GIS - BASED EVALUATION OF TEMPORAL SOIL EROSION RISK ANALYSIS USING RUSLE MODEL: A CASE OF KOKA LAKE WATERSHED, OROMIA, ETHIOPIA

Amanuel Efrem Abera

Thesis submitted to the Department of Architecture

College of Civil Engineering and Architecture (CoCEA),

Office of Graduate Studies
Adama Science and Technology University

June, 2025

Adama, Ethiopia

GIS - BASED EVALUATION OF TEMPORAL SOIL EROSION RISK ANALYSIS USING RUSLE MODEL: A CASE OF KOKA LAKE WATERSHED , OROMIA, ETHIOPIA

Amanuel Efrem Abera

Under the Supervision of

Temesgen Abraham Gebreselassie (PhD)

Thesis submitted to the Department of Architecture

College of Civil Engineering and Architecture (CoCEA),

Office of Graduate Studies

Adama Science and Technology University

Jnue, 2025

Adama, Ethiopia

DECLARATION

I hereby declare that this research entitled "**GIS - Based Evaluation of Temporal Soil Erosion Risk Analysis Using RUSLE Model: A Case of Koka Lake Watershed , Oromia, Ethiopia**" is my original work. That is, it has not been submitted to any other university. All materials used for this thesis have been duly acknowledged through citation.

Amanuel Efrem	______________________	_______________
Name of student	Signature	Date

RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read this thesis entitled "**GIS - Based Evaluation of Temporal Soil Erosion Risk Analysis Using RUSLE Model: A Case of Koka Lake Watershed , Oromia, Ethiopia"** prepared under my guidance by **Amanuel Efrem**. Therefore, I recommend the submission to the department following the applicable procedures.

Temesgen Abraham Gebreselassie (PhD)	_________________	________________
Name of Major Advisor	Signature	Date

APPROVAL PAGE OF THE THESIS

I, the advisor of this thesis entitled "**GIS - Based Evaluation of Temporal Soil Erosion Risk Analysis Using RUSLE Model: A Case of Koka Lake Watershed, Oromia, Ethiopia"** and developed by **Amanuel Efrem** hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

____________________	____________________	____________________
Major Advisor	Signature	Date
____________________	____________________	____________________
Co-advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by **Amanuel Efrem** have read and evaluated the thesis entitled "**GIS - Based Evaluation of Temporal Soil Erosion Risk Analysis Using RUSLE Model: A Case of Koka Lake Watershed , Oromia, Ethiopia"** and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted.

____________________	____________________	____________________
Chairperson	Signature	Date
____________________	____________________	____________________
Internal Examiner	Signature	Date
____________________	____________________	____________________
External Examiner	Signature	Date

Final approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and College Graduate Committee (CGC).

______________________	______________________	________________
Department Head	Signature	Date
______________________	______________________	________________
College Dean	Signature	Date
______________________	______________________	________________
Office of Postgraduate Studies, Dean	Signature	Date

ACKNOWLEDGEMENT

First and foremost, I want to praise, and thanks to Almighty God, the Lord of everything, who is credited with all of the completion of this thesis work. I would like to express my deepest thank and gratitude to my advisor Temesgen Abraham (PhD.) for serving as advisor and for their support, dedication, timely advice and willingness to consult me at any time, their tolerance, experience and answering all my questions during the time of my thesis work. I gratefully acknowledge Adama Science and Technology University. Finally, Last but not least, with all love and respect I would like to thank my dearest wife, course instructors and friends for their thoughtful encouragement all the time during my thesis work.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATION AND ACRONYMS

Abbreviation/Acronym	**Full Form**
RS	Remote Sensing
ML	Machine Learning
GIS	Geographic Information System
GEE	Google Earth Engine
LULC	Land Use/Land Cover
CA	Cellular Automata
RF	Random Forest
SVM	Support Vector Machine
OLI/TIRS	Operational Land Imager/Thermal Infrared Sensor
ETM+	Enhanced Thematic Mapper Plus
MSS	Multispectral Scanner System
ROI	Region of Interest
OA	Overall Accuracy
PA	Producer's Accuracy
FRAGSTATS	Fragmentation Statistics Software
DEM	Digital Elevation Model
CSA	Central Statistical Agency

Abstract

Soil erosion poses a severe threat to land productivity, water resources, and ecological stability, particularly in erosion-prone areas like the Koka Lake watershed in Oromia, Ethiopia. This study aimed to assess the spatial and temporal dynamics of soil erosion over a 24-year period using an integrated GIS-based Revised Universal Soil Loss Equation (RUSLE) model. Multi-source data including satellite imagery (Landsat), Digital Elevation Models (DEM), soil surveys, land cover data, and rainfall records were employed to compute RUSLE factors (R, K, LS, C, and P) for the years 2000, 2006, 2012, and 2024. Advanced geospatial tools such as Google Earth Engine (GEE), ArcGIS 10.8, and ENVI facilitated image classification, factor modeling, and erosion mapping. The major findings revealed a sharp increase in soil erosion over the first decade of the study period with maximum annual soil loss rising from 129.69 t/ha/year in 2000 to 163.21 t/ha/year by 2012, primarily driven by deforestation, agricultural expansion, and lack of conservation practices. Spatial analysis identified erosion hotspots in steep upland agricultural zones with sparse vegetation and inadequate soil management, particularly in the northeastern and central parts of the watershed. However, by 2024, erosion rates declined to 126.76 t/ha/year, reflecting the positive impact of soil and water conservation interventions such as terracing, afforestation, and gully rehabilitation under programs like the Sustainable Land Management (SLM) initiative. Vegetation cover and topographic features (slope length and steepness) were the most influential parameters affecting erosion severity, while poorly implemented support practices contributed to erosion persistence in some areas. This study highlights the ongoing challenge of soil erosion in the Koka Lake watershed and demonstrates that integrated soil and water conservation measures—such as terracing, afforestation, and gully rehabilitation—have significantly reduced erosion rates by 2024. The use of geospatial technologies and the GIS-based RUSLE model proved essential in assessing erosion severity and identifying high-risk areas, offering a powerful decision-support tool for land management. It is recommended that these practices be strengthened and scaled up, particularly in erosion hotspots, alongside the establishment of long-term monitoring systems and active community participation, to ensure the sustainable management of the Lake Koka watershed.

Keywords: RUSLE, Soil Erosion, Temporal variation of soil erosion, Koka Lake

CHAPTER ONE

1. INTRODUCTION

1.1. Back ground of the study

Water-induced soil erosion is one of the most prevalent forms of land degradation worldwide (Rhodes, 2014). It is characterized by the movement and separation of soil particles caused by rainfall and surface runoff (Eswaran, 2019). It is a major threat to food security, water quality, and biodiversity because it reduces the fertility of agricultural land and silts up water bodies and reservoirs (Hossain et al., 2020). According to the Food and Agriculture Organization (FAO, 2015), about 33% of the soils on Earth are degrading primarily due to water erosion. According to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), over 90% of the Earth's soil may have deteriorated by 2050, posing a severe threat to the ability to support both human populations and natural ecosystems. As a result, addressing soil erosion has become a top priority in international frameworks such as the Sustainable Development Goals (SDGs) of the United Nations, particularly SDG 15.3, which seeks to have no land degradation by 2030 (Schillaci et al., 2023).

Rainfall and erosive discharge cause valuable topsoil to be lost due to water-induced soil erosion, a significant environmental problem (Issaka, 2017). According to Alexandrides et al. (2015), this type of soil degradation is widely regarded as the most dangerous and has a negative impact on the output of natural ecosystems and agriculture, putting the livelihoods of smallholder farmers at risk. According to Guerre et al. (2020), soil erosion is a complex and widespread worldwide land degradation process that diminishes ecosystem services and functions. The main source of soil deterioration worldwide, water-induced soil erosion, is responsible for more than two-thirds of farmland degradation in Africa (Tully et al., 2015).

The phenomena of soil erosion can be influenced by a wide range of natural and human factors (Zhang et al., 2020). The rapid population growth and its consequences, which negatively impact soil resources, have exacerbated this problem (Blum, 2013). Due to a number of variables, including population growth, natural resource deterioration is happening far more swiftly in emerging nations (Wassie, 2020). The primary causes of soil erosion are agricultural intensification, steep-slope farming, and land cover degradation (Tsegaye, 2019). According to Borelli et al. (2013), these are the main reasons for soil erosion and are closely linked to population pressure. The issue is especially serious in areas where agricultural intensification, land degradation, and other human activities are prevalent, claim Ganasri and Ramesh (2016).

Ethiopia has a wealth of natural resources due to its diverse agroecological zones and farming methods (Mosissa, 2019). However, the combination of human pressure, high rainfall, and hilly topography has resulted in a considerable amount of land degradation, particularly in the country's highlands (Vanmaercke et al., 2010). The capacity of land and water resources to carry out essential ecosystem functions and services has been significantly impacted by this environmental degradation (Kanianska, 2016). Among sub-Saharan African countries, Ethiopia is known to have the worst land degradation (Gebreselassie et al., 2016). A major danger to the productivity of agricultural soil is soil erosion, a common process of land degradation throughout the nation. Average erosion rates have been estimated by studies to be between 3.4 and 84.5 t/ha/y, with farmed land showing even higher rates of 50 to 179 t/ha/y (Hurni et al., 2015). According to Yigezu (2021), an estimated 940 million t of soil had been lost from Ethiopia's 60 million hectares of rainfed agricultural land. An estimated US$4.3 billion is spent year on the direct economic effects of soil erosion on productivity loss (Mirzabaev et al., 2022). Additionally, 88% of the people, whose livelihoods are mostly dependent on the agricultural sector, and 50% of the agricultural land have been impacted by soil loss and the ensuing sedimentation of infrastructures downslope (Sonneveld et al., 2011).

With the use of the RUSLE model and GIS technologies, the primary objective of this study was to ascertain the range and rate of soil erosion. This strategy, which uses data to identify hyper-sensitive places and then makes wise recommendations, was desperately needed in the Koka Lake watershed and its environs to safeguard and preserve the natural agricultural environment.

1.2. Statement of the problem

One of the world's most urgent environmental issues is soil erosion, which contributes to decreasing soil fertility, decreased agricultural production, water body sedimentation, and biodiversity loss (Pimentel & Burgess, 2013). This problem is especially severe in Ethiopia because of the country's mountainous terrain, unpredictable rainfall, and unsustainable land-use practices (Abebe, 2020). Food security and rural livelihoods are seriously threatened by Ethiopia's predicted annual loss of 1.3 billion metric tons of fertile soil (Shafi, Wani, & Nazir, 2020). Notwithstanding these concerning numbers, a large number of studies carried out throughout Ethiopia tend to concentrate on general national assessments (Lautze et al., 2003), paying little attention to localized, watershed-level assessments, especially in the Lake Koka watershed.

A vital region for agricultural and water supply in central Ethiopia, the Lake Koka watershed is becoming more susceptible to soil erosion and sedimentation as a result of shifting land uses, deforestation, and population pressure. While some research has examined Ethiopian farmers' perceptions of soil erosion (Zerihun et al., 2016; Tegegne, 2014), these studies have mostly used qualitative techniques like surveys and interviews. Although useful, these methods lack the time tracking and spatial accuracy needed for efficient land management planning. Conventional field-based techniques for evaluating erosion are labor-intensive, time-consuming, and frequently do not provide thorough spatial coverage (Morgan, 2005).

Modeling and forecasting soil erosion across various landscapes has become much easier because to recent developments in geospatial technology, including remote sensing and Geographic Information Systems (GIS), in conjunction with the Revised Universal Soil Loss Equation (RUSLE) (Luvai et al., 2022). Because of its versatility, compliance with spatial data, and relative simplicity, the RUSLE model has gained popularity in erosion risk assessment. The dynamic interactions between land use, climate variability, and topography are rarely reflected by the integration of both dimensions, as most RUSLE studies have concentrated on either the temporal or spatial elements of soil erosion (Mahmood, 2024).

The usefulness of RUSLE-GIS models in evaluating soil erosion hazards across a range of terrains has been shown by numerous empirical investigations. Bewket and Teferi (2009), for example, used GIS-based RUSLE in the Blue Nile basin's Chemoga watershed to pinpoint erosion hotspots and guide focused conservation initiatives. Similarly, Woldemariam et al. (2018) demonstrated the usefulness of the model in capturing erosion patterns impacted by land cover and slope gradients by using RUSLE with high-resolution spatial data in the Fincha watershed. Mekonnen et al. (2020) used RUSLE and remote sensing to map annual soil loss and suggest mitigation measures in the Modjo watershed, which is close to Lake Koka. These studies highlight how crucial it is becoming to combine erosion models with GIS data for better land management.

But empirical research also points out important drawbacks. The majority of research has been carried out in regions where land-use patterns are well-established or where empirical data on sediment output are easily accessible. On the other hand, despite acknowledged erosion problems, areas such as the Lake Koka watershed have received comparatively little research attention. Additionally, very few research have used ground-truth data to test RUSLE results, which is essential for enhancing model reliability (Panagos et al., 2015). Studies that examine how soil erosion hazards change over time in response to changing land-use and climatic circumstances are also conspicuously lacking. For instance, Haregeweyn et al. (2017) recognize that erosion varies throughout Ethiopia but urge further detailed research that evaluates erosion in specific environmental conditions.

Comprehensive, empirical research that incorporates the temporal and spatial aspects of soil erosion is lacking, particularly in regions with complicated topography and varying climates like the Lake Koka watershed. Although RUSLE has been used extensively, it has not yet been proven to be beneficial in the unique socioeconomic and environmental circumstances of Lake Koka. In order to create sustainable land management techniques and successful soil conservation plans suited to the Lake Koka watershed, these deficiencies must be filled.

1.3. Objectives of the Study:

1.3.1. General Objective

The General objective of the research is to analyze soil erosion risks and assess the spatial and temporal dynamics of erosion over recent decades in the lake koka watershade.

1.3.2. Specific objectives

- Quantify the current soil erosion rate and spatial distribution in the Lake Koka watershed.
- Analyze soil erosion trends and hotspots over three decades (2000, 2006, 2012 and 2024).
- To classify soil erosion risk zones in the Lake Koka watershed using GIS.

1.4. Research Questions

1. What is the current rate of soil erosion and its spatial distribution within the Lake Koka watershed?
2. How have soil erosion trends and hotspots changed over a three-decade period, specifically in the years 2000, 2006, 2012, and 2024?
3. How can GIS technologies be utilized to map and assess soil erosion risk in the Lake Koka watershed?

