathrm{Absc} * \mathrm{FC} * \mathrm{fd.d} \qquad \text{(Equation 4)}$$

Where P is phosphorus, Absc: Absorbance, FC: collective factor, fd: dilution factor.
P (ppm) represents the concentration of the substance in parts per million, which is a measure of the amount of solute present in a solution relative to the total solution volume. Absorbance stands for absorbance, which is a measure of how much light is absorbed by a sample at a particular wavelength. It's often determined using a spectrophotometer.
FC: stands for the dilution factor or the sample volume correction factor. It accounts for any dilutions made to the sample before measurement. f was represented as the conversion factor, which converts the absorbance value to the desired concentration units. It's often specific to the instrument or method used. d was denoted the path length of the sample cell in the spectrophotometer, typically measured in centimeters.

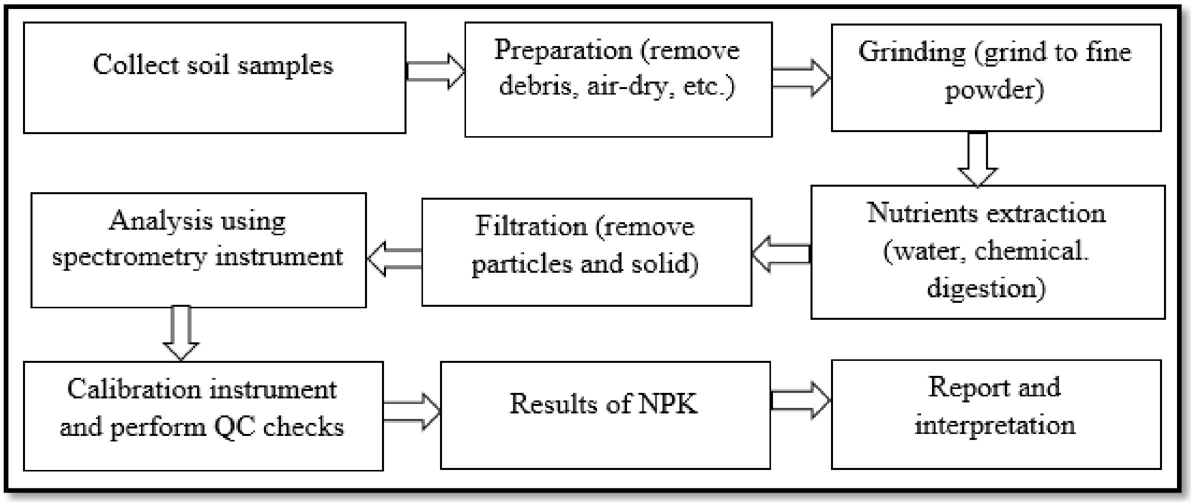

Figure 5: Flow diagram for analyzing soil samples in the study area (DUSABIMANA,2024)

Measuring soil nutrient levels and analyzing their impact involves multiple steps. Initially, soil samples are collected and prepared by removing debris and air-drying. These samples are then ground into a fine powder. The next step involves nutrient extraction through methods such as water or chemical digestion, followed by filtration to remove particles and solids. The prepared samples are analyzed using a spectrometry instrument, with calibration and quality control checks performed to ensure accuracy. The levels of Nitrogen (N), Phosphorus (P), and Potassium (K) are measured, interpreted, and reported.

3.3. Data processing and analysis

Data were processed using the RUSLE model, an empirical approach developed to estimate long-term mean annual soil loss from rill and interrill erosion (Kaushik and Santasmita, 2020). The RUSLE model accounts for raindrop impacts on climate, soil, topography, and land use affecting rill and interrill erosion (Magdoff & Weil, 2004). It estimates annual soil loss within a Geographic Information System (GIS) platform (Yitayew & Pokrzywka et al., 1999). The RUSLE model is represented by the following equation:

$A = R * K * LS * C * P$ (Magdoff and Weil, 2004), (Equation 5)

Where A represents the annual average soil loss, K is the soil erodibility factor, P is the support practice factor, C is = Cover management factor, R is = Rainfall erosivity factor; and LS = Slope length and slope steepness factor.

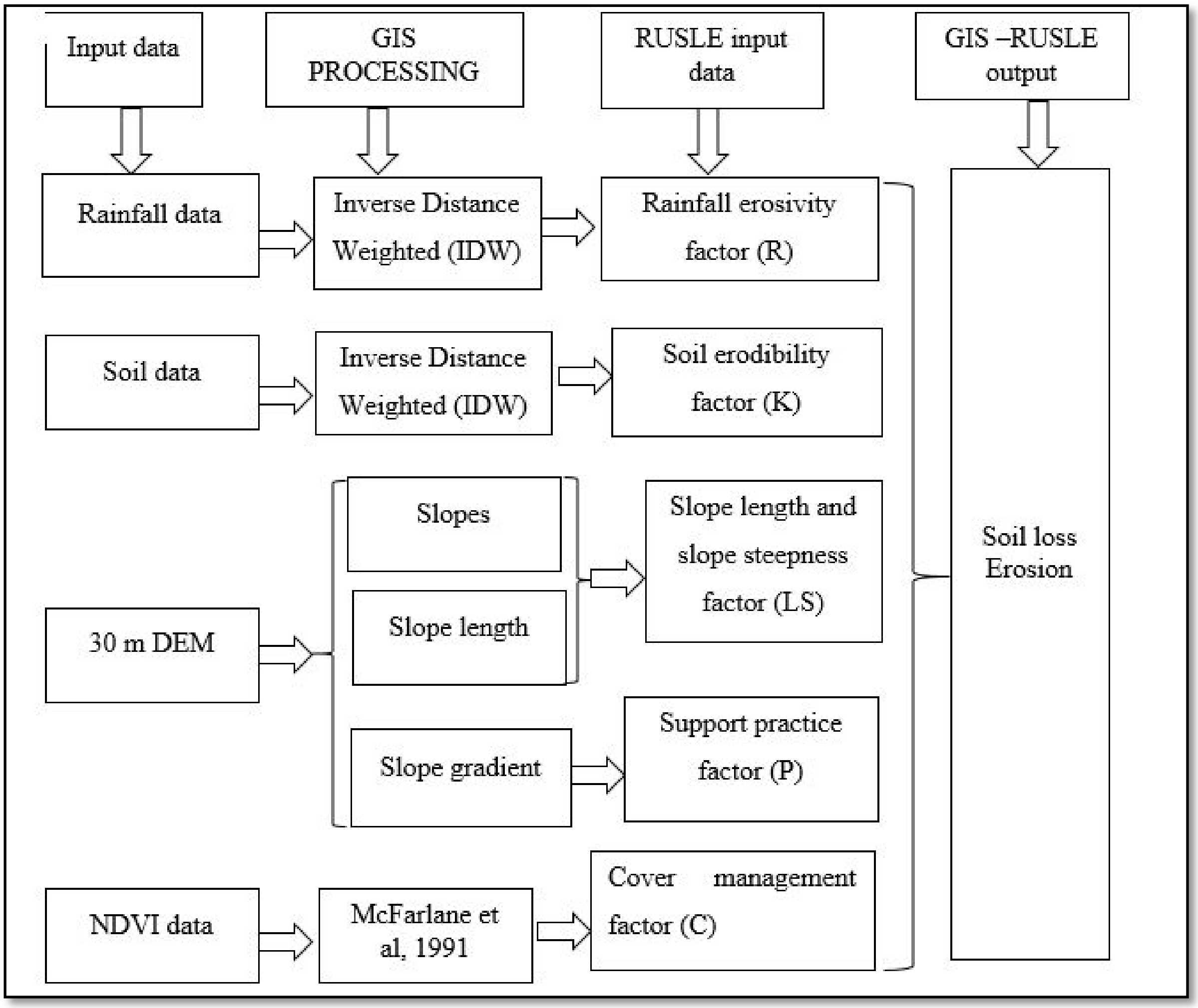

Figure 6: Flow diagram for estimating soil erosion using the (RUSLE) model (DUSABIMANA, 2024)

Figure 6 illustrates a workflow for modeling soil erosion using the Revised Universal Soil Loss Equation (RUSLE) combined with Geographic Information Systems (GIS). The process starts with gathering input data, including rainfall data, soil data, a 30-meter Digital Elevation Model (DEM), and Normalized Difference Vegetation Index (NDVI) data. These inputs are processed using GIS techniques, such as Inverse Distance Weighted (IDW) interpolation for rainfall and soil data, to obtain spatially relevant parameters like the rainfall erosivity factor (R) and soil erodibility factor (K). The DEM is utilized to calculate slope length and gradient, contributing to the slope length and steepness factor (LS). NDVI data, as per McFarlane et al., 1991, is used to determine the cover management factor (C) and the support practice factor (P). These factors

(R, K, LS, C, and P) are then integrated into the RUSLE model through GIS to estimate soil loss from erosion, ultimately producing outputs useful for assessing and mitigating erosion risks effectively.

3.3.1. Generation of erosion factors maps

- **Slope length and steepness factor, and support practice factor**

The P factor considers the impact of anti-erosion techniques, such as contour farming, strip cropping, terracing, and subsurface drainage, on reducing soil loss by influencing drainage patterns. In this study, the P-factor support practice factors were used, with contouring ranging from 0.55 to 1, strip cropping varying from 0.27 to 0.5, and terracing ranging from 0.1 to 0.2 The P-values were estimated using the Wenner (1981) method, which is based on the linear relationship between the slope (S) of an area and the amount of conservation practice (P), as described by the equation:

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

P represents the conservation practice amount and S is the slope percentage. The P value ranges from 0 to 1, where 0 indicates a highly effective man-made erosion resistance facility, and 1 indicates the absence of such a facility (Ham et al., 2016).