1.5. Significance of the Study

The current study measured soil erosion in the Lake Koka catchment, and gave meaningful contributions towards sustainable water and land resources management in Ethiopia. The goal of this study was to inform regional planners, policy makers, and local societies for land-use decisions and conservation planning. The study established areas with the highest degree of erosion, which were utilized by conservation agencies, NGOs, and local communities to design interventions for water and soil conservation, reduce erosion and sedimentation within Lake Koka, and minimize effects downstream. Improved resource optimization and project efficiency were a consequence of this.

The research provided valuable information for land use planning, which improved sustainable agriculture by identifying lands with potential erosion, improving soil fertility, and improving agricultural yield. This resulted in improved food security and rural economic resilience. Farmers benefited from capacity building in sustainable land management practices through the findings of the study.

The data gathered assisted policymakers in creating effective measures for erosion control, environmental policies, and sustainable land management regulations that reinforced the region's soil erosion resilience and maintained Lake Koka's ecological stability. The research also informed legislation that fostered long-term sustainability and collective stewardship among stakeholders.

1.6. Scope of the Research

The study focused on assessing soil erosion in the Lake Koka watershed, specifically sheet and rill erosion due to surface runoff, using the RUSLE model to calculate the average annual loss of soil. This was a thrilling possibility. It spanned the entire Lake Koka watershed, from flat plains to steep mountains with varying elevation and potential for erosion. Methodologically, the study utilized GIS methods as well as the RUSLE model and made use of different data layers, including rainfall erosivity, soil erosion, slope, land cover characteristics, and conservation practices to assess erosion risk.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Conceptual Literature

2.1.1. Soil Erosion: Definition and Concepts

Morgan (2009) previously defined soil erosion as the markedly accelerated process of soil removal brought on by human intervention with the natural equilibrium between soil creation and removal. Furthermore, Gebayew (2015) defined soil erosion and soil loss as follows: "Soil erosion is the gross amount of soil moved by drop detachment or runoff, and soil loss is the soil moved off a particular slope or field."

The separation of soil particles from the soil mass and their movement by erosive forces such as wind and water are the two stages of soil erosion, according to Paland & Samanta (2011). The particles move into a third phase known as deposition after they have lost energy. Along with problems like soil compaction, low organic matter, and inadequate drainage, this process is a typical way that soil deteriorates. Soil erosion is a major worldwide concern since it significantly affects the sustainable use of agricultural land. In addition to human activities like farming, deforestation, mining, construction, and industrial operations, natural processes like wind, snowmelt, and raindrop/runoff acts can also cause soil erosion.

A significant environmental problem with worldwide ramifications, soil erosion has an impact on infrastructure, biodiversity, water quality, agriculture, and climate change. There are two types of erosion impacts: onsite and offsite. Degradation of the soil, loss of organic matter, decreased water infiltration, and lower soil production are examples of onsite consequences. Floods, drainage network obstruction, and water contamination are examples of offsite consequences. The dangers of offsite effects can be reduced by controlling onsite effects. Gebreyesus (2011) asserts that addressing onsite repercussions requires an understanding of erosion rates and critical components.

2.1.2. Forms of soil Erosion

A serious environmental problem that has an impact on infrastructure, agriculture, biodiversity, water quality, and climate change is soil erosion. Onsite and offsite effects are two ways to classify the effects of erosion. Degradation of the soil, decreased water infiltration, loss of organic matter, and lower soil production are examples of onsite consequences. Floods, blockages in drainage systems, and water contamination are examples of offsite impacts. Offsite effect hazards can be reduced by controlling onsite effects. Addressing onsite repercussions requires an awareness of erosion rates and critical components, according to Gebreyesus (2011).

Sheet erosion: is the process by which a thin, uniform layer of the top productive/surface soil gradually disappears over a large area, usually from a field, with each rain that causes runoff. This type of erosion is dangerous since it virtually hides its detrimental consequences from the farmer. Another name for it is the farmer's death (Telkar, S., & Pote, 2018).

Rill erosion: Channelization starts as soon as runoff happens, and erosion stops being uniform. Although it does not instantly dissolve any particles below the flow line, the impact of raindrops in rills increases the flow's ability to detach and carry flow. Regular tillage practices carried out on time can remove rills, which are tiny channels (Telkar, S., and Pote, 2018).

Gully erosion: happens when water continuously passes through small ditches, progressively eroding soil from the area and depositing it at deeper depths. This is a severe and obvious type of erosion. Numerous soil activities, including the production of food and biomass, water storage, filtration, and transformation, the maintenance of habitat and gene pools, human physical and cultural contexts, the origin of nutrients, and soil quality, are significantly impacted by this phenomenon. According to Hailu Kendie et al. (2015), gully erosion is a serious problem in Ethiopia, particularly in the highlands, where it causes topsoil degradation.

2.1.3. Factors Affecting Soil Erosion

At the field level, soil erosion is influenced by a number of interrelated processes and causes, including both biophysical and socioeconomic influences. These elements include patterns of precipitation and runoff, wind and climate, soil properties, vegetation, topography, and conservation methods. The primary elements that have a major impact on soil erosion and sediment transportation to river channels are changes in land use and climate (Chowdary et al., 2013). These elements fall into three categories: protection, resistance, and energy. The energy group, which includes wind, runoff, and rainfall, increases the risk of erosion. The mechanical and chemical characteristics of the soil that affect its capacity to withstand erosion are included in the resistance group. Last but not least, the protection category incorporates elements that lessen soil erosion, like plant cover and conservation techniques.

Climate

The amount and intensity of precipitation have the most effects on soil erosion, especially in regions with little vegetation or agricultural activity. Another important aspect is wind erosion, particularly during dry seasons. Erosion is also influenced by other environmental factors, like as temperature. Another factor is the intensity of the rainfall as well as the size and velocity of the raindrops (Blanco and Lal, 2010). Light amounts of material from rainfall produce soil erosion in Western Europe; the severity of the erosion is based on the volume of rainfall rather than its intensity.

Soil factor

Wang et al. (2013) defined soil erodibility as the soil's vulnerability to erosion agents. According to Deore (2005), a number of soil properties, including texture, structure, moisture content, roughness, and organic matter content, influence this vulnerability. In general, soils with superior soil structure, higher infiltration rates, and higher levels of organic matter are more resistant to erosion. On the other hand, sandy soils with coarse textures and inadequate drainage also have low K-values, as do soils with a high clay content because of their resistance to detachment. Silt loam and other medium-textured soils have moderate k-values because of their moderate vulnerability to runoff and detachment. High silt content soils are the most erodible because they decrease infiltration.

Vegetative cover

The earth and atmosphere are connected through vegetation. It reduces runoff by making the soil more permeable to rainfall. In addition to beneficial microclimate changes, it protects the soil from winds, which reduces wind erosion. In order to create a more solid mass that is less vulnerable to erosion from wind and water, plant roots weave with one another and bind the soil together. Surface erosion speeds up when vegetation is removed (Morgan, 2009).

Topography

The ground's topography influences the flow velocity of surface runoff, which in turn influences the runoff's erosiveness. Compared to smaller, lower slopes, especially those with little vegetative cover, longer, steeper slopes are more likely to experience extremely high levels of erosion following heavy rainfall. Steeper terrain also increases the likelihood of mudslides, landslides, and other gravity erosion processes (Whisenant, 2008).

Conservation practice

Conservation techniques including terracing, contouring, and strip cropping, in particular, minimize soil loss in agricultural settings. Improved infiltration, for instance, may reduce runoff in terracing areas, hence reducing soil loss and sediment delivery. The percentage of soil lost during upslope and downslope cultivation is known as the support practice factor (P-factor), and it is frequently used to assess how effective such practices are. P-values, which range from 0 to

1, have been allocated to land use classifications based on values found in the literature (Kaltenrieder, 2007).

Impacts of Soil Erosion

Both areas where soil is worn and deposited exhibit the effects of soil erosion; the earth's surface may become deteriorated or eroded. Because the issue leads to a major decline in the ecological, social, and economic advantages of land for crops and other environmental services, it is endangering ecosystems and human well-being globally. Approximately 50% of the world's 1 billion inhabitants live in Africa, where soil erosion impacts them. However, other agricultural issues receive more attention than soil erosion and its effects (Blanco and Lal, 2008).

On-site effects

Loss of soil, the development of gullies and rills, a drop in soil moisture and organic matter, and a decrease in surface soil depth are some of the on-site consequences of soil erosion. The most productive topsoil, which contains humus and plant nutrients, is typically lost due to water erosion, especially sheet erosion. If this soil is carried into the sea, it may never be recovered. The creation of soil is an extremely gradual process that can take anywhere from 100 to 400 years to reach a depth of 1 cm (Mirsal, 2008). Because cropland soils are frequently left bare following harvest, erosion is more likely to occur. The primary onsite effect of soil erosion is the long-term decline in soil productivity.

Many of Ethiopia's formerly fertile and surplus production areas are becoming badlands due to significant soil erosion (Gete et al., 2014). According to estimates, the country loses between 1.9 and 7.8 billion tons year, which costs the nation around 1 billion ETB. The country's highlands are regarded as the most severely damaged areas in the world. In general, soil erosion causes the quality of the soil to deteriorate, which lowers crop and other agricultural output. According to Blancco and Lal (2008), it is especially high in the main crop production areas that use monocropping and extensive tillage.

Off-site effects

In addition to harming the nearby agricultural region, erosion has an adverse effect on the environment. The primary off-site consequences of soil erosion by water are sedimentation and water contamination. Sedimentation should be the primary issue for the preservation, development, and use of our soil and water resources (Julien, 2010). Erosion produces sediment, which lowers reservoir life expectancy and storage capacity while raising flood damage and water treatment expenses. Before planning reservoirs, the amount of sediment delivered to a watershed's exit should be evaluated in order to assess sedimentation and water quality issues. According to Braimoh et al. (2008), the majority of reservoirs in Ethiopia that were constructed for various purposes are filled with sediment within less than 50% of their anticipated service lives. However, fertilizers, insecticides, and other chemicals that farmers apply to the land may be washed away by the flowing water. Streams, rivers, reservoirs, and other water bodies become contaminated as a result, endangering the system's living things.

2.2. Conceptual literature review

Conceptual models are built upon simplified versions of sediment and water balance equations, where spatial details are generalized. According to Merritt et al. (2003), these models offer a broad representation of watershed processes but often overlook complex interactions within the system. As a result, a detailed understanding of the catchment area is essential when applying them. Conceptual models act as an intermediate approach between empirical and physically based models. Unlike empirical models, which rely heavily on data correlations, conceptual models reflect assumptions about the underlying processes that govern system behavior, even though these processes may be simplified or aggregated.

Several models fall under this category, including the Hydrologic Simulation Program–Fortran (HSPF), the Agricultural Catchment Research Unit (ACRU) model, and the Agricultural Non-Point Source Pollution Model (AGNPS). These tools have been widely applied in research focused on erosion and water quality.

Physically based models, on the other hand, are grounded in the actual physics of sediment transport and erosion processes. The parameters they use are, in principle, measurable and represent real-world properties (Merritt et al., 2003). These parameters can often be obtained through direct field measurements, reducing the reliance on long-term hydrometeorological datasets. One advantage of physically based models is their applicability beyond the conditions under which they were calibrated. Common examples of such models include the Morgan-Morgan-Finney (MMF) model, the Water Erosion Prediction Project (WEPP), and the Soil and Water Assessment Tool (SWAT).

2.2.1. Revised Universal Soil Loss Equation (RUSLE)

The Revised Universal Soil Loss Equation (RUSLE), developed by Renard et al. (1997), is designed to estimate the long-term average annual rate of soil erosion on a field slope based on several key factors, including rainfall characteristics, soil properties, topography, land cover, and management practices. In a Geographic Information System (GIS) environment, RUSLE is particularly useful for assessing soil erosion spatially, as it enables analysis at the grid-cell level.

This allows for the identification of erosion-prone areas across large watersheds, where different contributing factors can be evaluated and managed accordingly.

Despite its utility, one limitation of RUSLE is its inability to simulate sediment deposition or account for gully erosion processes. Nonetheless, its strength lies in its ability to model sheet and rill erosion effectively.

The equation used in RUSLE is as follows:

$$A = R \times K \times LS \times C \times P$$

Where:

- **A** represents the estimated average annual soil loss (tons per hectare per year),
- **R** is the rainfall erosivity factor,
- **K** is the soil erodibility factor,
- **LS** combines the slope length (L) and slope steepness (S) factors,
- **C** is the cover-management factor, and
- **P** refers to the support practice factor (Wischmeier and Smith, 1978).

Each component of the equation reflects a different aspect of erosion risk, making RUSLE a practical and widely used tool in soil conservation planning.

2.3. Empirical Literature

An estimated 75 billion tons of soil are lost each year due to soil erosion, a major problem that has serious negative effects on the environment and the economy (FAO, 2020). The issue is especially serious in Ethiopia because of the country's rugged landscape, extensive deforestation, and unsustainable farming methods (Tadesse et al., 2018). Soil erosion is particularly severe in the highlands, where Lake Koka is situated, endangering both the region's ecological balance and agricultural livelihoods (Zewdu et al., 2021). Soil erosion has significant negative effects on the ecosystem, such as increased sedimentation of water bodies, biodiversity loss, and land degradation. Due to sediment accumulation in reservoirs, soil erosion reduces crop yields, raises the cost of land restoration, and reduces the efficiency of hydropower systems, all of which have detrimental economic implications (Alemayehu & Birhanu, 2019). Food insecurity and the uprooting of rural communities who mostly depend on agriculture for their livelihoods are two social repercussions of soil erosion (Yimer et al., 2015). Affected regions face a daunting task as a result of this intricate cycle of social instability, economic loss, and environmental deterioration.

In the case of Lake Koka, the lake is essential for maintaining fishing, giving drinking water to the neighboring areas, and providing irrigation. However, the lake's water quality and storage capacity have been harmed by substantial sedimentation brought on by increased soil erosion in the watershed (Fikadu et al., 2020). Deforestation for fuelwood and agricultural development, intensive farming methods without appropriate conservation measures, and overgrazing, which eliminates protective vegetation, are the main causes of soil erosion in the Lake Koka watershed (Teshome & Desta, 2019). The erosion process is made worse by the terrain of the area, which includes steep slopes and a lot of rainfall (Mekonnen et al., 2021). Prior studies on soil erosion in the Lake Koka region have mostly concentrated on individual components like sedimentation or qualitative evaluations (Zewdu et al., 2021). To perform temporal analyses and comprehend the long-term patterns in soil erosion, quantitative research is desperately needed, especially that which makes use of Geographic Information Systems (GIS) and the Revised Universal Soil Loss Equation (RUSLE). The development of practical methods for reducing soil erosion and safeguarding the ecosystem and nearby communities would greatly benefit from such study (Tadesse et al., 2018).

The detachment, transport, and deposition of soil particles on land surfaces are described by soil erosion modeling, which uses mathematics (Kefale, 2020). Since a model is a reduced depiction of reality, it can be utilized to address issues with soil erosion. Data collection for field research for soil erosion forecasting and assessment is expensive, time-consuming, and takes years. In addition to offering a thorough grasp of the erosion processes, field investigations are limited by the intricacy of relationships and the difficulty of extrapolating from the findings. In addition to simulating the watershed's erosion processes, soil erosion models may be able to take into consideration other complex interactions that affect erosion rates.

Plot experiments, which determine net soil loss for bare soil or particular soil crop combinations on farmed fields, field surveys, which measure observable soil erosion features like rills and gullies, and erosion modeling, which employs equations or models based on empirical data, are the three primary categories into which the current methods for assessing soil erosion fall. The best methods for assessing the danger of erosion, according to FAO (1986), are based on predicting soil losses using simulations of the effects of vegetation cover, slope, slope length, climate, soil erodibility, and soil conservation practices. Soil erosion models aim to provide both explanatory and predictive capacities (Petter, 1992). The available models can be grouped into a variety of categories. Understanding the ideas behind the development of erosion models and the various model types may be useful in order to assess the behavior of the models for different sites with varying parameters. The various kinds of water erosion models that are available in the literature can be grouped based on the guiding concepts that were applied throughout the model's construction. In order to assess soil erosion, erosion models can be broadly divided into three classes according to the development principle. These component models may be philosophically and physically grounded, and they may be statistical or empirical (Morgan, 2005).

Empirical models, according to Petter (1992), relate the causes of erosion and soil loss by establishing important parameters using field observation, measurements, experiments, and statistical techniques. These models link input and output using a transformation function and make the assumption that everything is stationary. The Universal Soil Loss Equation (USLE), Revised Universal Soil Loss Equation (RUSLE), and Soil Loss Estimation Model for South Africa (SLEMSA) are examples of common empirical erosion models. Because RUSLE is so user-friendly, it is extensively utilized and accepted.

Recently, a number of published studies have estimated and predicted the rate of soil loss globally using the RUSLE model. Along with GIS and RS, this model has also been widely tested and used by numerous studies to assess the likelihood of soil erosion in Ethiopia's highlands (Haregeweyn et al., 2017). These investigations bolstered the corpus of evidence demonstrating the efficacy of the RUSLE model in precisely estimating the rate of soil loss under various circumstances.

Even though information on sediment deposition and rainfall intensity at shorter periods is lacking, the RUSLE model can be utilized to evaluate soil loss in the study watershed. This model was selected due to its low data requirements, ease of usage, and compatibility with remote sensing and GIS. For the Ethiopian context, the majority of input parameters have been adjusted. This study will be the first to assess soil erosion susceptibility in the Mojo watershed using a GIS framework, although earlier research in the Ethiopian highlands has employed RUSLE models (Hurni, 1985).

In the Koka Lake watershed of Oromia, Ethiopia, soil erosion is a serious danger to ecological balance and agricultural output (Zeleke & Hurni, 2001). Overgrazing, inappropriate land use, and rapid deforestation increase erosion rates, which causes silt building in the lake and affects biodiversity, water quality, and storage capacity (Teshome & Desta, 2019; Zewdu et al., 2021). This study provides important insights into conservation techniques by analyzing geographical and temporal soil erosion patterns over three decades using the Revised Universal Soil Loss Equation (RUSLE) coupled with GIS (Renard & Foster, 1983; Panagos et al., 2015). In order to assess soil erosion in China's mountainous regions, Liu et al. (2012) used GIS-based RUSLE to map areas that are prone to erosion and identify important factors impacting soil loss. Effective soil conservation planning is made possible by the combination of GIS tools and RUSLE, which overlay data on several erosion parameters like slope, rainfall intensity, and vegetation cover to enable more accurate spatial projections.

2.4. Conceptual Framework

An important environmental problem that has an impact on ecosystem health, water quality, and agricultural output is soil erosion. Evaluating the vulnerability of soil erosion is essential for conservation and land management plans. In order to evaluate soil erosion susceptibility thoroughly and holistically, the researcher seeks to create a conceptual framework that combines environmental elements and socioeconomic indicators (European Environment Agency/EEA, 2000). The conceptual framework illustrates a cause-and-effect chain that starts with driving factors (activities) and moves on to impacts and responses. These occurrences can have intricate interactions with one another. The conceptual framework also emphasizes the relationship in an integrated manner between the causes of soil erosion issues, their effects, and society's reaction to them. Figure 2-1 displays the conceptual framework used for the assessment of soil erosion vulnerability.

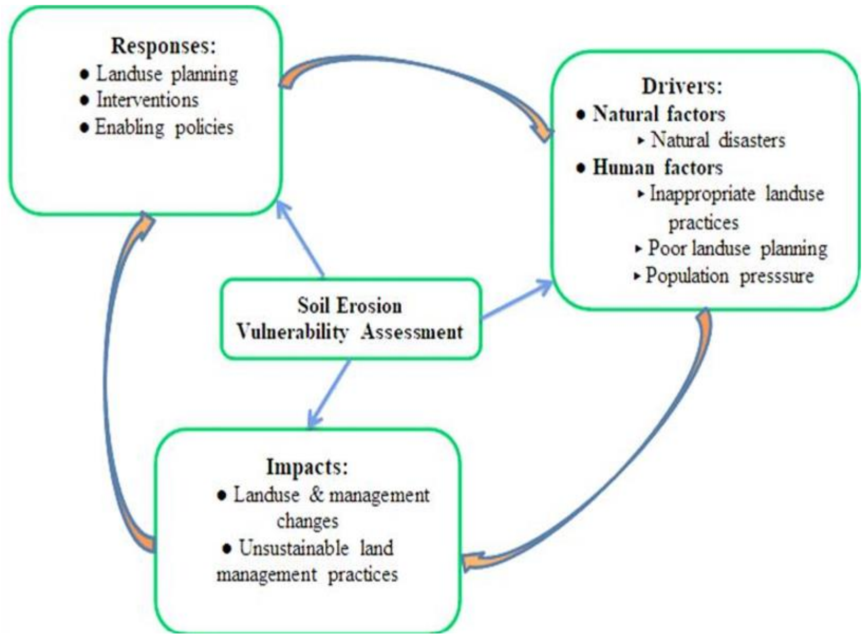

Figure 2-1: Conceptual Framework of the study

Adapted from: EEA, 2000

CHAPTER THREE

3. RESEARCH METHEDOLOGY

3.1. Study Area Description

Koka Lake, also known as Koka Reservoir, is located in the central Rift Valley of Ethiopia, approximately 90 kilometers southeast of Addis Ababa. It lies between 8° 4′ 22″ - 8° 42′ 10.25″ N latitude and 39° 29′ 13.86″–38° 55′ 14.08″ E longitude, within the Oromia Regional State. The lake is part of the Awash River Basin, one of Ethiopia's most significant river systems. Lake Koka is bordered nearest major city Mojo town 50 kilometers to the northwest and Koka town to the south and Adama to the northeast.

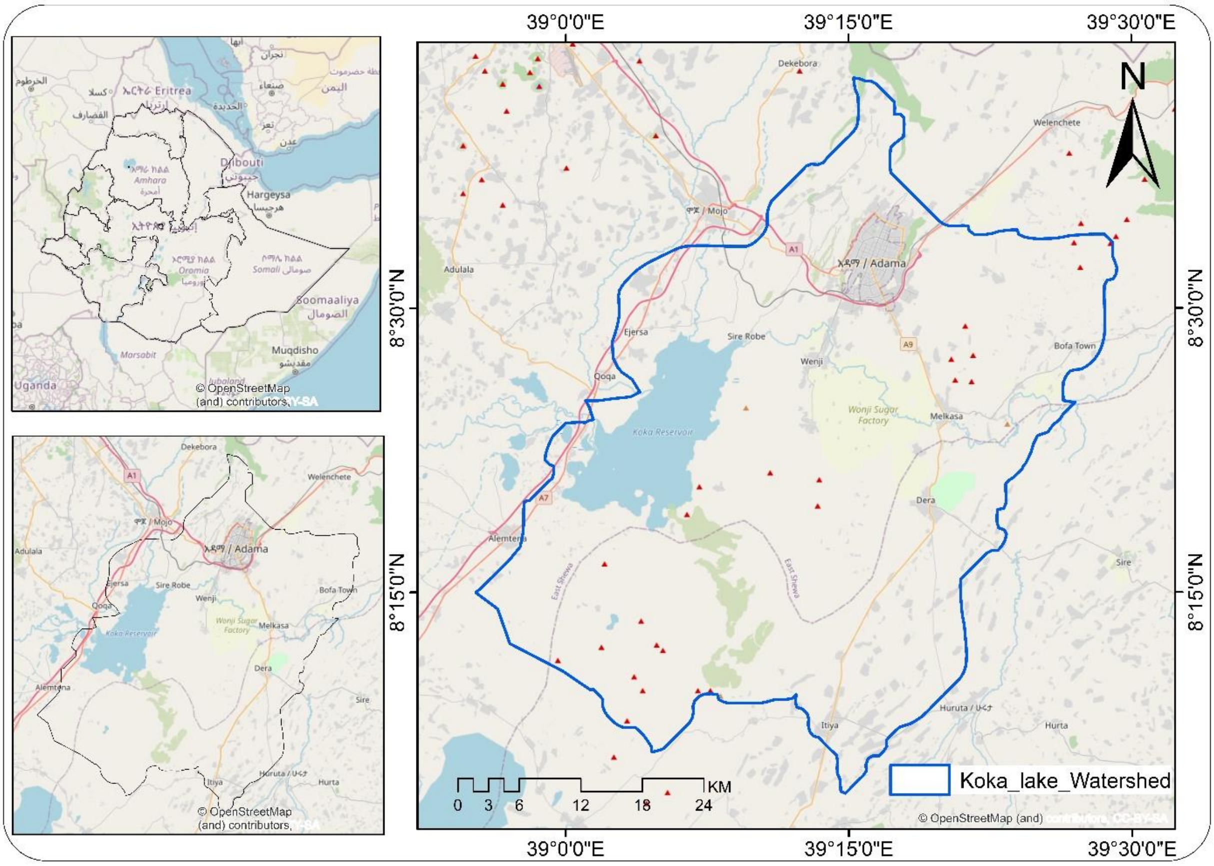

Figure 3-1: Location map of the study area

3.2. The research approach and design

The study was structured on the fusion of GIS technology, remote sensing, and Revised Universal Soil Loss Equation (RUSLE) model. The study based on flexible forms of data like climatic, topographic, soil, satellite image, and conservation practices were analyzed and processed to spatially and temporally predict soil erosion risk.

3.3. Data type and source

This study utilized a range of spatial and thematic datasets to estimate soil erosion in the Lake Koka watershed using the RUSLE model integrated with GIS. The land cover data for the years 2000, 2006, 2012, and 2024 were obtained from the Copernicus Global Land Service, which provides high-resolution global land cover classifications. These datasets were essential for identifying land use/land cover (LULC) types and assigning appropriate cover management (C) and support practice (P) factors within the RUSLE framework.

To estimate the rainfall erosivity factor (R), CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) was used as the primary source of precipitation data. CHIRPS provides long-term satellite-based rainfall data with high temporal resolution, making it suitable for detecting rainfall variability over time and its influence on erosion processes. Soil data, including information on texture, structure, and organic matter content, were acquired from ISRIC – World Soil Information. These parameters were critical for calculating the soil erodibility factor (K), which measures a soil's susceptibility to detachment and transport by rainfall and runoff.

Topographic information was derived from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) at a 30-meter resolution, accessed via USGS (United States Geological Survey). The DEM data were used to compute the slope gradient and slope length, both of which are vital for determining the LS factor (slope length and steepness), a key variable in the RUSLE model that significantly influences erosion potential. In addition, conservation practice data were gathered through literature reviews and field observations to assign P-factor values.

Table 3-1: Data type and source

No.	Data Type	Source	Purpose/Use
1	Land Cover Data (2000, 2006, 2012, 2024)	Copernicus Global Land Service	To classify LULC and derive C and P factors for RUSLE
2	Precipitation Data	CHIRPS (Climate Hazards Group InfraRed Precipitation)	To calculate the R-factor (rainfall erosivity)
3	Soil Data (Texture, Organic Matter, etc.)	ISRIC–World Soil Information	To derive the K-factor (soil erodibility)
4	Digital Elevation Model (DEM)	SRTM (30m resolution) via USGS	To generate slope and slope length (LS-factor)
5	Conservation Practice Data	Literature & field observations	For assigning P-factor based on land use and slope

3.4. Tools and Software

This study utilized a combination of specialized packages of software to process and analyze spatial data in the Lake Koka watershed. The software packages included ArcGIS 10.8, Google Earth engine and R statistical software. These software packages were significant for various stages of data processing such as remote sensing, GIS mapping, statistical analysis, and modeling. Geographic Information Systems (GIS) also proved very helpful for the analysis and management of spatial data, allowing for the integration of multiple datasets to conduct a comprehensive assessment of soil erosion risk (Moore et al., 2019).

3.5. Data Preparation and Pre-processing

The first step in data preparation was obtaining topographic information from DEM. Slope steepness and length, which were the important parameters in soil erosion, were computed from DEM elevation. Topography was highly dependent on rainfall, and steep slopes were more susceptible to soil erosion (Panagos et al., 2015). Topographic parameter (LS) and watershed boundary were computed with the help of DEMs in the USLE model.

Satellite high-resolution imagery was utilized to classify land use and cover. Since land-use types influence the rate of soil erosion, land cover classification (urban, forestry, and agriculture) was important (Hurni, 1993). Crop type and vegetation contributed significantly to erosion, and thus the cover-management factor (C) in the RUSLE model was associated with land cover. For quantitative analysis, supervised or unsupervised classification methods were more appropriate (Foody, 2018).

Following land use classification, GIS environment was employed to integrate several layers of information like soil properties, rainfall conditions, and land cover. Ensuring an equable spatial resolution and projection over all datasets thus allowed them to be able to perform suitable spatial analysis and modeling of soil erosion (Ahmed et al., 2020). The detailed modeling and mapping of soil erosion hazard required GIS-based integration.