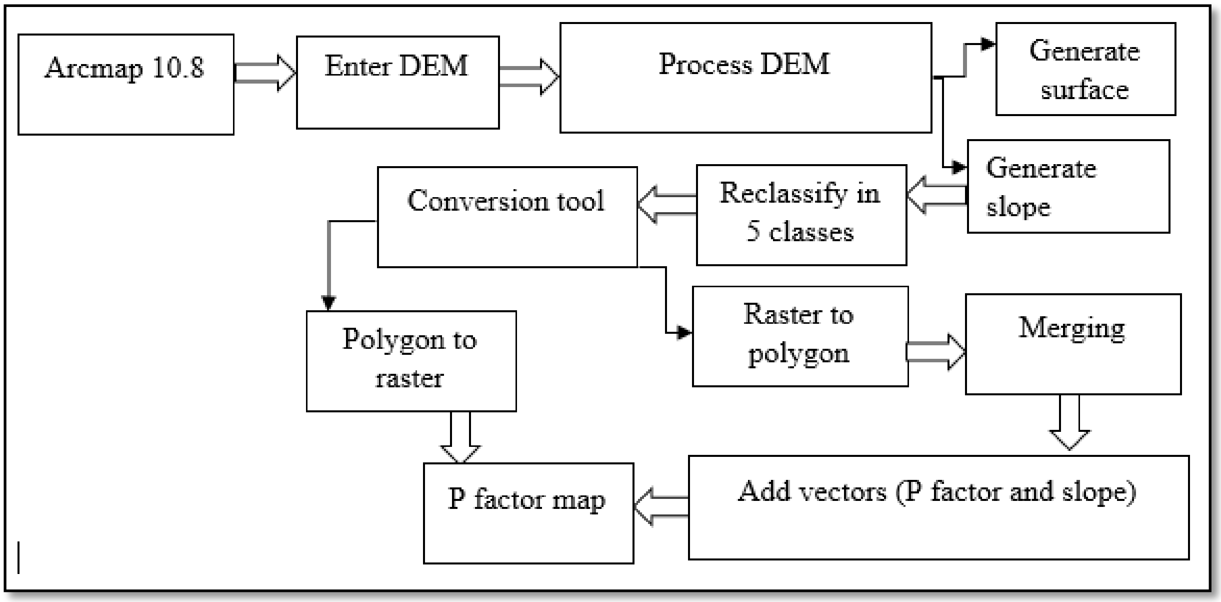

Figure 7: Flowchart for estimating the support practice factor (P) in the study area (DUSABIMANA, 2024)

The figure presents a workflow for generating a P-factor map using GIS tools. The process starts with using ArcMap 10.8 to obtain a Digital Elevation Model (DEM), which is then processed using the Arc Toolbox. Within the toolbox, the Spatial Analysis Tool is used to generate surface and slope data. This slope data is reclassified into five classes and converted from raster to polygon format. The conversion tool is utilized to change the polygons back into raster format, and vectors representing the P factor and slope are added during the merging step. The final output is a P-factor map created from these combined data layers.

- **Slope length and steepness (LS) factor**

The LS factor is a product of slope length (L factor) and slope steepness (S factor). It was estimated using a 30-meter resolution DEM provided by the USGS Earth Explorer. This DEM was used in ArcGIS to create a slope density map expressed in percentages. Slope steepness helps understand the terrain's nature, affecting runoff characteristics, recharge, and infiltration capacity. To obtain the slope length (L) and slope steepness (S), the 30-meter spatial resolution DEM, previously analyzed to remove spurious data, was used.

This resolution was chosen for accurately defining flow direction. The map above shows the

'Slope Length and Slope Steepness Factor' (LS Factor) in the Kinigi, Nyange, and Shingiro sectors, which are critical for assessing soil erosion risk. The LS Factor, a component of the Revised Universal Soil Loss Equation (RUSLE), combines slope length and steepness to estimate potential erosion rates.

The calculation of the LS factor involved estimating the slope (S) by computing flow direction and flow accumulation in the study area, using the formula by McRoberts et al. (2002):

$$\mathbf{LS} = Power[\Big(flow\ accumulation * \frac{cell\ size}{22.13}]0.4\Big) * Power[\sin\,(slope * \frac{0.001745}{0.0896}]1.3)$$

(Equation 7)

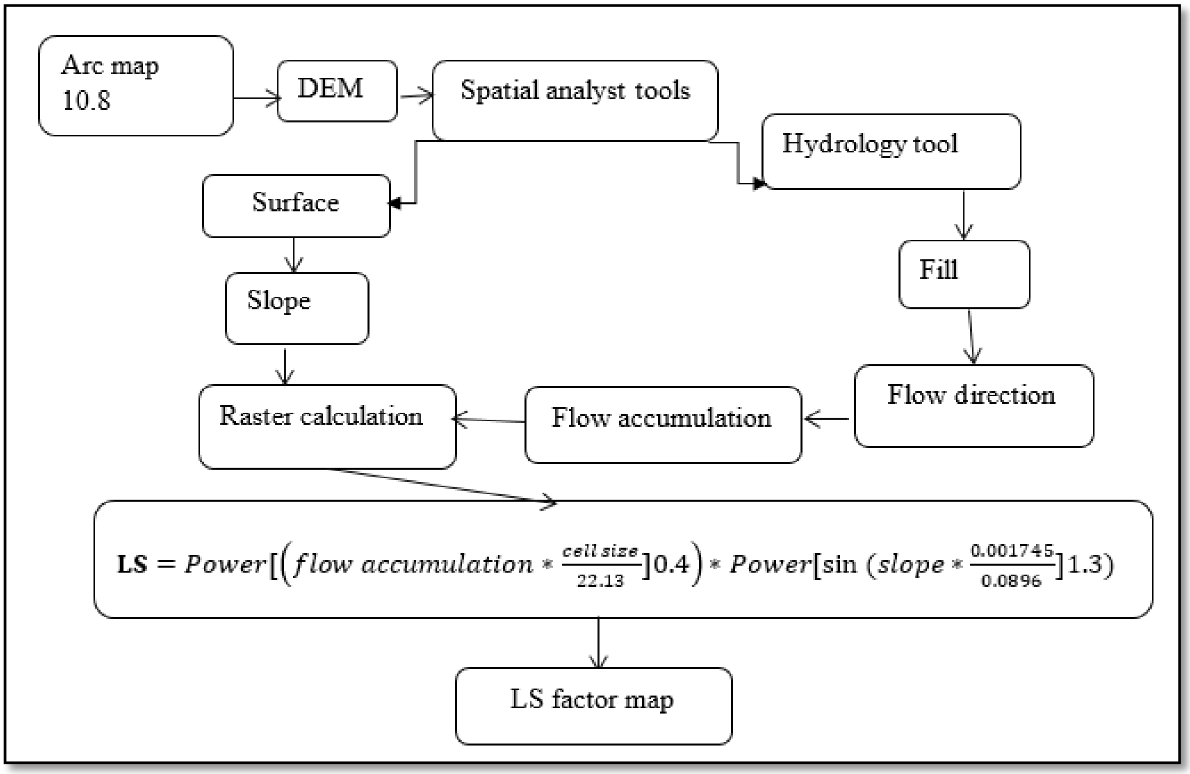

Figure 8: Flowchart for estimating slope length and steepness in the study area (DUSABIMANA, 2024)

The figure illustrates the process for creating an LS factor map using GIS tools. Starting with ArcMap 10.8, a Digital Elevation Model (DEM) is processed through Spatial Analyst Tools to derive surface and slope data. Concurrently, the Hydrology Tool is utilized, starting with a fill operation, followed by determining flow direction and flow accumulation.

Raster calculations are then performed to integrate the slope and flow accumulation data. The LS factor is calculated using the formula shown in Equation 7, incorporating both flow accumulation and slope data, which results in the creation of an LS factor map.

- **Soil erodibility (K) factor**

The K factor represents the susceptibility of soil to erosion. The RUSLE estimates the soil erodibility factor based on soil properties closely correlated with soil erodibility, including the fractions of sand, silt, clay, and organic carbon. The K-factor was calculated using the Sharpley and Williams (1990) method as follows:

$$\mathbf{K} = \left\{0.2 + 0.3\exp\left(0.0256\mathrm{SAN}\left(1-\frac{\mathrm{SIL}}{100}\right)\right]\right\} \mathrm{X}\left(\frac{\mathrm{SIL}}{\mathrm{CLA}+\mathrm{SIL}}\right)^{0.3} \mathrm{X}\left[0.1-\frac{0.25\mathrm{C}}{\mathrm{C}+\exp\left(3.72-2.95\mathrm{C}\right)}\mathrm{X}\left[0.1-\frac{0.7\mathrm{SN1}}{\mathrm{SN1}+\exp\left(-5.51+2.95\mathrm{SN1}\right)}\right]\right. \qquad \text{Equation (8)}$$

Where K is the soil erodibility, SAN is the subsoil sand fraction, SIL is the subsoil silt fraction, and CLA is the subsoil clay fraction (all in %). C represents the topsoil carbon content (in %). SN1 is equal to (1 - SAN/100).

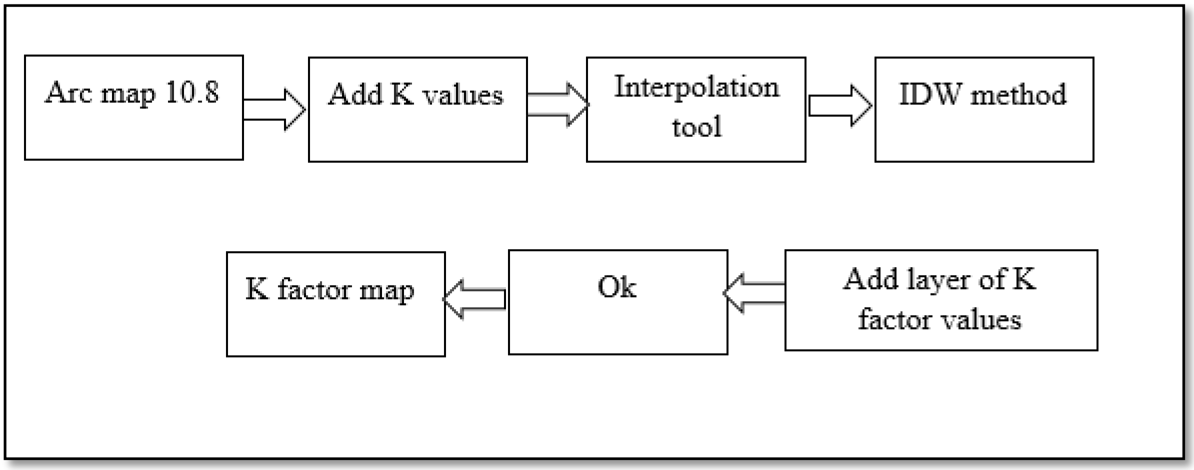

Figure 9: Flowchart for estimating the soil erodibility (K factor) in the study area (DUSABIMANA, 2024)

The figure outlines the workflow for creating a K-factor map using GIS tools. The process begins with ArcMap 10.8, where K values are added to the study area. The study area is then extracted using the Arc Toolbox, specifically the Spatial Analysis Tool for interpolation. The Inverse Distance Weighting (IDW) method is applied to interpolate the K factor values across the study area. These interpolated values are then added as a layer of K factor value.

❖ Cover Management Factor (C Factor)

The Cover Management Factor (C Factor) in the Revised Universal Soil Loss Equation (RUSLE) represents the effect of vegetation and ground cover on soil erosion. The C factor reflects the impact of cropping and management practices on erosion rates. It represents the effects of vegetation, soil cover, and soil-disturbing activities on erosion, highlighting conditions that can be managed to reduce erosion. C factor values range from nearly zero for well-protected soil to 1 for finely tilled, ridged surfaces that generate significant runoff and leave the soil highly susceptible to rill erosion (Zhang et al., 2011).