3.5.1. Temporal Analysis

The period from 2000 to 2024 was selected for the temporal analysis of soil erosion in the Lake Koka watershed to ensure comprehensive evaluation of long-term land degradation trends. One of the primary reasons for selecting this time frame is the availability of consistent, high-quality land cover data. Land use/land cover data for the analysis were obtained from the Copernicus Global Land Cover database. In addition, the selected period corresponds with critical policy and land management interventions. For instance, the early 2000s mark the initiation of

Ethiopia’s Sustainable Land Management Program (SLMP) and other national conservation strategies aimed at combating land degradation. Analyzing erosion trends from 2000 to 2024 allows for assessment of the impact of these interventions and supports alignment with ongoing land restoration targets under national development agendas and global frameworks such as the Sustainable Development Goals (SDGs). To visualize the spatial-temporal dynamics of soil erosion within this period, four key years 2000, 2006, 2012, and 2024 were selected for erosion risk mapping. These years were chosen at six-year intervals to represent major phases within the overall period. The year 2000 serves as the baseline, reflecting the conditions prior to widespread conservation efforts. The years 2006 and 2012 capture the midpoints where significant land cover shifts were observed, and 2024 reflects the current status, highlighting the cumulative effect of both degradation and rehabilitation processes.

3.6. Soil Loss Estimation Using RUSLE

The gradual loss of soil made it hard to determine the extent without a reliable model. Among the most excellent tools used in the estimation of soil erosion, the Revised Universal Soil Loss Equation (RUSLE) was the best. Based on five important variables rainfall, soil, slope, cover, and conservation practices RUSLE estimated the long-term average annual rate of soil erosion. The equation was:

$$A = R \times K \times LS \times C \times PA$$

Where:

- **R** is the rainfall erosivity factor,
- **K** is the soil erodibility factor,
- **LS** is the slope length and steepness factor,
- **C** is the cover-management factor,
- **P** is the support practices factor.

3.6.1. Rainfall Erosivity

The annual rainfall data collected by meteorological stations in the Lake Koka watershed was used to calculate the Rainfall Erosivity (R) factor. Both the intensity and overall rainfall amount contributed to the R-factor, which measured the erosive potential of rainfall. Understanding the risk of soil erosion was crucial, as it increased with higher precipitation levels, particularly on steeper terrain.

3.6.2. Soil Erodibility (K)

Soil Erodibility (K) factor was computed from soil maps of the Shuttle Radar Topography Mission (SRTM) dataset, which had a vertical resolution of 30 meters and a spatial resolution of 60 meters. The K-factor was employed to represent the level of soil erosion, and its ratio depended on texture, permeability, and organic content (Tesfaye et al., 2015). Understanding the impact of rainfall and runoff on different kinds of soil was necessary due to this factor.

3.6.3. Topographic Factors (LS)

Steepness and slope length (L) were integrated into the Topographic Factor (LS), which was derived from the DEM. Steeper and longer slopes led to runoff water flowing at greater velocities, thus producing more erosion. To comprehend the influence of topography on water movement and soil loss, the LS factor needed to be accounted for (Wischmeier & Smith, 1978). DEMs were also of great assistance in determining the LS factor since DEMs provided high-quality elevation data.

3.6.4. Land Cover Factor (C)

This land cover-soil erosion relationship was called the Land-Cover Factor (C). Satellite information was used to calculate it through land cover classification. Different crops and vegetation types affected the C-factor, with high-density vegetation areas possessing a low C-factor since the vegetation would keep the rain and runoff from striking the soil (Atoma et al., 2020). However, the RUSLE model considered the impact of vegetation on erosion as a most significant factor and hence incorporated its C-factor parameter.

3.6.5. Support Practice Factor (P)

The Support Practice Factor (P) was a measurement of the impact of conservation practices on soil erosion. Practices such as transcription, contour tillage, and reforestation were used to slow runoff as well as reduce soil erosion. The P-factor, as measured using LULCC maps, indicated how efficient conservation practices were in reducing soil erosion (Renard & Foster, 1983).

3.6.6. Application of the RUSLE Model.

Using the RUSLE model, soil erosion was estimated across the Lake Koka catchment considering the five factors (R, K, LS, C, and P). Model erosion risk maps categorized locations into high-risk, medium-risk, and low-risk areas. The maps provided recommendations for conservation in areas at the highest risk of soil loss. Temporal analysis was conducted to examine changes in erosion risk over time, for instance, land use change, rainfall patterns, or conservation (Zhao et al., 2013).

3.7. Data analysis procedure

The flowchart illustrates the methodological framework for assessing soil erosion using the Revised Universal Soil Loss Equation (RUSLE) model integrated with GIS and remote sensing tools. It begins with the data collection and analysis phase, which is supported by five primary data sources: rainfall data, soil data, Shuttle Radar Topography Mission (SRTM) data, satellite imagery, and field observations. Each data source contributes to the derivation of specific RUSLE factors that collectively estimate soil erosion rates across a watershed.

Rainfall data is used to compute the Rainfall Erosivity Factor (R-Factor). This involves analyzing mean annual rainfall (RF) values to quantify the erosive force of precipitation, which is a key determinant of soil detachment and transport. Similarly, soil data, particularly the identification of major soil types, informs the calculation of the Soil Erodibility Factor (K-Factor). This factor assesses the inherent vulnerability of soil to erosion based on its texture, structure, permeability, and organic matter content.

The SRTM data provides a Digital Elevation Model (DEM) used to determine slope and elevation characteristics, which are essential for estimating the Slope Length and Steepness Factor (LS-Factor). This factor accounts for the influence of topography on runoff velocity and its capacity to erode soil. The steeper and longer the slope, the greater the risk of erosion.

This analysis supports the computation of the Cover Management Factor (C-Factor) and the Support Practice Factor (P-Factor). The C-Factor measures the protective effect of vegetation and crop cover in reducing erosion, while the P-Factor reflects the effectiveness of soil conservation practices like contour farming, terracing, or strip cropping.

Lastly, field observations are used to gather ground truth data that validates the accuracy of satellite-derived classifications. This ensures that land use mapping and erosion control assessments are consistent with actual field conditions. It also supports land use classification, which is critical for accurately estimating C and P factors.

All these inputs R, K, LS, C, and P are then synthesized and analyzed in the results interpretation phase. This final step integrates the processed data to estimate soil erosion rates, identify high-risk zones, and support evidence-based land management and conservation strategies.

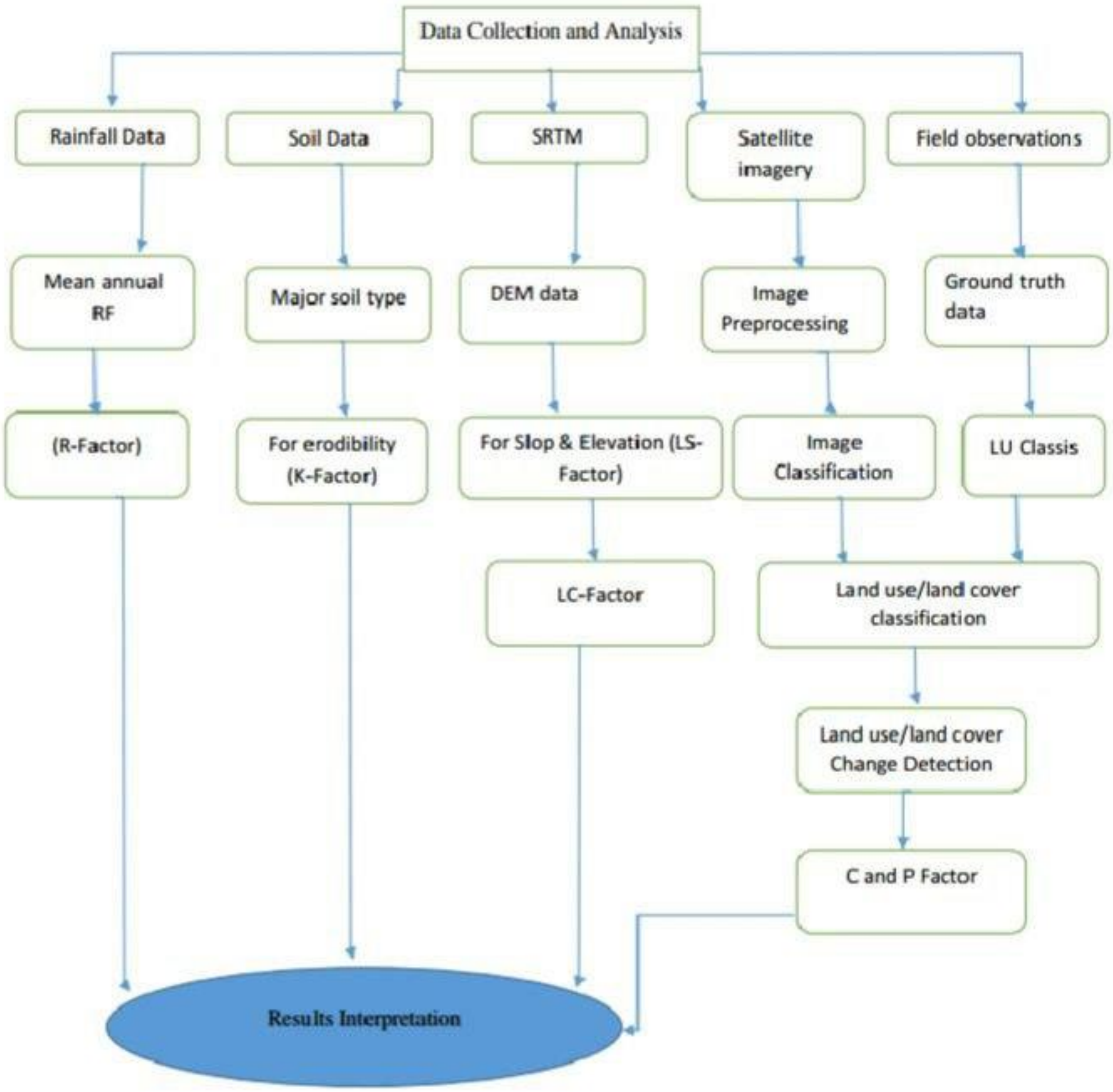

Figure 3-2: Methodological flowchart

4. RESULT AND DESCUSSION

4.1. Introduction

Chapter Four presents the major findings of the study based on integration of the Revised Universal Soil Loss Equation (RUSLE) within a GIS framework. In this chapter, an extensive spatial and temporal analysis of soil erosion within the Koka Lake watershed has been carried out on the basis of various parameters including the LS (slope length and steepness), C (cover management), R (rainfall erosivity), and P (support practice) factors. All these constituents feature prominently in measuring the intensity of the soil loss over the study area.

4.2. Application of GEE for soil erosion monitoring

The use of Google Earth Engine (GEE) has revolutionized the process of soil erosion monitoring by enabling the integration of multi-temporal satellite imagery with cloud-based geospatial analysis tools. GEE facilitates efficient data acquisition, preprocessing, and analysis across large spatial and temporal scales, making it particularly suitable for monitoring soil erosion dynamics over time. Through the application of GEE, variables such as land use/land cover (LULC), vegetation indices (e.g., NDVI), rainfall erosivity, and topographic factors can be extracted and analyzed to estimate soil loss using the Revised Universal Soil Loss Equation (RUSLE) model. In this study, GEE was employed to process Landsat imagery and derive biophysical parameters essential for erosion modeling. The platform allowed for automated classification, slope derivation from DEMs, and temporal assessment of vegetation cover, significantly reducing computational time and improving consistency in spatial analysis. The integration of GEE in soil erosion assessment enhances the ability to detect erosion-prone areas, evaluate land management practices, and support decision-making in watershed conservation planning.

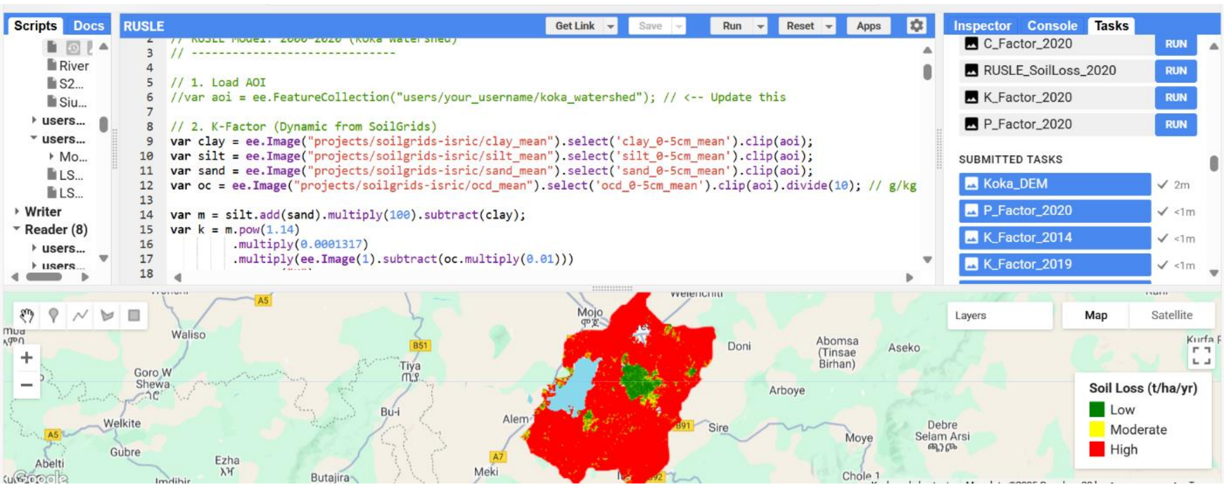

Figure 4-1: Application of GEE for soil erosion monitoring

4.3. Parameters that affect soil erosion

4.3.1. LS Factor

Elevation

Elevation is a fundamental topographic parameter that significantly influences the hydrological behavior of a watershed, particularly the velocity and erosive force of surface runoff. As rainfall occurs, gravity acts more strongly on water moving from higher to lower elevations, resulting in greater flow energy and potential soil detachment in steeper areas (Moore et al., 1991). This relationship between slope and runoff energy has been well-documented in various erosion models, including the Revised Universal Soil Loss Equation (RUSLE), which uses slope length and steepness as key factors in predicting erosion risk (Renard et al., 1997). In the Koka Lake watershed, the elevation varies significantly, from 1338 meters to 2462 meters above sea level. Such a wide altitudinal gradient implies the presence of steep slopes, particularly at the northern and southern edges, contributing to higher gravitational potential and thus faster surface runoff during rainfall events.