For this study, Landsat 8 OL-TIRS data was acquired from USGS Earth Explorer (path 170/row 052) to obtain NDVI. NDVI values range from −1.0 to +1.0, with higher values indicating green vegetation and lower values representing other surface materials. Bare soil has NDVI values close to 0, while water bodies have negative NDVI values. Factor (C) was determined through the NDVI, it was computed using map algebra functions with the following formula:

$\mathbf{C} = (-\mathrm{NDVI} + 1)$ (Kuo et al, 2016) Equation (9)

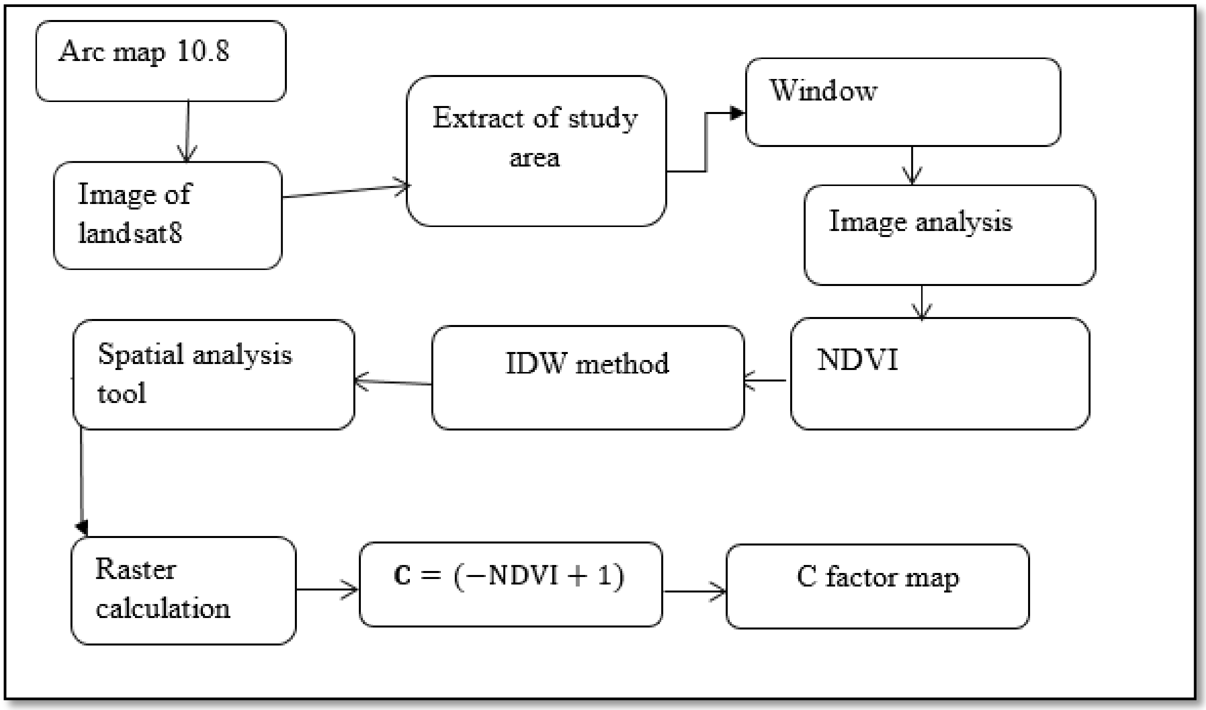

Figure 10: Flowchart for estimating the cover management (C factor) in the study area (DUSABIMANA, 2024)

The figure outlines the process for creating a C factor map using GIS tools and Landsat 8 imagery data. The process begins with ArcMap 10.8, where an image from Landsat 8 is imported. The study area is delineated, and image analysis is conducted within a defined window to compute the Normalized Difference Vegetation Index (NDVI). Spatial analysis tools are utilized, employing the Inverse Distance Weighting (IDW) method for interpolation. A raster calculation is then carried out using the formula shown in Equation 9. The result of this calculation produces the C factor map, which is used for further analysis and applications.

❖ Rainfall erosivity factor (R factor)

The R-factor quantifies the erosive potential of rainfall. In RUSLE, it is typically computed as the average of long-term individual storm erosivity indices (EI). This multi-year averaged index measures the kinetic energy and intensity of rainfall, describing its impact on sheet and rill erosion. The R-factor accumulates erosivity from individual rainstorm events and averages this value over several years. It serves as the driving force for the sheet and rill erosion processes, with variations in R-values reflecting differences in erosivity across the study area's climate. The R factor was determined by using the Prasannakumar et al. (2011) formula as follows:

$$\mathbf{R} = \sum_{i=1}^{12} 1.735x10^{1.5}\log_{10}(Pi/P)_{-0.08188)} \qquad \text{(Equation 10)}$$

Where R represents the rainfall erosivity factor (MJ mm ha-1 h-1 year-1); Pi denotes monthly rainfall (mm); and P represents annual rainfall (mm).

According to (Joshi, V.et al 2016) in their study at Ivory Coast and Burkina Faso, The average R-value can be estimated by multiplying the average annual rainfall amount (mm) by 0.5.

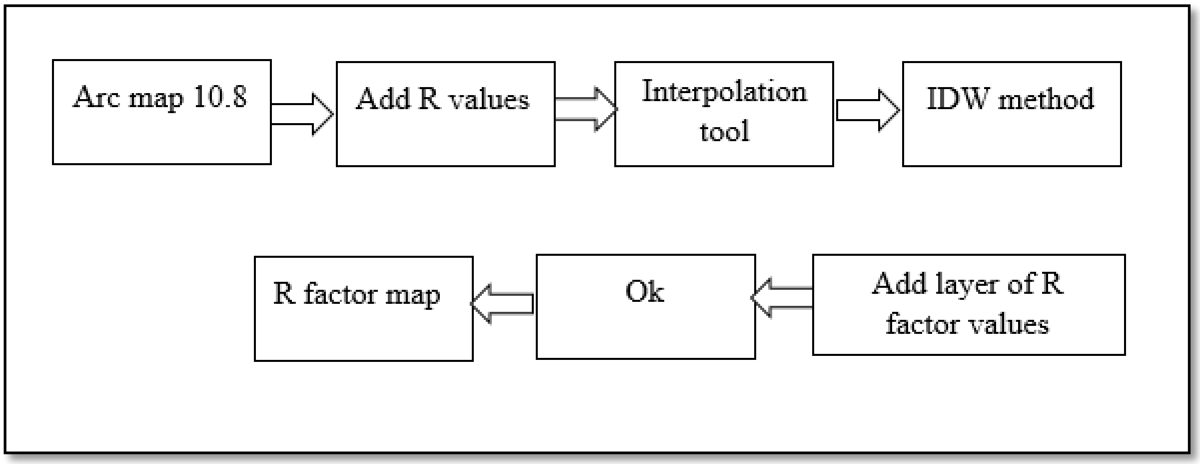

Figure 11: Flowchart depicting the process of estimating the rainfall erosivity (R factor) in the study area (DUSABIMANA, 2024)

The figure outlines the workflow for generating an R-factor map using GIS tools. It begins with ArcMap 10.8, where R values are inputted. The study area is extracted, and the Spatial Analysis Tool within the Arc Toolbox is used for interpolation. The Inverse Distance Weighting (IDW) method is applied to interpolate R-factor values across the study area. After adding a layer of R-factor values, the process is validated to produce the final R-factor map.

3.3.2. Quantification of soil erosion on community livelihoods

Interviews with various stakeholders, such as local communities, farmers, businesses, nongovernmental organizations (NGOs), and government officials were conducted to assess the influence of soil erosion in the study area. Collaborate with local farmers to collect data on crop yield variations, identify crop types vulnerable to soil erosion, and assess socioeconomic resulting from decreased agricultural output due to soil erosion.

Z=1.96
p=0.5
E=0.05
If p is not known, use p=0.5 for maximum variability.

$$n = \frac{Z1.96^2\ 0.5(0.5-1)}{0.05^2} = \frac{3.8416x0.25}{0.0025} = 384. \qquad \text{(Equation 11)}$$

So, you would need a sample size of approximately 385 households.

This calculation indicates that to estimate the population proportion with a 95% confidence level and a margin of error of 0.05, a sample size of 385 is required when the proportion p is unknown and assumed to be 0.5 for maximum variability.

CHAPTER IV: RESULTS

4.1. Preliminary results location specific factor maps

This chapter discusses findings on soil erosion factors (R, K, C, P, LS factors) and average annual soil loss (A) computed with the RUSLE equation in ArcGIS 10.8. Additionally, it explores the erosion's effects on soil nutrients like nitrogen, phosphorus, and potassium (NPK), as well as socio-economic impacts within the study area.

4.1.1. The erosivity of rainfall (R factor)

In 2021, the rainfall erosivity (R-factor) ranged from 60.2 to 252.2 mm ha-1y-1. Monthly, the R factor averaged 0.4 mm ha-1y-1. The highest R factor recorded was 0.44 mm ha-1y-1, while the lowest was 0.39 mm ha-1y-1 in the same year.

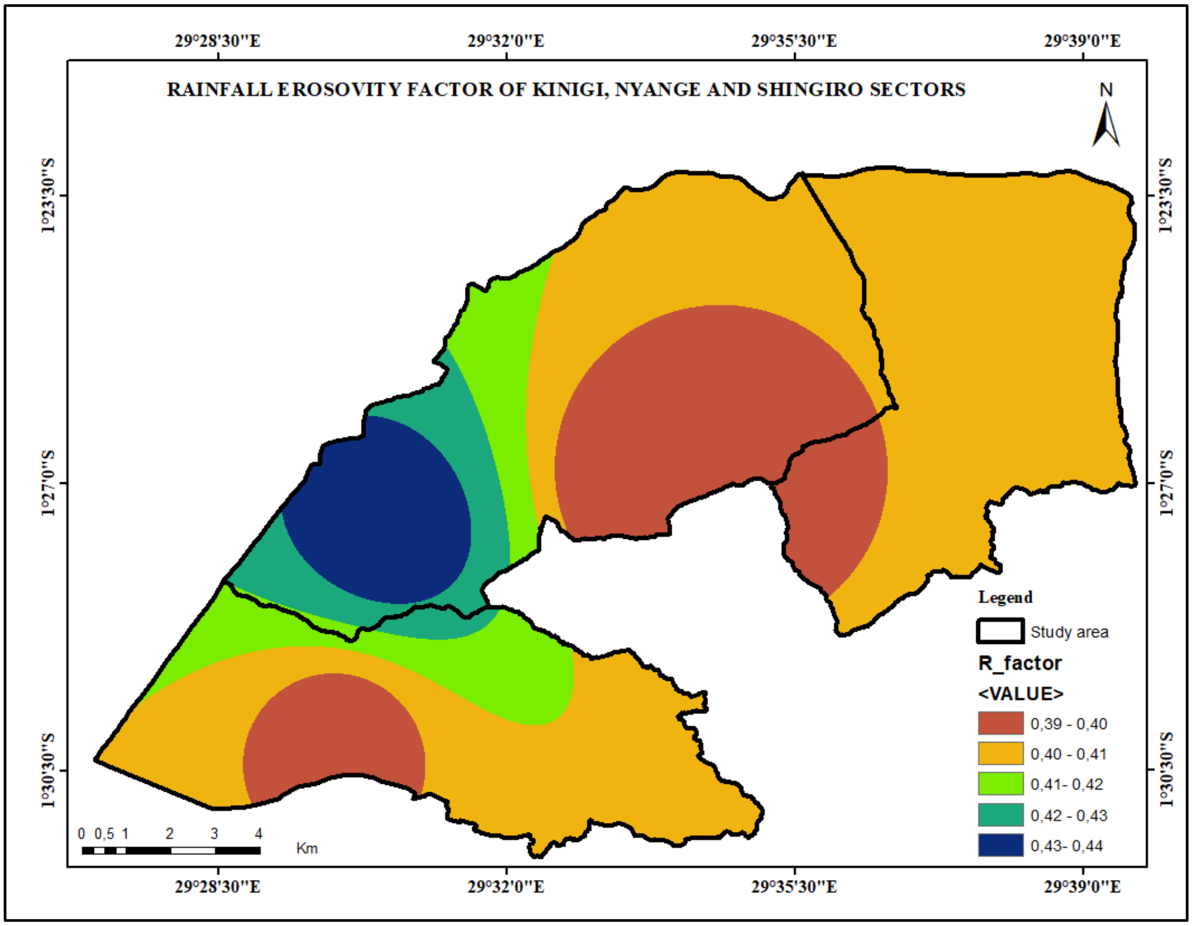

Figure 12: Spatial variation of the R factor across the study area (DUSABIMANA, 2024)

Figure 12 depicts the rainfall erosivity in the study area, showing R-factor values ranging from 0.39 to 0.44. Higher values indicate increased potential for rainfall-induced soil erosion.

Areas with higher values of the R factor, particularly in the Kinigi sector, are most susceptible to rain-induced erosion. This suggests a need for robust soil conservation and water management strategies in these areas to mitigate erosion risks. Conversely, regions with lower R factor values indicate lower erosivity, where standard erosion control measures may be sufficient to mitigate the effects of rainfall-induced soil degradation.

Table 1 below displays the distribution of erosivity classes and their proportions in the study area. The table highlights that the moderate erosivity class is predominant, covering 55.7% of the study area. High, very high, and severe erosivity classes occupy 10.0%, 6.0%, and 6.8% of the study area, respectively.

Table 1: R factor values categorized into five classes

Rainfall erosivity (t $ha^{-1}year^{-1}$)	Class category	Area (ha)	Area (%)
0,39 - 0,40	Low	10476	21,38
0,40 - 0,41	Moderate	27304	55,71
0,41- 0,42	High	4920	10,04
0,42 - 0,43	Very high	2961	6,04
0,43- 0,44	Severe	3347	6,83

4. 1. 2. Soil erodibility factor (K factor)

The study identified soil data results and corresponding soil erodibility (K) values from a soil erodibility monograph, considering factors such as particle size, organic matter content, and permeability class.

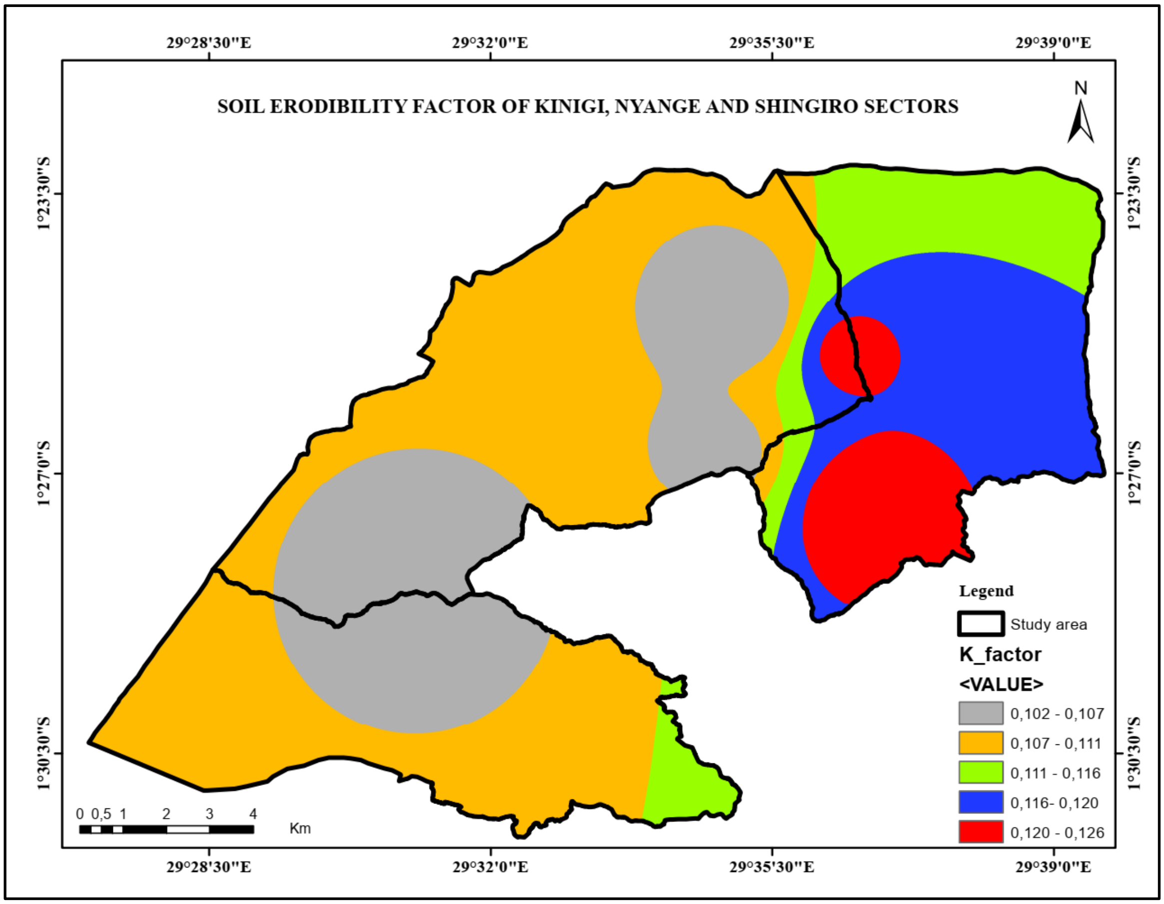

Figure 13: Spatial variability of the K-factor across the study area (DUSABIMANA, 2024)

The K factor values for texture groups in this study range from 0.10 to 0.13. Most of the study area exhibits a higher K factor value of 0.126, indicating areas with greater susceptibility to erosion, while the lowest value signifies areas with comparatively less erosion susceptibility based on soil types.

This map illustrates the distribution of the soil erodibility factor (K-factor) across the Kinigi, Nyange, and Shingiro sectors. Table 2 below highlights the significance of each K-factor class. Lower K-factor values denote soils with lower erodibility, often protected by vegetation or more cohesive. Higher K-factor values indicate soils more susceptible to erosion, typically due to less protective vegetation cover or inherently vulnerable soil types, such as loosely compacted or sandy soils.

Table 2: K-factor values categorized into five classes within the study area

Soil erodibility (t $ha^{-1}year^{-1}$)	Class category	Area (ha)	Area (%)
0,102 - 0,107	Low	11929	24,34
0,107 - 0,111	Moderate	20863	42,57
0,111 - 0,116	High	5512	11,25
0,116- 0,120	Very high	7193	14,68
0,120 - 0,126	Severe	3511	7,16

The findings reveal that approximately 24.34% of the study area falls into the low class (< 0.107), while 42.57% is classified as moderate (0.107-0.111), comprising the largest area. Additionally, 11.25% of the study area is categorized as high (0.111-0.116), 14.68% as very high (0.116-0.120), and 7.16% as severe (0.120-0.126) in terms of soil erosion risk.

4. 1. 3. Cover management factor (C-factor)

Figure 17 illustrates the spatial distribution of the cover management factor (C) in the study area. C factor values range from 0.13 to 0.51, with lower values indicating effective vegetation cover and management practices that substantially reduce erosion potential.

As the values increase, the C-factor increases, suggesting less effective cover and higher erosion risk. Areas with the highest values require urgent attention to improve vegetation cover or other protective measures to mitigate soil erosion.

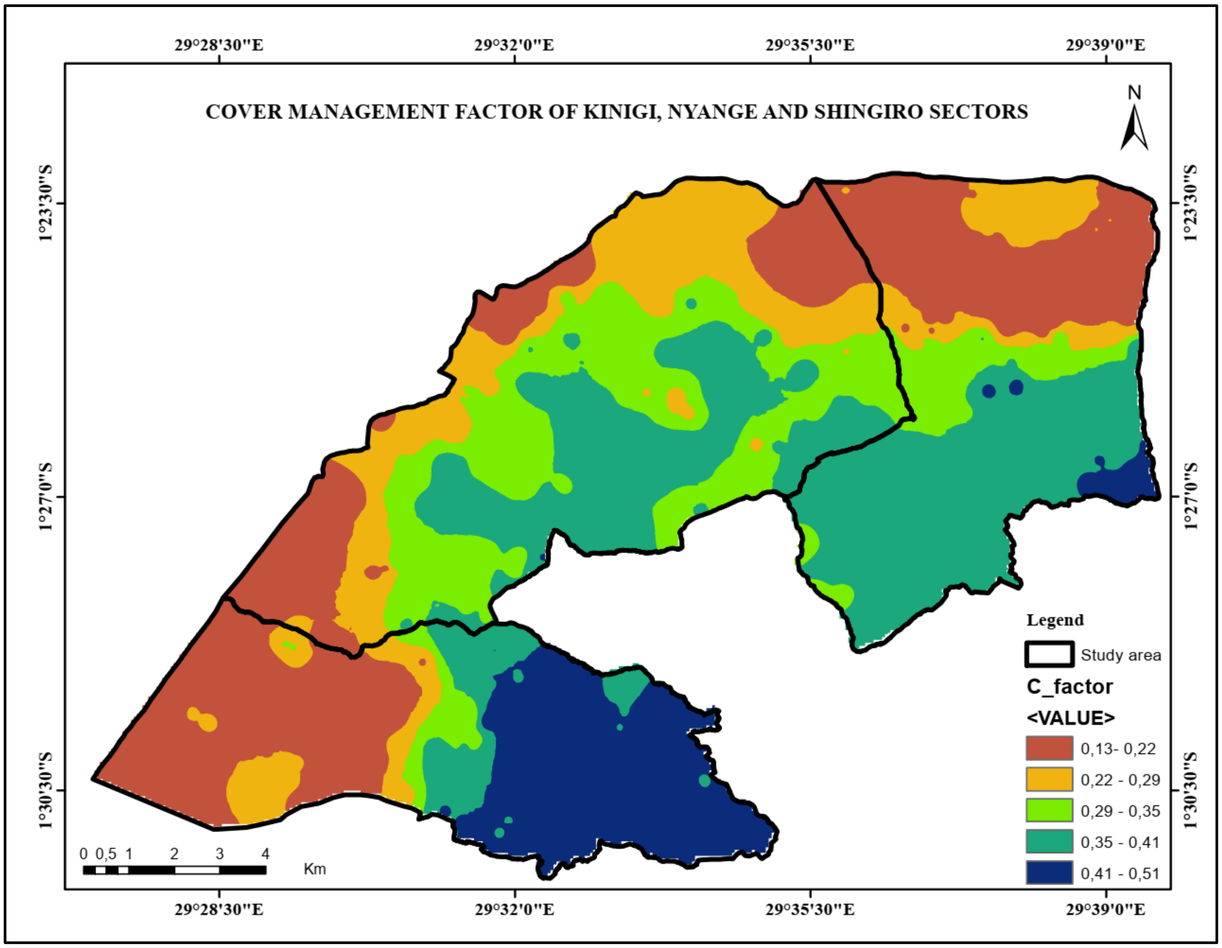

Figure 14: Spatial distribution of C-factor of Kinigi, Nyange, and Shingiro Sectors (DUSABIMANA, 2024)