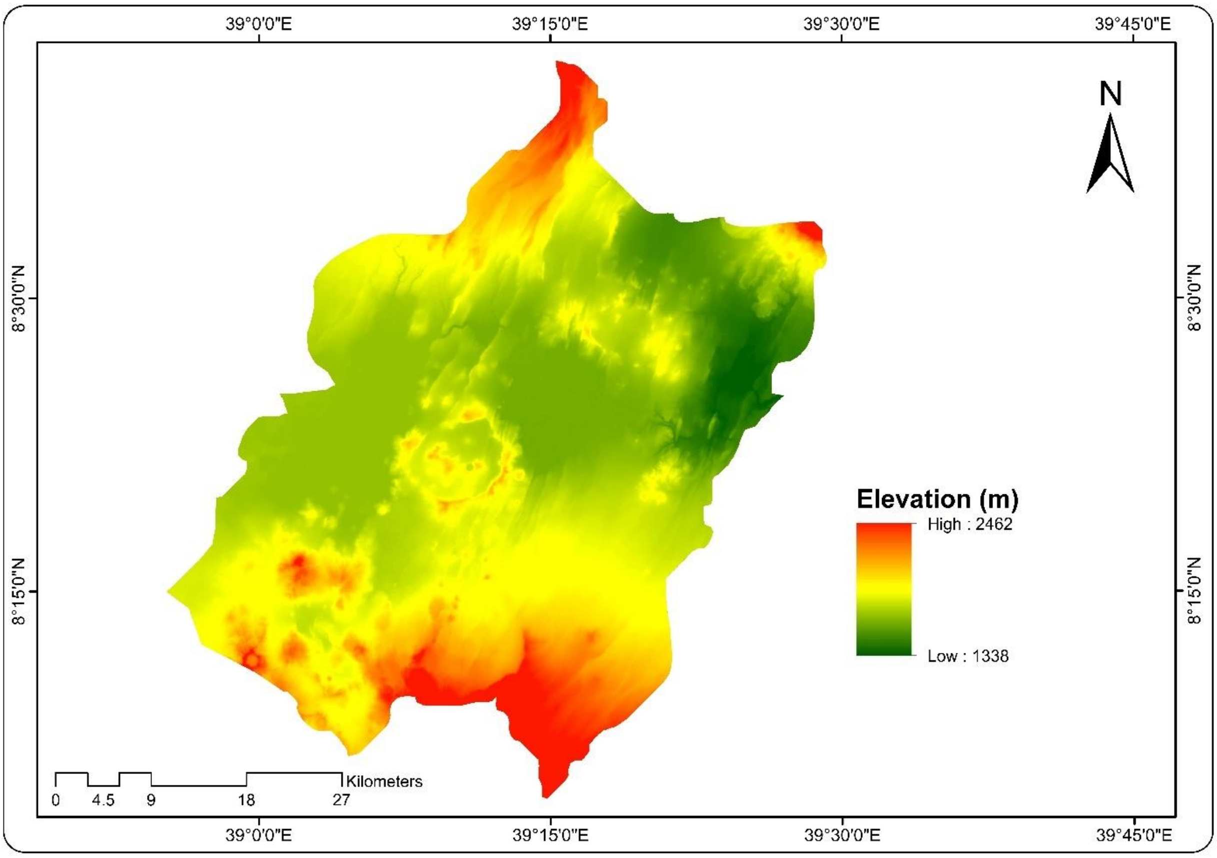

Figure 4-2: Elevation

Slope

Slope gradient is one of the most critical topographic factors influencing soil erosion, as it directly affects both the speed and volume of surface runoff. Steeper slopes accelerate water movement, increasing the kinetic energy of runoff and enhancing the potential for soil particle detachment and transport (Morgan, 2005). In the Koka Lake catchment, slope mapping revealed that the northern and eastern regions experience the highest gradient levels, with slopes ranging from 0° to 63.71°. These steep zones are particularly prone to rill and gully erosion, as the high velocity of overland flow, especially during intense rainfall events, quickly overwhelms the soil's resistance to erosion (Zhang et al., 2004). Such areas often become focal points for land degradation if not managed properly.

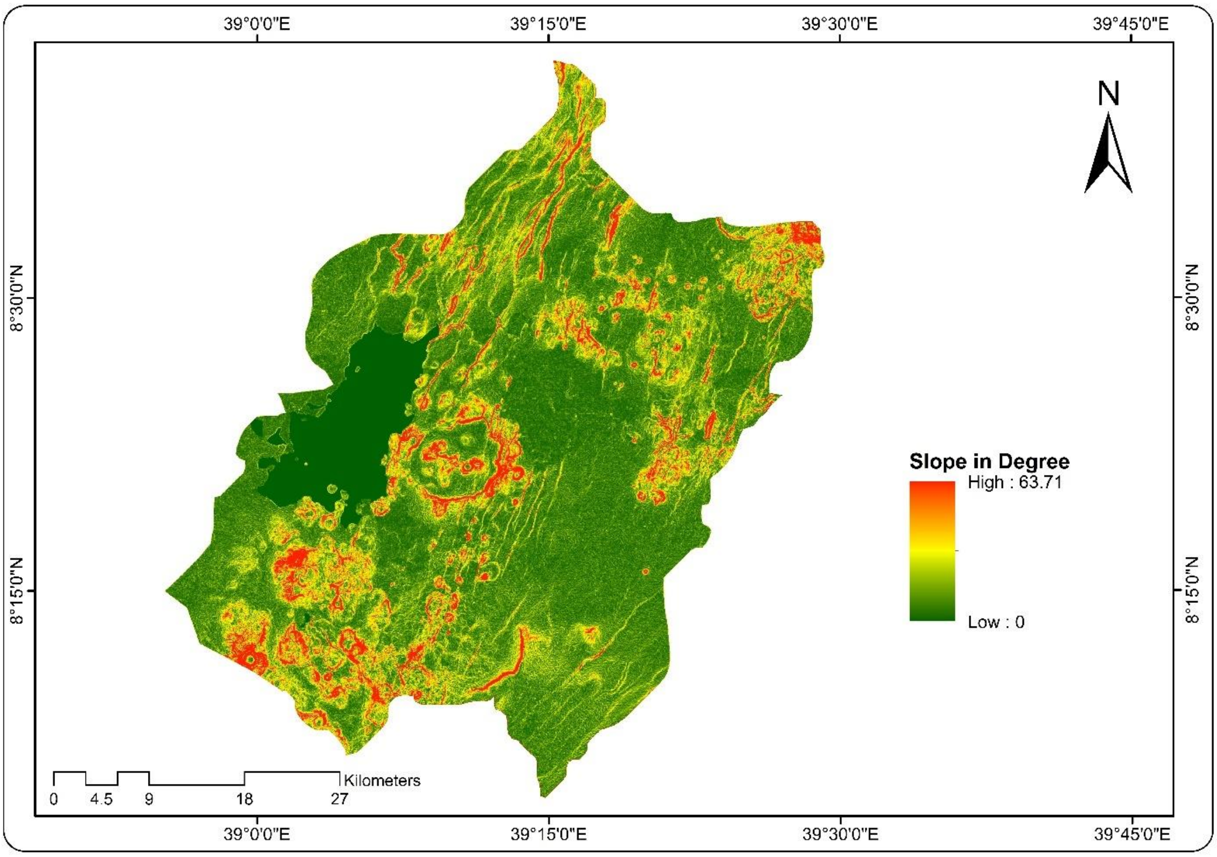

Figure 4-3: Slope

The relationship between slope steepness and erosion has been emphasized in several empirical and modeling studies. The Revised Universal Soil Loss Equation (RUSLE), for example, incorporates slope length and steepness as core parameters for estimating erosion rates, acknowledging that erosion risk escalates exponentially with increasing slope gradient (Renard et al., 1997). Additionally, steep slopes pose practical challenges for conventional agriculture and conservation efforts. Practices like tillage on steep land can exacerbate soil loss by disturbing the soil structure and promoting downslope runoff. According to Poesen et al. (2003), land on steep gradients often experiences reduced infiltration and increased surface flow, making it more vulnerable to sheet erosion and rill development.

The LS factor, which is the combined effect of slope length (L) and slope steepness (S), is a critical topographic parameter in predicting soil erosion in models such as the Revised Universal Soil Loss Equation (RUSLE). It quantifies how both the length and incline of a slope influence erosion potential, with longer and steeper slopes contributing to higher erosive energy of surface runoff (Renard et al., 1997). In the Koka Lake watershed, elevation and slope data revealed a pronounced altitudinal gradient, particularly in the northern and eastern parts of the catchment. These areas not only exhibit steep slopes but also lie at higher elevations, where gravitational potential energy accelerates runoff, thereby amplifying the capacity for soil detachment and transport (Moore & Burch, 1986). The integration of slope and elevation into the LS factor map showed values ranging from 0 to 19.08, with the highest values clustered in the elevated, steep-slope regions.

Several studies have demonstrated the effectiveness of the LS factor in identifying erosion hotspots. Moore and Wilson (1992) noted that areas with high LS values experience significantly more erosion due to the compound effect of increased water velocity and flow accumulation. Similarly, Nearing (1997) emphasized that slope steepness has an exponential relationship with soil loss, making the LS factor a particularly sensitive indicator in mountainous or undulating terrains. In the context of the Koka watershed, the spatial distribution of the LS factor highlights regions that are most vulnerable to rill and gully erosion, especially where vegetation is sparse or land is under cultivation. These high-LS zones should be prioritized for soil and water conservation interventions such as terracing, contour bunding, or reforestation, to reduce the kinetic energy of runoff and mitigate soil degradation.

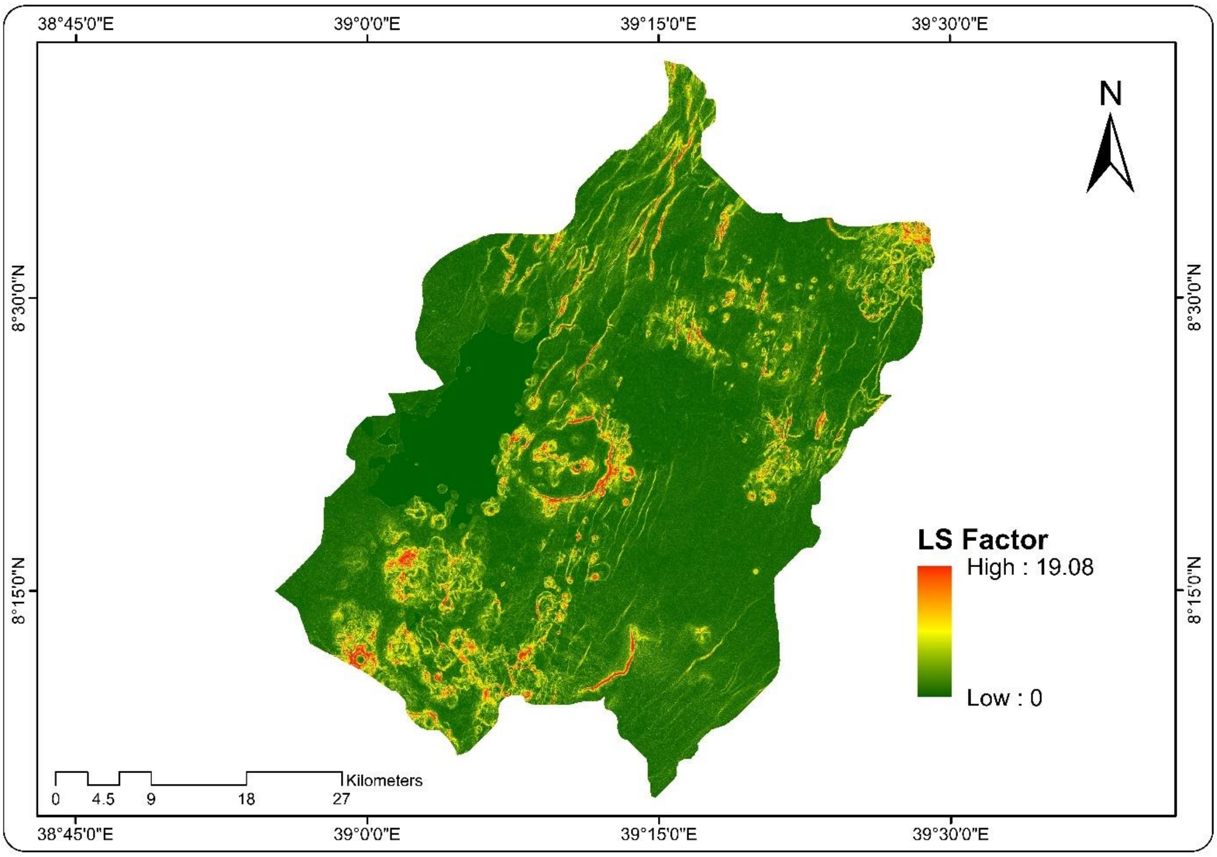

Figure 4-4: LS Factor

4.3.2. C Factor

The C factor explains the effect of land management and land cover on the erosion rate. It explains how land use practices or vegetation mitigate the erosive power of rainfall and run-off. In this study, the C factor map indicates enormous spatial variability across the watershed. Closed forests or shrublands with high density vegetation cover reported low C-values, which suggest little erosion hazard. In contrast, naked land, open fields, and poorly farmed agricultural fields exhibited high C-values, denoting high exposure to soil erosion. Analysis of the C-factor confirms the crucial role of vegetation in soil conservation and highlights the significance of land degradation and deforestation as causes of erosion. The findings indicate the importance of sustainable land management and afforestation practices in erosion-prone areas.