Table 3 displays the results of the cover management factor, indicating that approximately 26.11% of the study area falls into the low class (<0.22), while 15.95% is classified as moderate (0.22-0.29). Additionally, 17.94% of the study area is categorized as high (0.29-0.35), 28.32% as very high (0.35-0.41), and 11.67% as severe (0.41-0.51) in terms of soil erosion, from high to severe values of C factor indicated minimal erosion potential (e.g., dense forest or well-managed vegetation) and C factor from low values to moderate values present maximum erosion potential (e.g., bare soil or poorly managed land.

Table 3: Cover management factor (C) values categorized into five classes

C factor values (t ha^{-1}year^{-1})	Class category	Area (ha)	Area (%

0,13- 0,22	Low	12641	26,11
0,22 - 0,29	Moderate	7721	15,95
0,29 - 0,35	High	8687	17,94
0,35 - 0,41	Very high	13710	28,32
0,41 - 0,51	Severe	5651	11,67

4. 1. 4 Slope length and steepness factor (LS factor)

Values range from low (0-2.18), indicating lower erosion risk attributed to shorter and less steep slopes to high (up to 139.26, indicating higher erosion risk due to longer and steeper slopes).

The predominance of high values across the map indicates that many areas within these sectors have long and steep slopes, substantially increasing the potential for soil erosion.

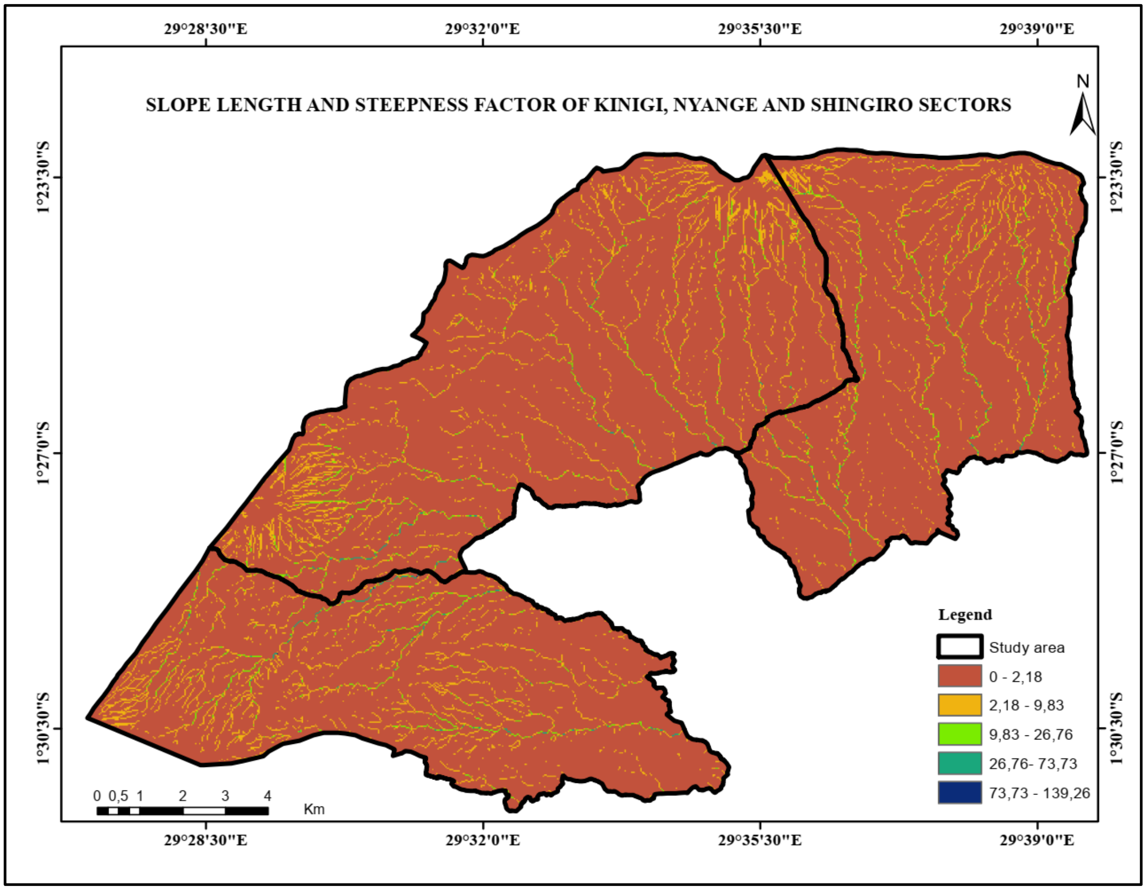

Figure 15: Spatial distribution of LS-factor of Kinigi, Nyange, and Shingiro Sector (DUSABIMANA, 2024)

This situation calls for immediate soil conservation actions, such as terracing, contour plowing, and establishing buffer strips, to decrease surface runoff velocity and improve soil retention. Conversely, specific areas with lower values indicate regions where the slopes are less severe and may not require intensive management practices, yet still need appropriate erosion control strategies to maintain soil health and productivity.

Table 4 presents the findings indicating that approximately 92.15% of the study area is classified as having low LS factor potential (<02.18), while 6.44% falls into the moderate to high LS factor range (2.18-9.83). Additionally, 1.12% of the study area is categorized as high (9.83-26.76), 0.17% as very high (26.76-73.73), and 0.003% as severe (73.73-139.26) in terms of LS factor.

Table 4: Values of LS factor in five classes

LS values (t $ha^{-1}year^{-1}$)	Class category	Area (ha)	Area (%)
0 – 2.18	Low	183483	92.15
2.18 – 9.83	Moderate	12830	6.44
9.83 – 26.76	High	2450	1.23
26,76- 73,73	Very high	344	0.17
73,73 - 139,26	Severe	7	0.003

4. 1. 5. Support practice factor (P factor)

In the study area, P factor values range from a minimum of 0.1 to a maximum of 139.26. The map indicates values ranging from low (most effective, 0.1) to high (least effective, 0.9) P-factors. Moderate effectiveness of soil conservation practices is typically observed with P-factor values ranging from 0.55 to 0.8. Areas with highly effective erosion control measures (P-factor close to 0.1) are notably limited.

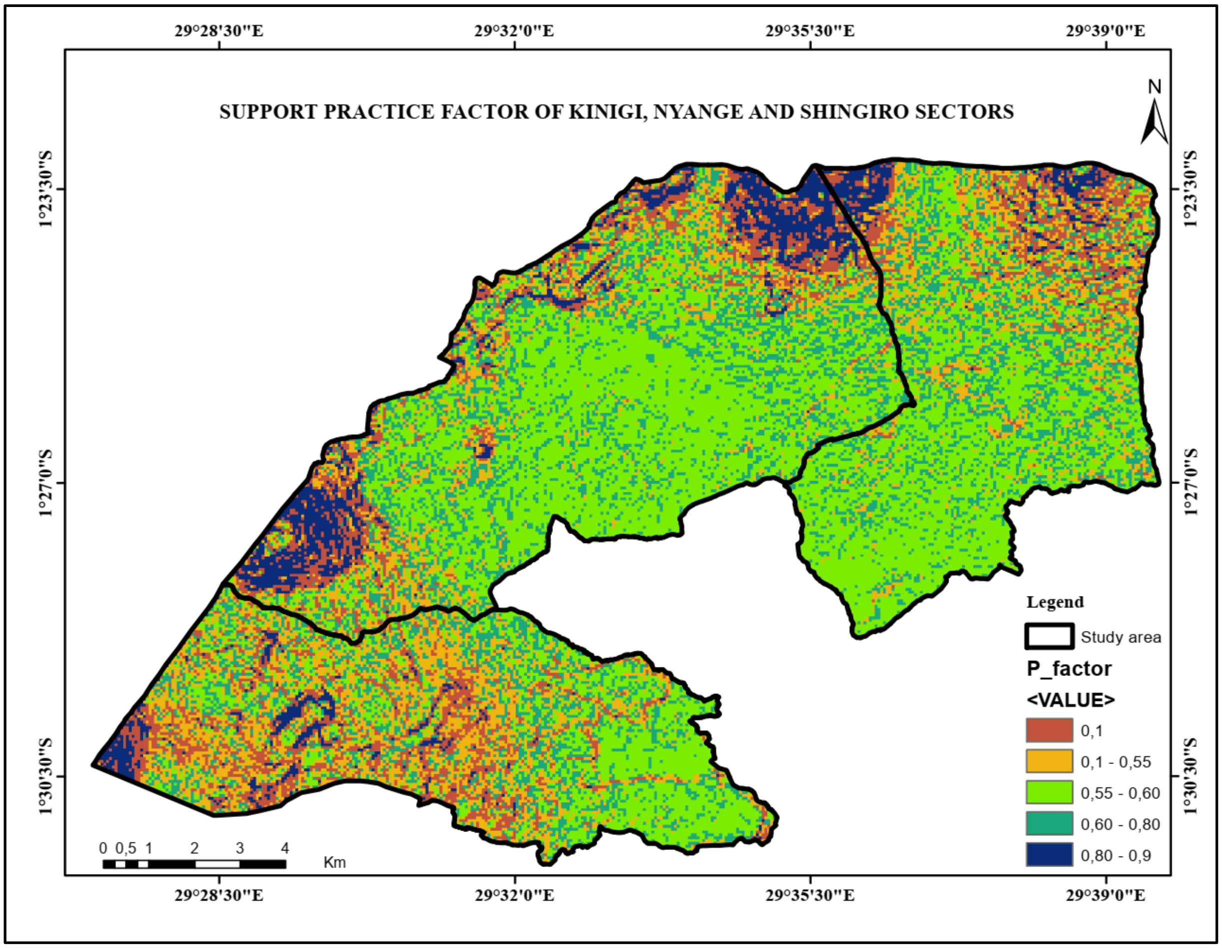

Figure 16: Spatial distribution of P-factor of Kinigi, Nyange, and Shingiro Sectors (DUSABIMANA, 2024)

Table 5 displays the findings indicating that approximately 30.95% of the study area is classified as having low erosion risk potential (<0.55), suggesting limited erosion control practices. Additionally, 39.74% falls into the moderate to high erosion risk range (0.55-0.60), while 22.81% is categorized as high (0.60-0.80) and another 22.81% as very high (0.50-0.80) in terms of soil erosion risk. About 6.50% of the study area is classified as severe (0.80-0.90) in soil erosion risk.

Table 5: Values of the P factor classified it into five classes

P-factor values (t $ha^{-1}year^{-1}$)	Class category	Area (ha)	Area (%)
0,1 - 0,55	Low	15209	30,95

0,55 - 0,60	Moderate	19529	39,74
0,60 - 0,80	High	11208	22,81
0,80 - 0,9	Very high	3197	6,50

4.2. Annual soil loss of Kinigi, Nyange, and Shingiro Sectors and its impacts on soil nutrients

Average annual soil erosion rates ranged from 2 tons per hectare per year in flat areas to 640 tons per hectare per year in hilly terrain. The map depicts different levels of soil loss intensity measured in tons per hectare per year.

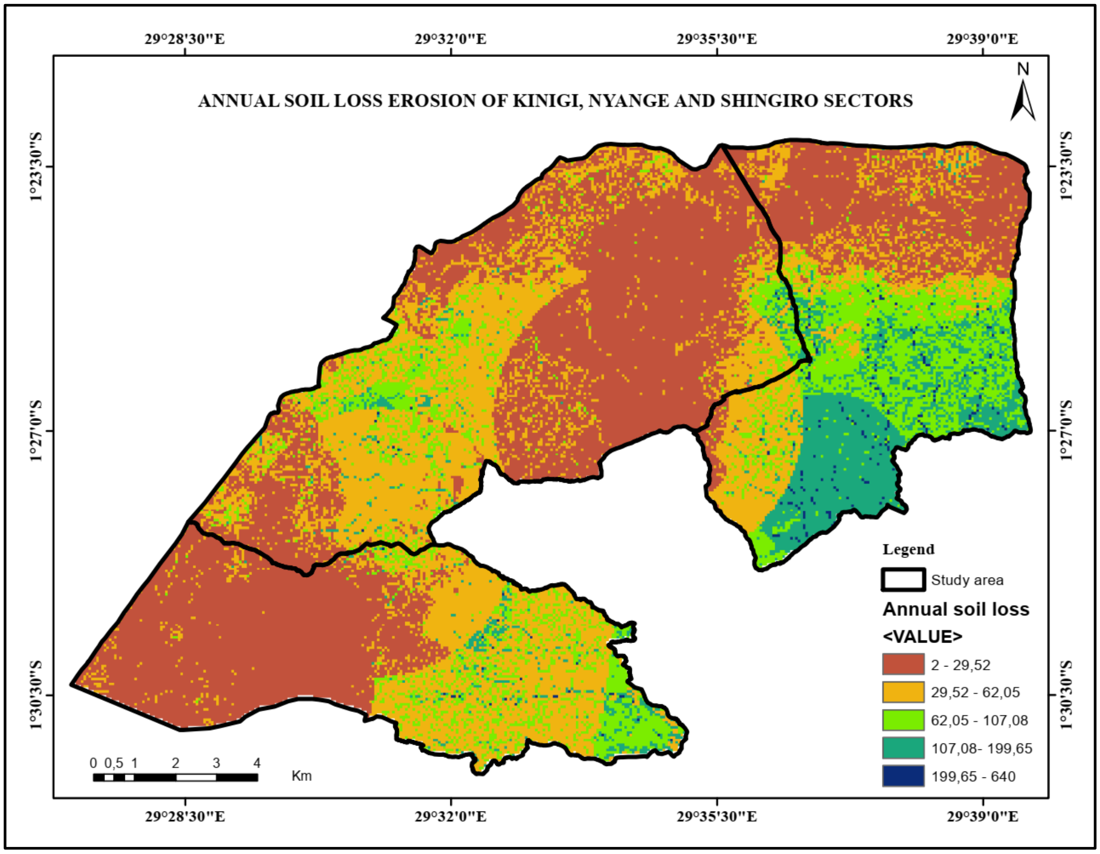

Figure 17: Spatial distribution soil loss erosion of Kinigi, Nyange, and Shingiro Sectors (DUSABIMANA, 2024)

Regions experiencing the most severe erosion suffer losses ranging from 199.65 to 640 tons per hectare per year. Moderate erosion rates range from 29.52 to 199.65 tons per hectare per year, which still pose significant challenges to sustainable land use. Regions with the lowest recorded erosion rates, ranging from 2 to 107.08 tons per hectare per year, suggest soils that are relatively stable and conducive to sustainable agricultural practices.

Table 6 reveals that approximately 44.62% of the study area is categorized as having low potential erosion risk (<22.52 tons per hectare per year), while 31.62% falls into the moderate to high erosion risk category (29.52-62.05 tons per hectare per year). Additionally, 14.62% of the study area is classified as high (62.05-107.08 tons per hectare per year), 8.66% as very high (107.08-199.65 tons per hectare per year), and 0.49% as severe (199.65-640 tons per hectare per year) in terms of soil erosion risk. The spatial distribution indicates that the Nyange sector has areas classified as very high and severe erosion risk, whereas areas with low erosion risk are situated along the path surrounding Virunga National Park.

Table 6: Size of late annual soil loss in five classes

Yearly soil erosion rates (t $ha^{-1}year^{-1}$)	Class category	Area (ha)	Area (%)
2 - 29,52	Low	21504	44,62
29,52 - 62,05	Moderate	15238	31,62
62,05 - 107,08	High	7046	14,62
107,08- 199,65	Very high	4173	8,66
199,65 - 640	Severe	234	0,49

4.3 Soil erosion impacts on agriculture and livelihoods in Kinigi, Nyange and Shingiro sectors

A high percentage of respondents (80%) said that soil erosion affects their agriculture production and livelihoods while 20% of respondents answered that soil erosion does not affect their crop yield and livelihoods.

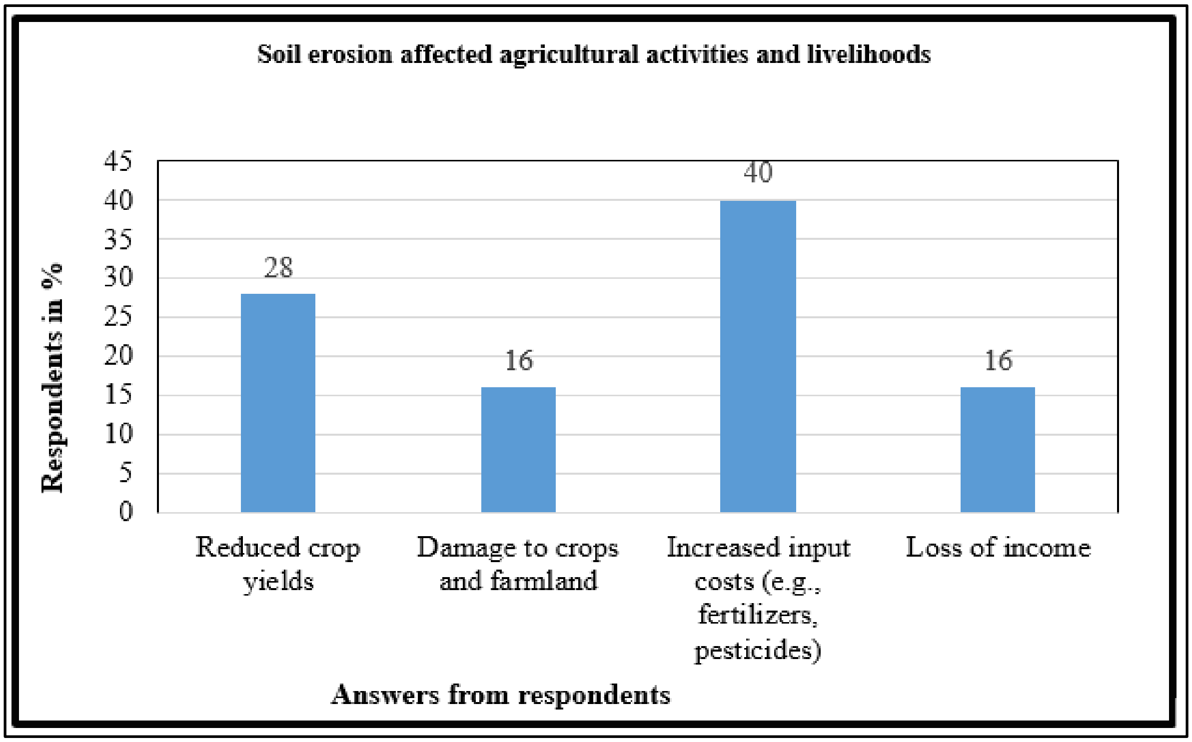

Figure 18: Soil erosion affects agriculture and livelihoods (DUSABIMANA, 2024)

The study indicates that a 28% reduction in crop yields underscores the direct impact on agricultural productivity, leading to diminished food availability and economic strain for farming communities. Furthermore, the study indicates that 16% of damages to crops and farmlands exacerbate these losses, disrupting farming operations and threatening long-term land fertility. Additionally, 40% indicated that increased input costs, including fertilizers and pesticides, escalates financial burdens on farmers, hindering profitability and sustainability. Consequently, 16% indicated a loss of income reflects the broader socioeconomic ramifications, as farmers face diminished earnings and heightened vulnerability to economic shocks.

4.4 Soil erosion impacts on infrastructure and communities in Kinigi, Nyange, and Shingiro sectors

Soil erosion has profound effects on infrastructure in the study area. It damages roads and bridges, hindering community access to essential services, markets, and schools. Soil erosion also destabilizes housing structures in vulnerable areas, leading to the potential displacement of households and threatening community safety and well-being. The impact of soil erosion on various types of infrastructure in the community, as indicated by the percentage of respondents. The most affected infrastructure is property (e.g., houses, buildings) with 33% of respondents identifying it as impacted. This is followed by road damage, noted by 30% of respondents. Road infrastructure damage (e.g., bridges, drainage) is reported by 21% of respondents.