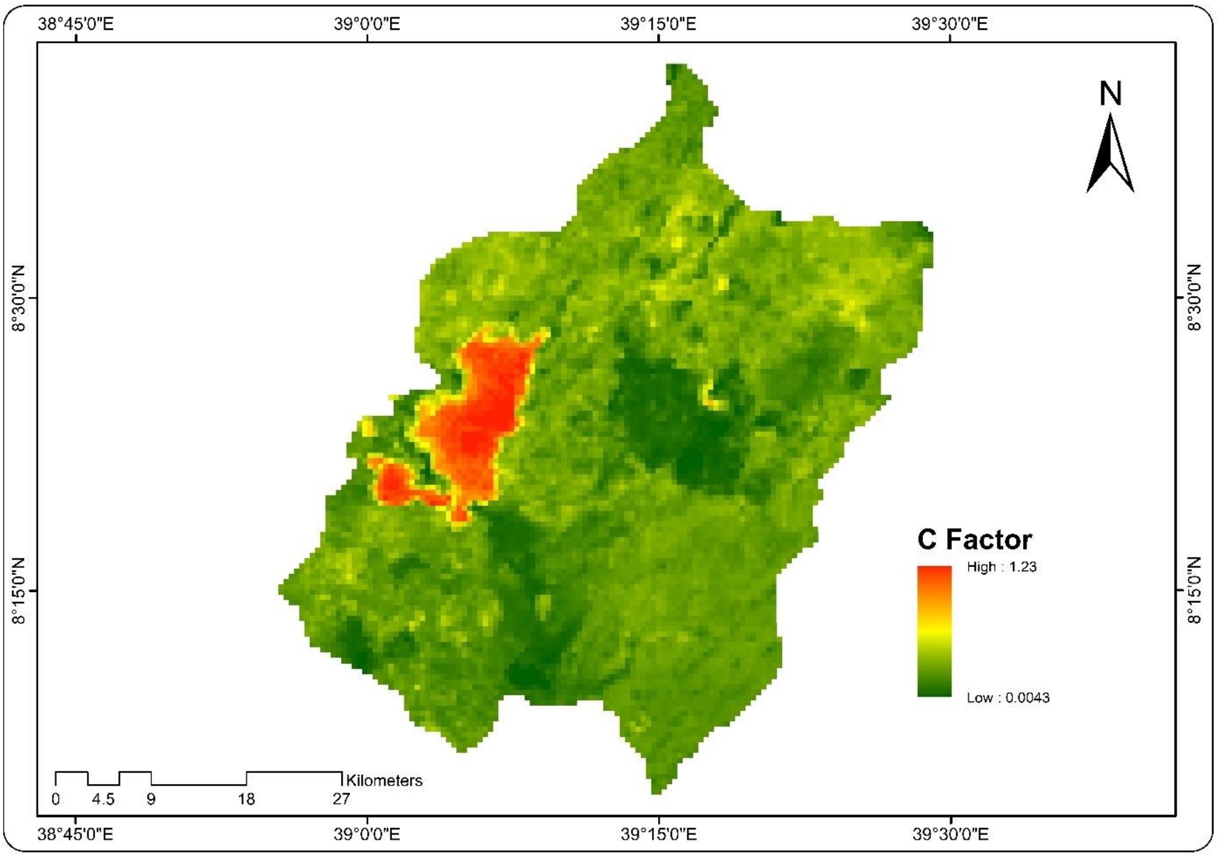

Figure 4-5: C Factor

4.3.3. R Factor

The R factor quantifies the impact of rainfall intensity and frequency on erosion. The R-factor map developed in this study showed that the majority of erosive rainfall occurs over the central and southern parts of the watershed. Heavy seasonal rainfall events that generate high surface runoff rates were associated with high R-values, particularly where the land surface is most exposed. The effect of rain on erosion is increased when combined with high slopes and poor vegetation cover. The results underscore the significance of certain erosion control practices in areas of high R-factor, for example, buffer strips, grassed waterways, and rainwater harvesting to slow down and decrease runoff speed and volume.

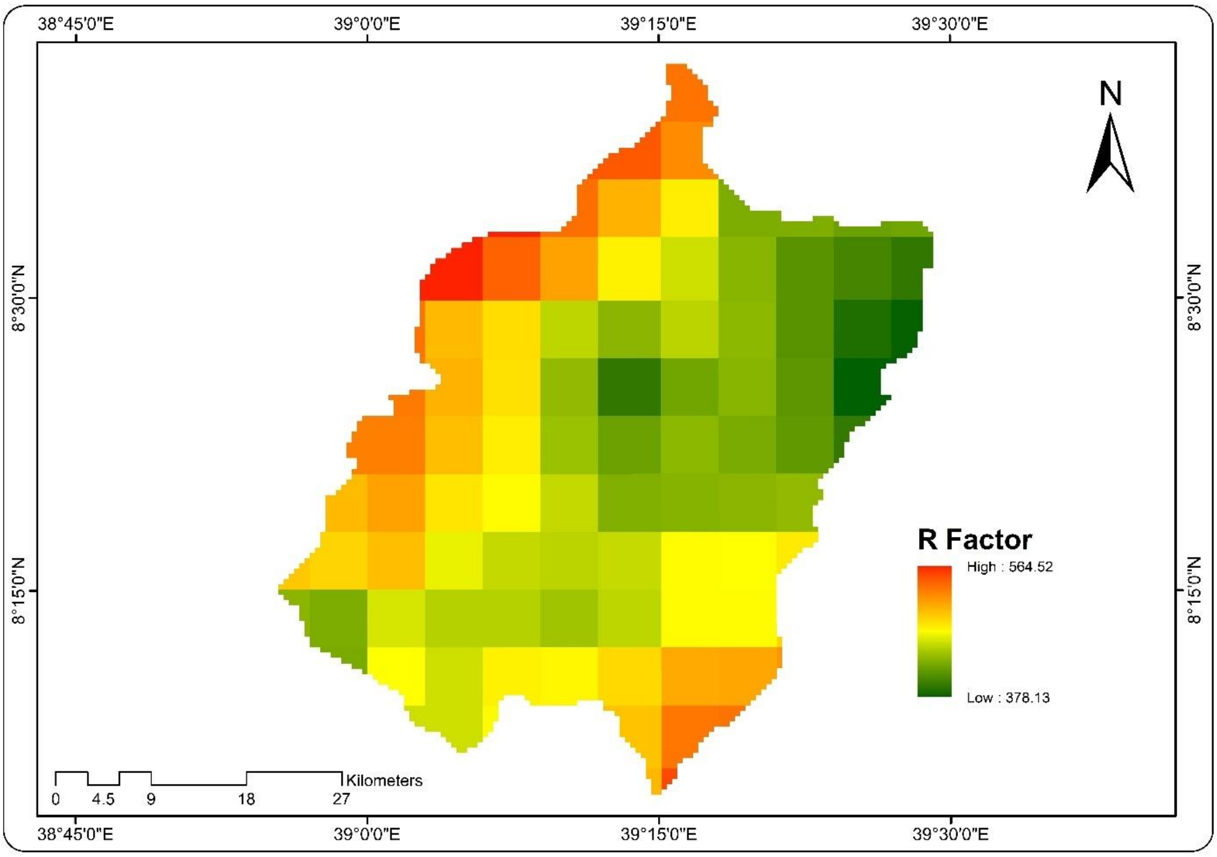

Figure 4-6: R Factor

4.3.4. Support practice (P) factor

The P-factor (support practice factor) represents the ratio of soil loss under a given support practice to that under conventional up-and-down slope tillage, thereby quantifying the effectiveness of soil and water conservation (SWC) measures in reducing erosion. This factor plays a critical role in land management planning, as it reflects the impact of interventions designed to reduce runoff velocity, minimize slope length, and mitigate erosive forces acting on the soil surface (Renard et al., 1997). Despite its importance, the accuracy of P-factor estimations is often challenged due to the complexity of field conditions and the variability in the quality and maintenance of conservation structures.

In this study, the P-factor was assessed through a combination of satellite image interpretation using ArcGIS 10.8 and extensive field verification. The analysis identified a variety of support practices implemented across the Koka Lake watershed. These included both modern and traditional soil conservation techniques such as soil and stone bunds, stone-faced soil bunds, hillside terraces stabilized with tree planting, trenches, cut-off drains, stone check dams, gully rehabilitation, area closure initiatives, and selective afforestation and revegetation in degraded uplands. Additionally, farmers in some parts of the watershed have adopted indigenous methods such as drainage ditches to manage runoff from farmlands.

The Sustainable Land Management (SLM) program has made notable progress in introducing and scaling up these practices. However, field observations revealed that a considerable portion of the watershed still suffers from improperly designed, poorly spaced, or inadequately maintained conservation structures. These deficiencies have compromised the effectiveness of interventions, placing previously rehabilitated areas—particularly degraded hillsides—at risk of renewed erosion. The lack of sustained farmer participation and limited institutional follow-up were identified as key contributing factors to this problem. Given these inconsistencies, it was deemed inappropriate to uniformly account for all support practices in the estimation of P-factor values across the watershed.

Following the guidelines of Wischmeier and Smith (1978), the watershed was classified into cultivated land and non-cultivated land use/land cover (LULC) categories. Cultivated land was further subdivided into six slope classes, with each class assigned a specific P-value reflective of the conservation practices present, particularly terracing. For non-agricultural land use types—such as forest, shrubland, and bare land—a default P-value of 1 was assigned, consistent with prior studies in the Ethiopian highlands (e.g., Gashaw et al., 2017), indicating the absence or minimal influence of support practices on erosion control. The assigned P-values, detailed in Table 4-1, were designed to realistically represent the actual field conditions and conservation interventions observed in the study area.

The P factor assesses the effectiveness of conservation practices to reduce soil erosion compared to land without protection. In this, various support practices were examined using ArcGIS 10.8 and field ground-truthing. Stone bunds, terracing, check dams, afforestation, and drainage ditches existed in parts of the watershed. However, many structures were spaced far apart, poorly maintained, or destroyed. Field inspections revealed that while efforts had been made through sustainable land management programs, they were not uniformly applied and institutional support was poor. Therefore, there were large areas where there was no control over erosion. P-values were provided by slope gradient and land use in RUSLE analysis according to Wischmeier and Smith's (1978) recommendations. The croplands were allocated six slope classes with matching P-values of 0.1 to 0.33, and a default value of 1 was used for other land uses with no conservation practice reported. This classification reflects the partial enforcement of erosion control and its partial impact across the watershed.

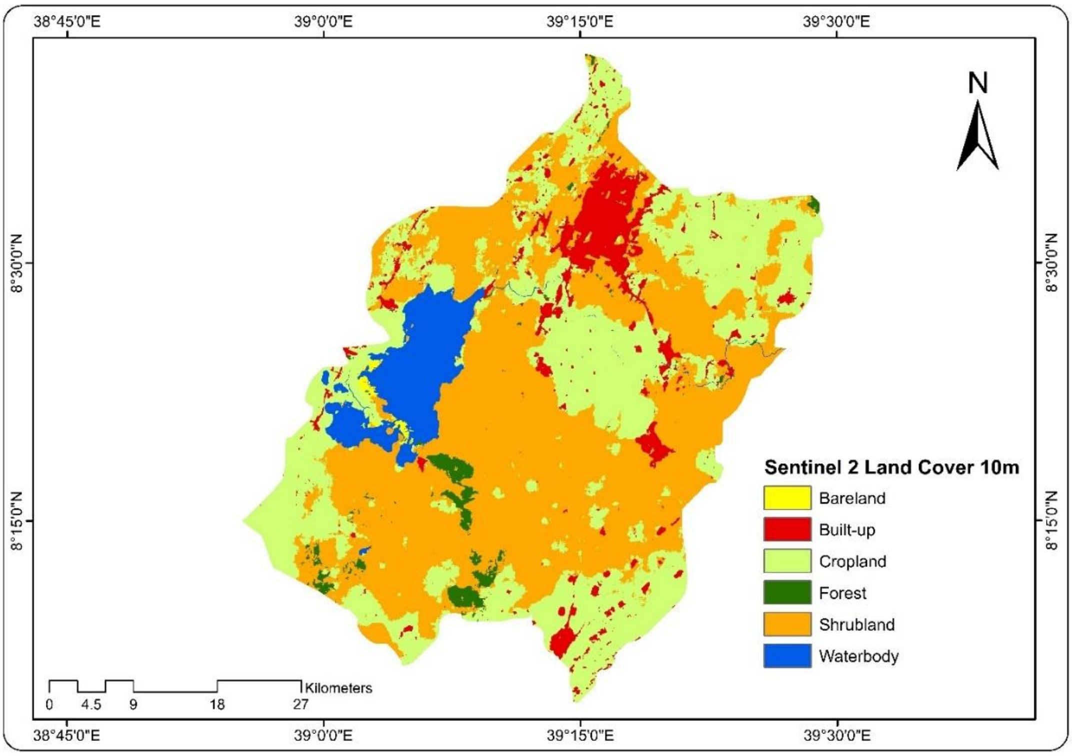

Figure 4-7: Sentinel 2 land cover for the year of 2024

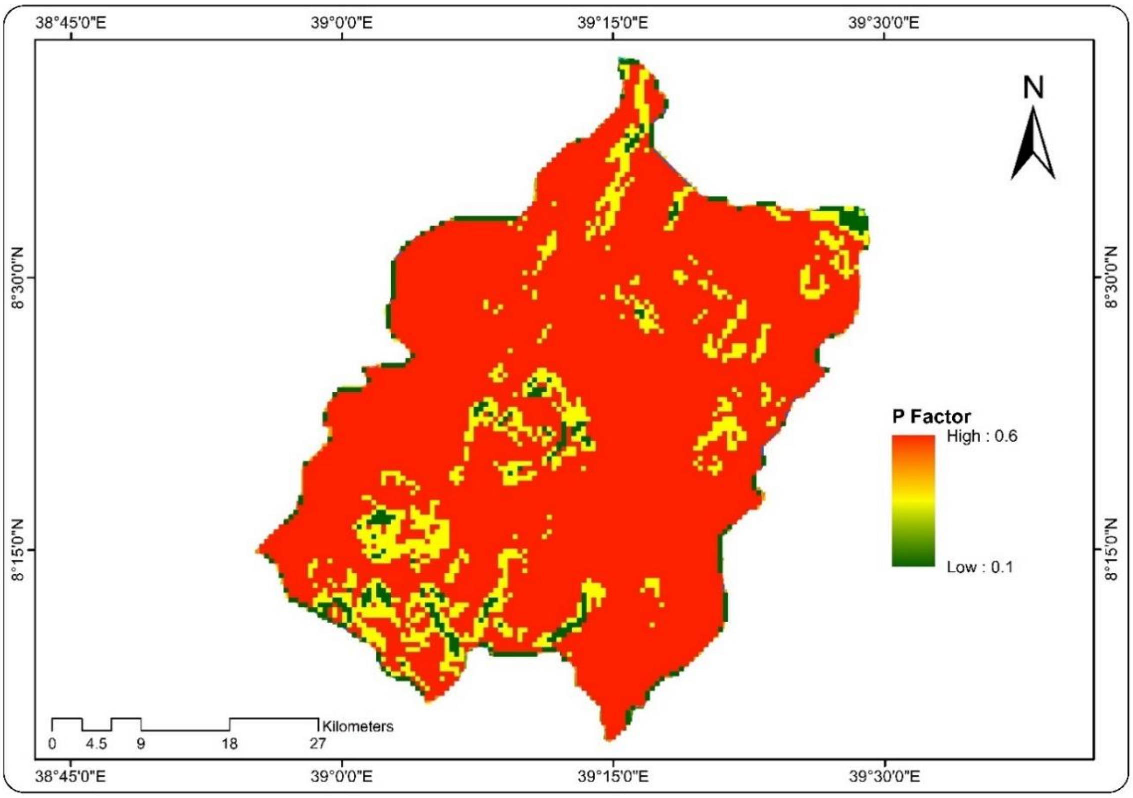

Figure 4-8: P factor

4.3.5. Annual soil loss

Yearly soil loss for the year 2024 was mapped to give a spatial representation of the distribution of erosion risk in the Koka Lake watershed. The analysis revealed that steep slope, high rainfall, and degraded land cover areas experienced the highest loss of soil. These areas are generally located in upland agricultural areas where conservation measures are lacking or nonexistent. In contrast, forest and protected areas had low erosion levels, supporting the protective function of vegetation. The findings illustrate how spatial differences in topography, land use, and management interact to affect erosion intensity. The 2024 map is a decision-support tool for the determination of critical areas for urgent soil conservation intervention.

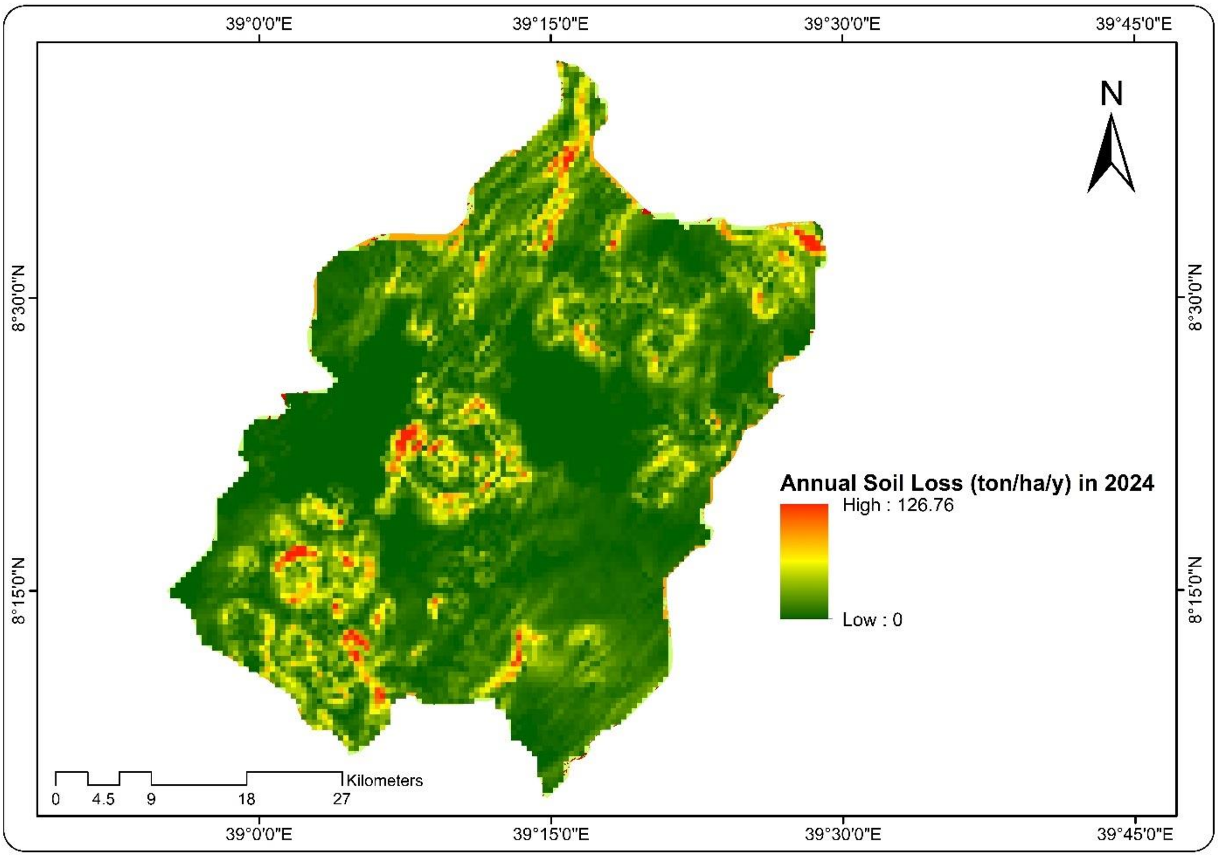

Figure 4-9: Annual soil loss in the study area for the year of 2024

4.3. Temporal variation of soil loss in the catchment

The temporal variation of soil loss across the Koka Lake catchment, as illustrated in Figure 4-9, reveals significant spatial and temporal fluctuations in erosion severity over the years 2000, 2006, 2012, and 2024. In the year 2000, the maximum soil loss was estimated at approximately 129.69 t/ha/year, with most of the catchment showing moderate to low erosion levels. By 2006, this figure increased to 148.81 t/ha/year, signaling a rising trend in erosion, likely driven by accelerated land cover changes and the expansion of agriculture onto steeper slopes without adequate soil and water conservation (SWC) measures. The problem intensified further in 2012, where soil loss peaked at 163.21 t/ha/year. This period coincides with observed degradation of vegetative cover and the failure or absence of physical conservation structures, particularly in the highland areas where the erosive power of surface runoff is more pronounced due to steep slopes and high rainfall intensity.

The spatial pattern across all years consistently shows that the northeastern and central parts of the watershed are erosion hotspots. These zones align with regions of higher elevation and steeper slopes, where overland flow gains speed and detaches soil more aggressively, especially under poor land management practices. The cumulative effect of these topographic and anthropogenic factors explains the persistent vulnerability in these parts of the watershed.
However, the trend appears to reverse by 2024, where the maximum soil loss reduces to 126.76 t/ha/year. This decline can be attributed to the implementation of integrated watershed management strategies, such as terracing, area closure, and reforestation efforts, under the Sustainable Land Management (SLM) program and community-based interventions.

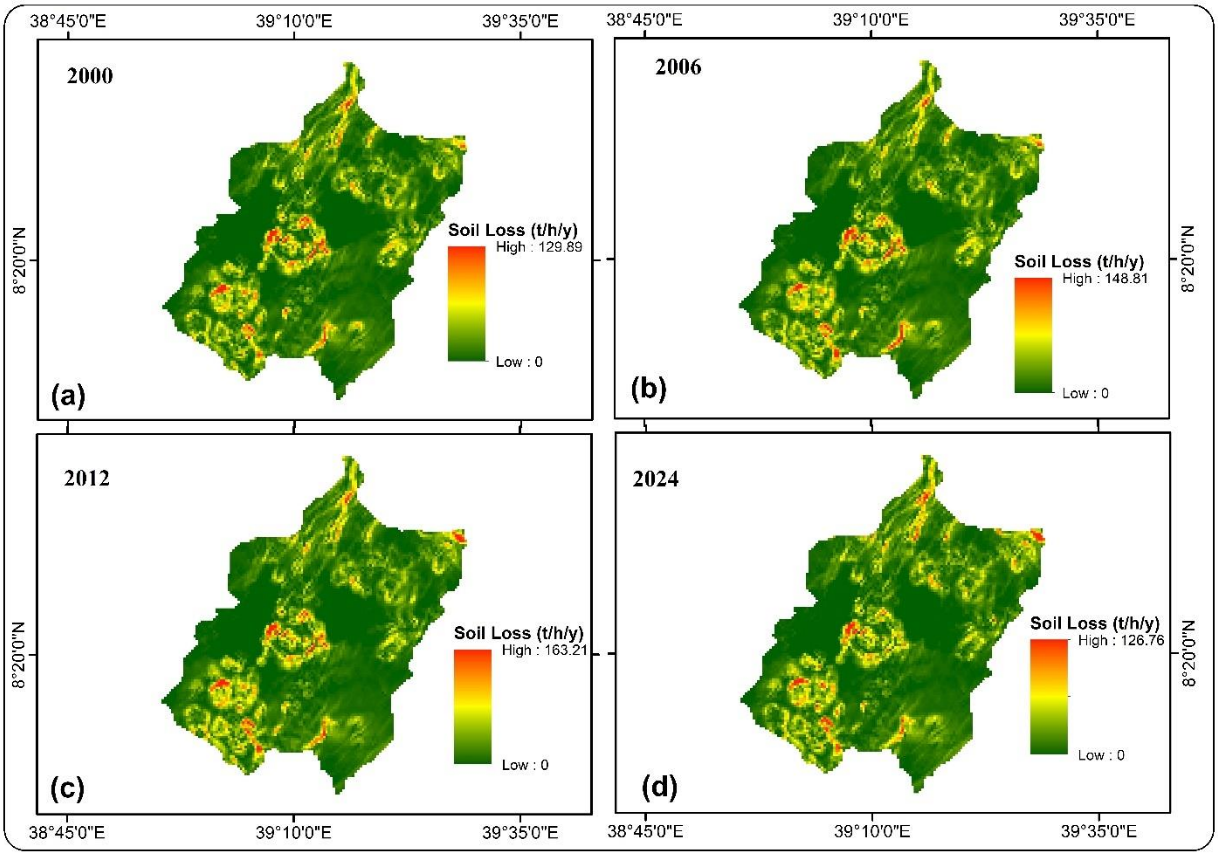

Figure 4-10: Temporal soil loss erosion; (a) 2000, (b) 2006, (c) 2012, (d) 2024

4.3.6. Average soil loss over time

The graph titled Average Soil Loss Over Time presents a quantitative assessment of soil erosion trends in the catchment from 2000 to 2020. Between 2000 and 2011, there is a clear upward trend in average soil loss, with peaks occurring around 2010 and 2011. This period reflects increased land degradation resulting from intensified agricultural activities, deforestation, and cultivation on steep slopes without adequate soil conservation measures. The spatial maps also confirm the presence of high soil loss values during this time, particularly in areas with steep terrain and low vegetation cover.

From 2012 onward, the graph shows a significant decline in average soil loss, reaching the lowest values around 2014 and 2015. This change corresponds with the implementation of physical and biological soil and water conservation practices across the catchment. Measures such as terracing, reforestation, and area closures were widely adopted, and government-led initiatives like the Sustainable Land Management Program (SLMP) contributed to reducing erosion rates.

The period between 2016 and 2019 shows moderate fluctuations in soil loss values. These variations reflect differences in the maintenance and distribution of conservation interventions, as well as changes in land use patterns and rainfall intensity. By 2020, average soil loss continues to decrease, indicating the long-term effectiveness of sustained land management practices.

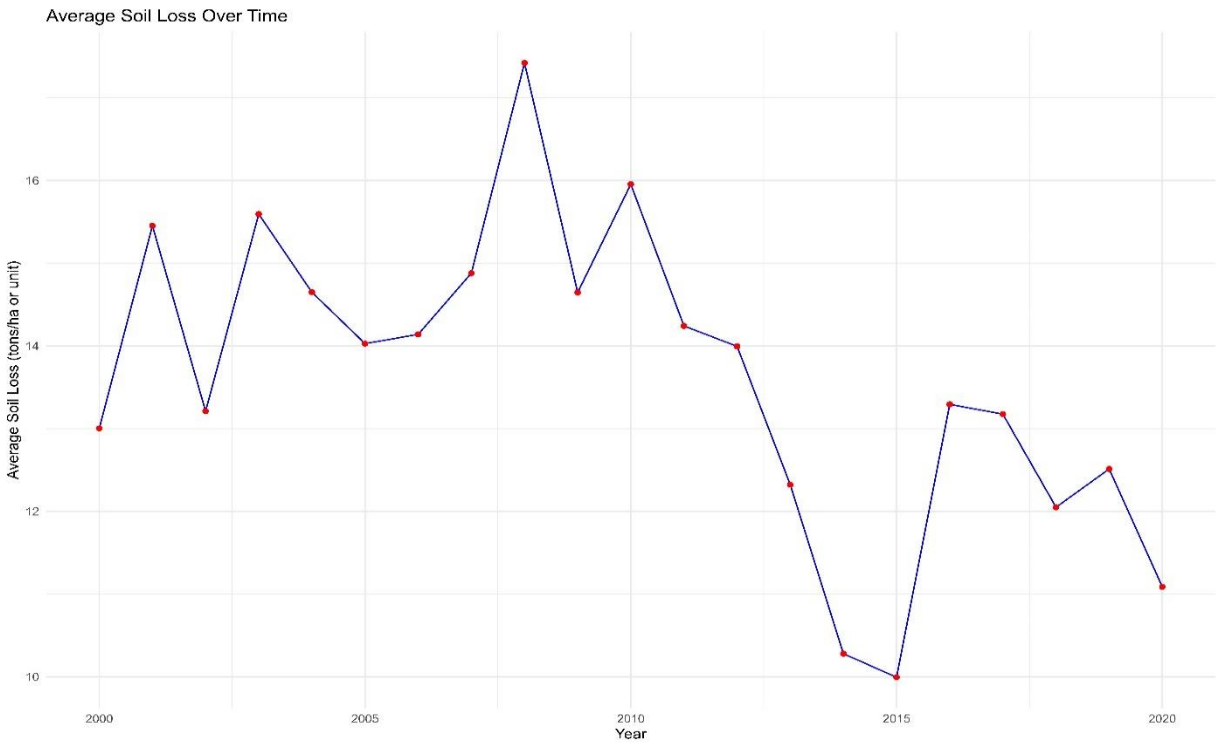

Figure 4-11: Average soil loss over time

4.4. Soil risk zone classification

The soil erosion risk map of the Lake Koka watershed clearly displays the spatial distribution of erosion severity, categorized into five levels: Very Low, Low, Moderate, High, and Very High. This classification is based on GIS-integrated soil erosion modeling, using established factors such as topography, rainfall intensity, land use/land cover, and soil characteristics.

The central and eastern parts of the watershed are dominated by *very low* to *low erosion risk* zones, shown in dark and light green. These areas consist of flat terrain and are covered with stable land use types such as forest, grassland, or well-managed farmland. Vegetation cover and gentle slopes in these regions effectively reduce surface runoff and soil displacement, resulting in minimal erosion rates. These zones are stable and do not require immediate conservation measures beyond routine land management.

Moderate erosion risk zones, depicted in yellow, are located between low-risk and high-risk zones, forming transitional belts. These areas are occupied by cultivated fields on moderately sloped terrain and degraded shrublands. The combination of exposed soils and medium slopes contributes to increased soil loss. These zones are already under stress and require soil conservation practices to prevent further degradation.