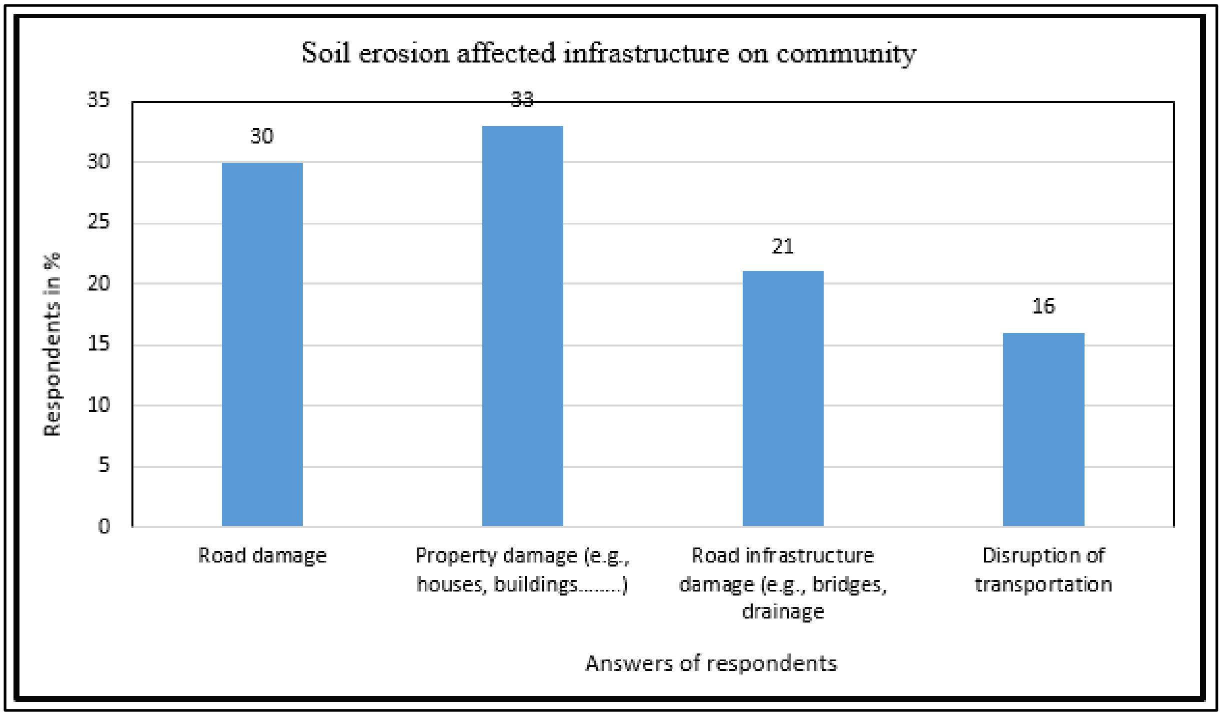

Figure 19: Infrastructure affected by soil erosion in Kinigi, Nyange, and Shingiro Sectors (DUSABIMANA, 2024)

Soil erosion's impacts in the study area are profound and wide-ranging, significantly affecting various aspects of infrastructure. 30% of road damages highlight the direct consequences on transportation networks, compromising access to essential services and hindering mobility for residents. Moreover, 33% of damage to properties underscores the threat posed to residential and commercial structures, leading to financial losses and displacement for affected individuals. 21% of damages to road infrastructures further exacerbate these challenges, impeding efforts to repair and maintain vital transportation arteries essential for economic activity and community connectivity. Additionally, 16% disruption of transportation emphasizes the broader implications for trade, emergency response, and social cohesion, as communities grapple with limited access to markets, healthcare facilities, and education.

4.5. Impact of soil erosion on the overall well-being of the community

The bar chart below depicts the effects of soil erosion on the overall community well-being, based on respondent reports. According to the chart, 29% of respondents indicated that soil erosion has led to the displacement of families, making it the most significant impact. Health issues were reported by 24% of respondents, highlighting the detrimental effects on community health. Increased vulnerability to natural disasters was noted by 22% of respondents, suggesting that soil erosion exacerbates the risk of such events. Additionally, 25% of respondents mentioned that soil erosion has impacted education, causing school closures and disrupted classes.

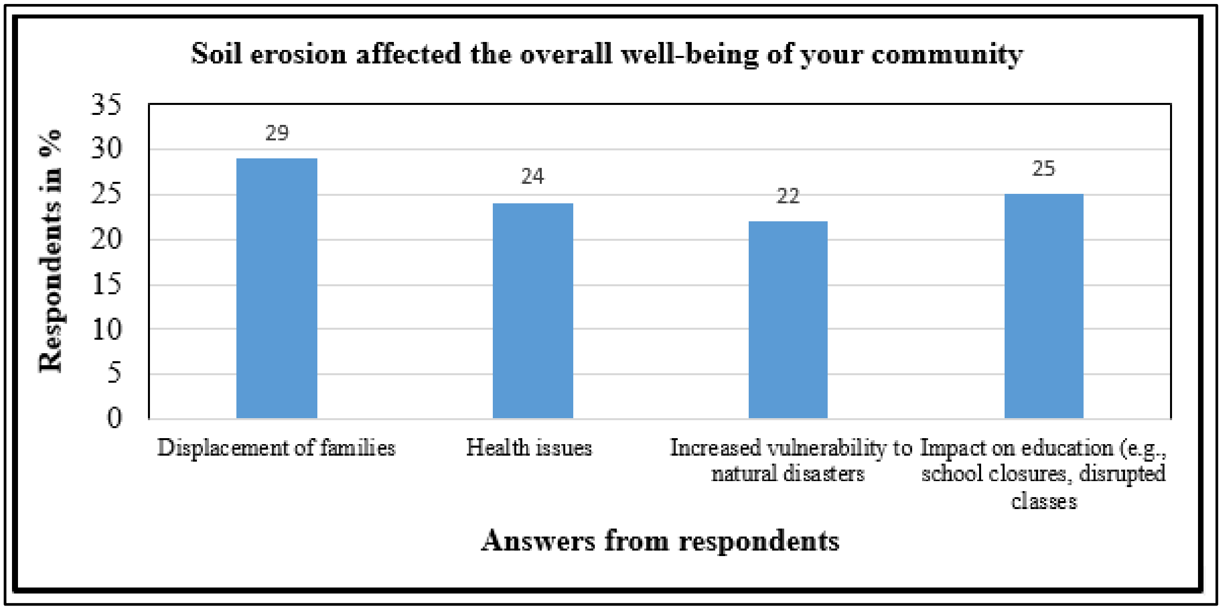

Figure 20: Affection of soil erosion on community overall well-being (DUSABIMANA, 2024)

The results indicate that 29 % of families are displaced due to soil erosion highlighting the disruptive nature of this environmental phenomenon, leading to the displacement of communities and the upheaval of social structures. Moreover, the prevalence of health issues at 24% underscores the direct and indirect health consequences resulting from degraded environments, including waterborne diseases, which significantly impact community well-being. The study indicates a 22% increase in vulnerability to natural disasters, highlighting the heightened risks faced by communities, such as floods and landslides. These risks not only endanger lives but also exacerbate existing vulnerabilities

Lastly, the substantial impact on education at 25% signifies the profound disruption to learning opportunities for children, perpetuating cycles of poverty and hindering long-term community development.

4.6. Effects of soil erosion on soil nutrients

Soil erosion has a notable impact on soil nutrient levels, leading to the loss of crucial elements like nitrogen (N), phosphorus (P), and potassium (K). In the study area, nitrogen concentrations ranged from 0.11% in areas with low to moderate erosion to 0.53% in areas experiencing high to severe erosion. Similarly, phosphorus levels were recorded at 8.55 ppm in low to moderate erosion areas and increased to 23.4 ppm in areas prone to high to severe erosion. Potassium concentrations also followed this trend, with 133 cmol $_{(+)}$/Kg in areas of low to moderate erosion and 186.4 cmol $_{(+)}$/Kg in areas of high to severe erosion. This nutrient loss due to erosion degrades soil fertility, adversely affecting agricultural productivity and ecosystem stability.

Table 7: Soil nutrient points fall in areas from high to severe erosion

No	N (%)	P(ppm)	K(cmol $_{(+)}$/Kg)	**Corresponding soil loss (t ha^{-1}year^{-1})**
1	0.25	20.3	88	74.56-134.60
2	0.24	9.8	187	134.60-254.70
3	0.19	27.1	536	74.56-134.60
4	0	53.2	64	74.56-134.60
5	0	6.6	57	74.56-134.60
Total	**0.68**	**117**	**932**	
Average	**0.53**	**23.4**	**186.4**	

In areas of high to severe erosion, the average nutrient levels and soil loss are as follows: Nitrogen (N) averages 0.53%, Phosphorus (P) averages 23.4 ppm, Potassium (K) averages 186.4 cmol$_{(+)}$/Kg, and soil loss ranges from 74.56 to 254.70 tons per hectare per year.

Table 8: Soil nutrient points fall in areas from low to moderate erosion

No	**N** **(%)**	**P** (ppm)	**K** (cmol$_{(+)}$/Kg)	**Corresponding soil loss** (t ha^{-1}year^{-1})
1	0.22	4.6	64	29.52-74.56
2	0.21	5.5	103	29.52-74.56
3	0	15.5	282	29.52-74.56
4	0	8.6	85	29.52-74.56
Total	**0.43**	**34.2**	**532**	
Average	**0.11**	**8.55**	**133**	

In areas of moderate annual soil loss erosion, the average nutrient levels and soil loss are as follows: Nitrogen (N) averages 0.11%, Phosphorus (P) averages 8.55 ppm, Potassium (K) averages 133 cmol$_{(+)}$/Kg, and soil loss ranges from 29.52 to 74.56 tons per hectare per year.

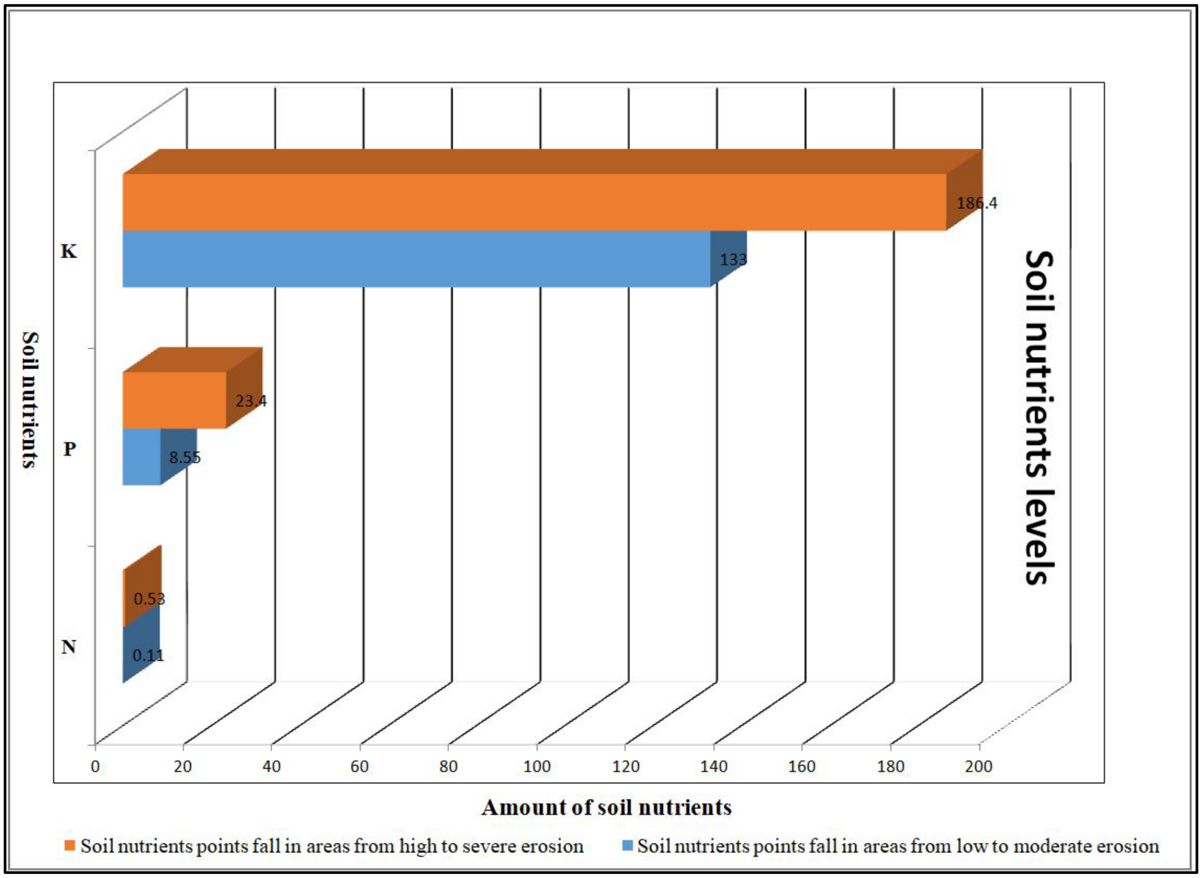

Figure 21: Flow chart of soil nutrient levels (DUSABIMANA, 2024)

The bar chart above illustrates the concentrations of nitrogen (N), phosphorus (P), and potassium (K) in areas with low to moderate erosion compared to those with high to severe erosion. Nitrogen levels rise from 0.11 % in low to moderate erosion areas to 0.53 % in high to severe erosion areas. Phosphorus levels rise from 8.55 ppm to 23.4 ppm, and potassium levels escalate from 133 $\mathrm{cmol}_{(+)}$/Kg to 186.4 $\mathrm{cmol}_{(+)}$/. This indicates that soil erosion significantly elevates the concentration of these essential nutrients.

CHAPTER 5: RESULTS DISCUSSION

5.1. Yearly soil erosion rates in the study area

This study found severe annual soil loss (199.65 - 640 t ha^{-1} $year^{-1}$) impacts 234 ha, accounting for 0.49% of the area. Very high erosion (107.08 - 199.65 t ha^{-1} $year^{-1}$) affects 4173 ha, which is 8.66% of the area. High erosion (62.05 - 107.08 t ha^{-1} $year^{-1}$) impacts 7046 ha, or 14.62%. Moderate erosion (29.52 - 62.05 t ha^{-1} $year^{-1}$) covers 15238 ha, representing 31.62% of the area. Low erosion (2 - 29.52 t ha^{-1} $year^{-1}$) affects the largest area of 21504 ha, accounting for 44.62% i.e. Nyange, Kinigi, and Shingiro sectors indicated soil loss because of soil erosivity (R) map in the Kinigi sector present high rainfall values than to other sectors, soil erodibility (K) map presented severe high soil loss erodibility in the large part of Nyange sector, it was presented severe high and high on a small part of Kinigi sector but Shingiro sector had low and moderate soil erodibility, the parts nearly VNP presented the low cover management factor (c) which were protected i.e. The C factor map of the study area showed lower values compared to the Kinigi and Shingiro sectors, which had higher C factor values i.e. not protected area which was caused by high rainfall, runoff and water from rivers, the support practice factor varied among the three sectors, reflecting differences in soil erosion is a significant environmental issue in tropical regions, particularly in Rwanda's mountainous areas. Studies have estimated annual soil loss rates ranging from 15.1-66.8 t/ha/year in western Rwanda (Maniraho et al., 2021) and 39.96 t/ha/year in the Rukarara watershed (Rizinjirabake et al., 2023). , soil erosion poses a significant challenge in Rwanda, particularly in the western and northwestern regions. Studies have shown high erosion rates, with average soil losses ranging from 39.2 to 48.6 t/ha/year nationwide (Nambajimana et al., 2019). More than 745,000 hectares of agricultural land in Rwanda are potentially eroded annually. This erosion results in the seasonal loss of over 3 million tons of crops (6 million tons annually), including an estimated 22,000 tons of maize and 15,000 tons of beans lost each season due to severe erosion (Abagale et al., 2012).

5.2. Soil erosion had socioeconomic impacts in the study area

Primary impacts of soil erosion on agriculture in the Kinigi, Nyange, and Shingiro sectors include rising input costs (e.g., Fertilizers, pesticides, on infrastructures, etc.) 40%, property damage (e.g., houses, buildings) was33% and overall being was 29 %. The displacement of families worsens pre-existing vulnerabilities stemming from soil erosion and environmental factors, decreasing agricultural productivity and economic stability, often necessitating increased investment in soil conservation measures. Soil erosion contributes to significant infrastructure costs, highlighting the need for integrated land and water management strategies to mitigate these effects similar trends are observed globally, where erosion exacerbates social vulnerabilities, underscoring the importance of sustainable land management practices to enhance community resilience against environmental shocks (Hewett et al., 2018). Soil erosion impacted agriculture in the primary livelihood which reduced agricultural productivity can led to lower income and increased vulnerability to food shortages (Ministry of Agriculture Rwanda, 2020). Musanze district in Rwanda faces significant environmental challenges related to soil erosion, landslides, and flooding. Heavy rains from the Volcano National Park contribute to severe crop destruction and soil erosion (Uzamukunda, 2015).

5.3. Soil erosion affected soil nutrient levels in the study area

In the study area, nitrogen (N) concentrations were measured at 0.11 ppm in areas experiencing low to moderate erosion and 0.53 ppm in areas with high to severe erosion, while in the Sebeya Watershed, nitrogen concentrations ranged from 430 to 600 ppm, showing a substantial difference in values. Phosphorus (P) concentration in the study area was 8.55 ppm in areas of low to moderate erosion and 23.4 ppm in areas of high to severe erosion, compared to 7 to 15 ppm in the Sebeya Watershed, indicating higher phosphorus levels in the study area. Potassium (K) levels were 133 ppm in areas of low to moderate erosion and 186.4 ppm in areas of high to severe erosion, whereas the Sebeya Watershed reported potassium concentrations from 0.4 to 0.6 ppm, demonstrating significantly higher potassium levels in the study area. These differences highlight the distinct soil nutrient dynamics between the study area and the Sebeya Watershed reported.

Soil erosion in agricultural lands leads to significant losses of nutrients. In Rwanda, annual losses were estimated at 155 kg/ha nitrogen, 3 kg/ha phosphorus, and 111 kg/ha potassium (Kabirigi et al., 2017). Considering an average nitrogen (N) ratio of 9 in arable land, one hectare (1 ha) of agricultural field contains approximately 0.2 tons of organic nitrogen per year. With

641,280 hectares affected by soil erosion and an average soil loss of 25 tons per hectare per year, an estimated 16 million tons of displaced soil annually results in a loss of about 128,256 tons of nitrogen per year (Lal et al., 1998).

CONCLUSION AND RECOMMENDATIONS

1. Conclusions

The study revealed significant annual soil erosion variations in the Kinigi, Nyange, and Shingiro sectors. The Nyange sector predominantly experiences high to severe erosion, with soil loss ranging from 62.05 to 640 tons per hectare per year. In the Kinigi and parts of the Shingiro sectors, erosion rates are moderate to high, ranging from 29.52 to 107.08 tons per hectare per year. Conversely, areas surrounding the Virunga National Park (VNP) in the eastern part of the study area exhibit lower erosion levels, ranging from 2 to 29.52 tons per hectare per year, indicating greater soil stability. The spatial distribution confirms that severe erosion risk areas are concentrated in the Nyange sector and a significant part of the Shingiro sector, while lower risk areas are closer to the park. The soil erosion impacts on social economic agriculture in the study area include increasing input costs was 40%, property damage at 33% and overall being was 29 %, and impact on land degradation about soil nutrients with the average nitrogen (N) concentration is 0.11% and 0.53%, Phosphorus (P) of the study found 8.55 ppm and 23.4 ppm and Potassium (K) found an average of 133 $\text{cmol}_{(+)}$/Kg and 186.4 $\text{cmol}_{(+)}$/Kg fall from low to severe erosion.

2. Recommendations

- Introduce soil conservation techniques in regions experiencing high to severe erosion, such as contour farming, terracing, and the adoption of cover crops, to mitigate soil loss.
- Increase tree planting activities in highly eroded areas to enhance soil stability and prevent further degradation. Promote sustainable agricultural practices, especially in moderately eroded areas to prevent the escalation of erosion.
- Develop infrastructure such as check dams, retaining walls, and drainage systems in very high and severe erosion zones to manage water flow and minimize soil displacement.
- Educate local communities and involve them in implementing erosion control measures.
- Advocate for policies that provide financial incentives or subsidies to farmers and landowners who adopt sustainable practices.

- To mobilize and redistribute nutrients, potentially leading to changes in soil fertility and agricultural productivity.

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APPENDIXES

Appendix 1: Materials were used to analyze sample soil nutrient fertilizers

The materials used for phosphorus analysis include a 50 ml volumetric flask, a 50 ml Erlenmeyer flask, a funnel, and various reagents. These reagents include a mixture of 70% $HClO4$ and distilled water in a 3:1 ratio, concentrated $HNO3$ with distilled water in a 1:2 ratio, and an ammonium vanado-molybdate solution prepared by dissolving 25 g of ammonium paramolybdate ($(NH4)6Mo7O24\cdot 4H2O$) in 400 ml of distilled water and 125 g of ammonium metavanadate ($NH4VO3$) in 300 ml of cooled distilled water. These solutions are mixed, followed by the addition of 143 ml of concentrated HCl, and diluted to 1 liter with distilled water.

The procedure for analyzing phosphorus nutrients involves the following steps:

- Weigh 1 gram of dried and finely ground soil (passed through a 0.5 mm sieve) and place it in a 50 ml Erlenmeyer flask using a small funnel.
- Gradually add 10 ml of 70% $HClO4$ and heat on a hotplate until white fumes appear and organic matter is destroyed. Allow to cool, then transfer to a 100 ml volumetric flask.
- Rinse the Erlenmeyer flask several times with distilled water, adding the rinses to the volumetric flask, and then fill it to the mark. Allow the solution to stand or filter it.

For spectrometric analysis:

- Take 10 ml of the prepared solution and transfer it to a volumetric flask.
- Add 20 ml of ammonium vanado-molybdate solution and dilute with distilled water to the mark.
- Mix well and allow the color to develop for approximately 10 minutes, then measure the absorbance at 410 nm.