The high and very high erosion risk zones, marked in orange and red, are concentrated in the western, northern, and southeastern regions of the watershed. These areas are characterized by steep slopes, extensive deforestation, and intensive agricultural activity. Soil erosion rates in these regions exceed 25 to 50 tons per hectare per year, indicating severe land degradation. These locations are identified as erosion hotspots and require immediate and focused soil conservation interventions, including terracing, reforestation, and the implementation of physical and biological conservation structures.

The spatial distribution and severity of erosion in this watershed are consistent with findings from other studies in Ethiopia. Gashaw et al. (2017) reported that areas with steep slopes and cultivated land in the Huluka watershed experienced soil losses exceeding 50 tons/ha/year due to land cover removal and poor land management. Hurni (1985) also confirmed that topographic steepness and unsustainable land use are primary contributors to high erosion rates in the Ethiopian highlands. Bewket and Teferi (2009) identified similar erosion hotspots in the Chemoga watershed, emphasizing the direct link between land use change and increased erosion risk.

Table 2: Soil erosion class adapted from literature indicated in source column.

Erosion Risk Class	Soil Loss Rate (tons/ha/year)	Description	Source
Very Low	< 5	Negligible erosion	FAO (2000); Morgan (2005)
Low	5 – 10	Minor erosion	FAO (2000); Hurni (1985)
Moderate	10 – 25	Moderate risk; affects productivity	Hurni (1985); Morgan (2005)
High	25 – 50	Severe risk, conservation needed	Hurni (1985); Gashaw et al. (2017)
Very High	> 50	Extreme risk; urgent intervention	Gashaw et al. (2017); FAO (2000)

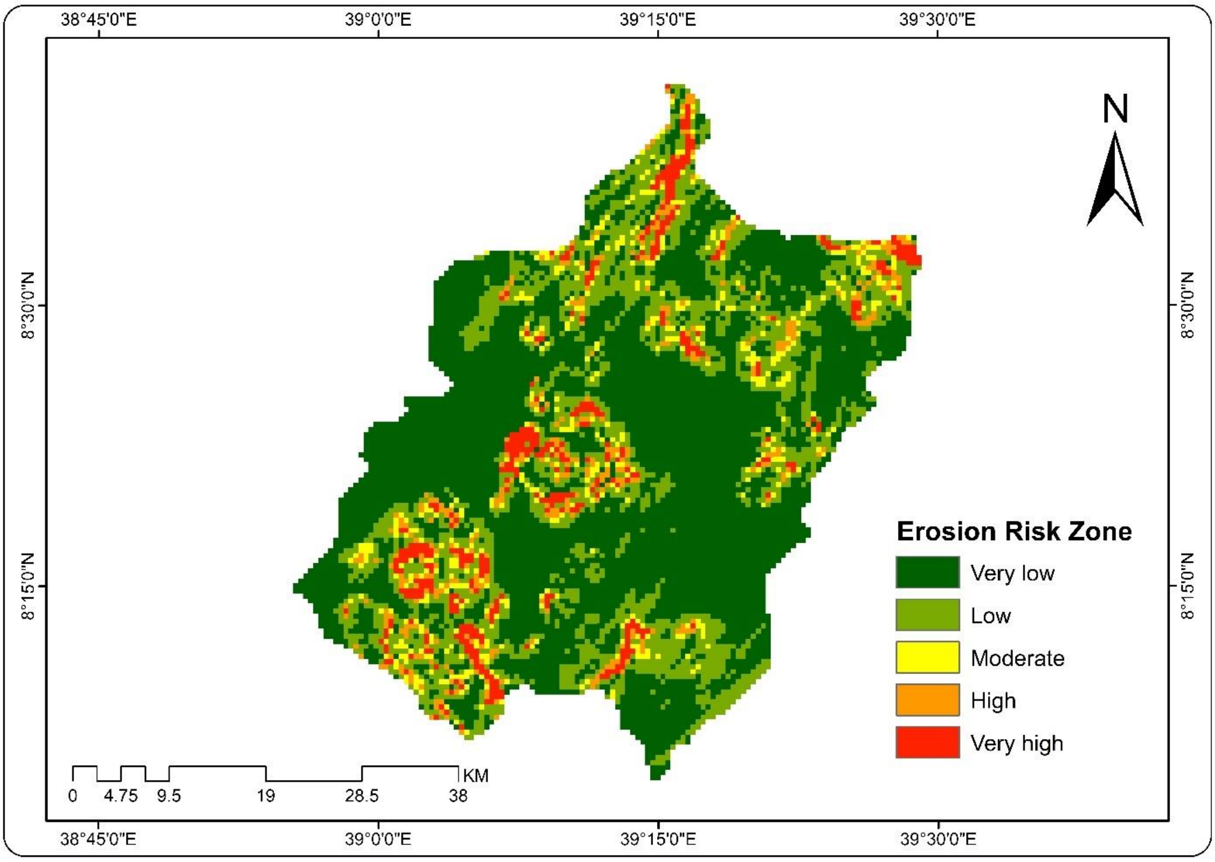

Figure 4-12: Classified risk zone in the study area

4.5. Discussions

The findings of this research on soil erosion monitoring in the Koka Lake watershed using Google Earth Engine (GEE) align with several studies that have highlighted the importance of integrating remote sensing and geospatial tools for large-scale erosion assessments. The application of GEE in processing multi-temporal satellite imagery and biophysical parameters for erosion modeling reflects a growing trend in the use of cloud-based platforms for environmental monitoring (Gorelick et al., 2017). Studies by Vanacker et al. (2005) and Bewket and Teferi (2009) confirm that steep slopes, high rainfall, and vegetation cover are critical factors influencing soil erosion, which is consistent with the findings in this study. GEE's ability to automate classification and generate key parameters, such as slope, elevation, and vegetation indices, has been shown to improve the accuracy and efficiency of erosion predictions (Hansen et al., 2013).

The research's focus on the Revised Universal Soil Loss Equation (RUSLE) model also aligns with a broad body of literature on soil erosion modeling. The RUSLE model has been widely used for estimating soil loss in different regions and environments (Renard et al., 1997). Studies in the Ethiopian highlands, such as those by Bewket and Teferi (2009), have shown that areas with high elevation and slope are particularly vulnerable to erosion, which is consistent with the findings from the Koka Lake watershed. The study's detailed analysis of the LS factor comprising slope length and steepness mirrors research by Moore and Wilson (1992), who also emphasized the exponential relationship between slope and soil loss. Moreover, the study's findings on the role of land use/land cover (LULC) and the C factor are in line with previous studies by Poesen et al. (2003), who noted that poor land management practices, such as cultivation on steep slopes without adequate conservation measures, significantly contribute to soil degradation.

The temporal analysis of soil loss in the Koka Lake watershed, which shows increased erosion in the years 2000-2012, followed by a decrease in 2024, underscores the impact of land use changes and conservation interventions. This pattern is consistent with similar findings in other studies across the Ethiopian highlands (Bewket, 2009; Gashaw et al., 2017), where erosion was exacerbated by deforestation and land expansion, particularly in areas with steep topography and high rainfall intensity. The decline in soil loss in 2024, attributed to integrated watershed management efforts like terracing, area closures, and reforestation, aligns with research by Morgan (2005) and Zhang et al. (2004), who showed that proper soil and water conservation practices can effectively mitigate erosion in erosion-prone areas. Furthermore, the spatial distribution of erosion hotspots in this study corroborates the findings of several authors (Nearing, 1997; Vanacker et al., 2005), who identified that high elevation, steep slopes, and degraded land cover areas are more susceptible to erosion.

These findings contribute to and support international policy frameworks, especially the United Nations Sustainable Development Goals (SDGs), particularly SDG 15.3, which targets land degradation neutrality (LDN) by 2030. The observed reduction in soil erosion by 2024 is indicative of progress toward LDN targets, demonstrating how spatial monitoring tools like GEE can guide policy implementation and measure environmental restoration outcomes. Moreover, the study aligns with the objectives of the United Nations Convention to Combat Desertification (UNCCD), which emphasizes sustainable land and water management to reduce erosion and land degradation in vulnerable regions, particularly in Africa. The integration of multi-temporal geospatial analysis with erosion modeling provides an evidence-based approach to support the UN Decade on Ecosystem Restoration (2021–2030) by identifying critical intervention areas and tracking rehabilitation efforts. These results also contribute to Ethiopia's commitment to restoring over 22 million hectares of degraded land, as part of the African Forest Landscape Restoration Initiative (AFR100).

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

This study highlights the critical issue of soil erosion in the Koka Lake watershed. The findings demonstrate that topography plays a central role in determining the severity of soil erosion, with areas of steep terrain experiencing the highest rates of erosion. Additionally, the study identifies that land use changes, particularly the expansion of agricultural activities and deforestation, have exacerbated soil erosion in the region. Areas with minimal vegetation cover, coupled with high rainfall intensity, were found to be the most vulnerable.

The temporal analysis of erosion dynamics revealed a worrying trend in the early years of the study period, with soil erosion increasing between 2000 and 2012. This period coincided with rapid land use changes, including agricultural expansion and urbanization, both of which contributed to higher soil erosion rates. However, the study also highlights a more optimistic finding between 2012 and 2024, where soil erosion rates decreased significantly. This improvement can be attributed to successful soil conservation practices such as terracing, reforestation, and the restoration of vegetative cover, which have been effective in reducing soil loss and stabilizing the watershed's ecosystem.

The study underscores the importance of continued and strategic soil conservation efforts, particularly in erosion-prone areas, and suggests that a combination of community-based initiatives and government support is essential for the long-term sustainability of the watershed. The reduction in erosion in recent years provides an encouraging outlook, showing that concerted efforts can make a meaningful difference in reversing environmental degradation.

In conclusion, the findings of this research stress the importance of effective soil erosion management in the Koka Lake watershed, as well as the role of conservation practices in mitigating environmental degradation. The positive changes observed in recent years offer hope for future restoration efforts and suggest that with sustained interventions, the impacts of soil erosion can be significantly reduced. The research also highlights the need for further monitoring and adaptive management to ensure the long-term health of the watershed and the surrounding communities.

5.2. Recommendations

- Focus on soil conservation methods such as terracing, reforestation, and agroforestry in erosion-prone areas, particularly in the hotspots identified in the study.
- Strengthen efforts to control soil erosion by improving land management, especially in regions with steep slopes and poor vegetation cover.
- Increase awareness among local communities about the impacts of soil erosion and the benefits of sustainable land use practices to reduce erosion.
- Establish a long-term monitoring system to track soil erosion trends and evaluate the effectiveness of conservation measures over time.

5.3. Implications for future studies

Future studies should focus on long-term monitoring of soil erosion dynamics, incorporating climate change projections to assess how shifting weather patterns influence erosion in regions like the Lake Koka watershed. Evaluating the effectiveness of different conservation techniques, especially in high-risk areas, will be crucial for identifying the most effective methods for soil erosion control. Additionally, investigating the impact of human activities on soil erosion and assessing the sustainability of erosion control programs will provide insights into socio-economic benefits and long-term success. The use of advanced GIS tools and high-resolution satellite imagery could enhance mapping and risk assessment, while cross-regional comparisons could broaden the understanding of soil erosion dynamics and applicable solutions.

REFERENCE

Abate, T. (2021). The role of Lake Koka in Ethiopia's regional economy and ecosystem services. Ethiopian Journal of Environmental Studies, 25(2), 112–124.

Abebe, S., & Sewnet, A. (2020). Rural land use problems and management options in Debre Tsyon Kebele, Ethiopia. *GeoJournal*, *85*(1), 145-157.

Ahmed, A., Zhang, Y., & Wang, X. (2020). Remote sensing for land use land cover change detection. Springer.

Alemayehu, A., & Birhanu, A. (2019). Impact of soil erosion on agricultural productivity in Ethiopia. Journal of Environmental Management, 45(2), 132–145.

Atoma, H., Sisay, B., & Azeb, H. (2020). Impact of land use on soil erosion in Ethiopia. Soil Erosion Journal, 35(2), 123–135.

Berry, L. (2003). Environmental management in Ethiopia: Land degradation and the role of agricultural practices. Environmental Management Review, 18(3), 234–249.

Bewket, W. & Teferi, E. (2009). Assessment of soil erosion hazard and prioritization for treatment at the watershed level: Case study in the Chemoga watershed, Blue Nile basin, Ethiopia. *Land Degradation & Development*, 20(6), 609–622.

Blum, W. E. (2013). Soil and land resources for agricultural production: general trends and future scenarios-a worldwide perspective. *International soil and water conservation research*, *1*(3), 1-14.

Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., ... & Panagos, P. (2017). An assessment of the global impact of 21st century land use change on soil erosion. *Nature communications*, *8*(1), 2013.

Chavez, P. S. (1996). Image-based atmospheric corrections: Revisited and improved. Photogrammetric Engineering & Remote Sensing, 62(9), 1025–1036.

Cohen, W. B., Maiersperger, T. K., & Pritchard, S. P. (2003). Radiometric correction of satellite images for land cover mapping. International Journal of Remote Sensing, 24(12), 2319–2333.

Congalton, R. G. (2018). Assessing the accuracy of land cover classification. Remote Sensing Applications, 4(4), 234–249.FAO. (1984). Soil erosion and its impacts on sustainable agriculture in Ethiopia. FAO Regional Office for Africa.

FAO. (2020). Soil erosion and sustainable land management in Ethiopia: A review of the challenges. Food and Agriculture Organization of the United Nations.

FAO. (2020). the state of the world's land and water resources for food and agriculture (SOLAW). Food and Agriculture Organization of the United Nations.

Fikadu, F., Getahun, F., & Temesgen, H. (2020). Assessment of soil erosion and its impact on water quality of Lake Koka. Ethiopian Journal of Environmental Studies, 12(1), 34–42.

Foody, G. M. (2018). Supervised classification of land cover from remote sensing data. Environmental Modelling & Software, 23(5), 537–546.

Gashaw, T., Tulu, T., Argaw, M., & Worqlul, A. (2017). Modeling soil erosion using RUSLE and GIS techniques: A case study of the Huluka watershed, Central Ethiopia. *Environmental Systems Research*, 6(1), 1–20.

Gezehagn, A., Tsegaye, M., & Melesse, A. (2018). Soil erosion and its impact on agricultural productivity in Ethiopia. Journal of Environmental Management, 214, 259–269. https://doi.org/10.1016/j.jenvman.2018.03.071

Gorelick, N., et al. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, 202, 18–27.

Guerra, C. A., Rosa, I. M., Valentini, E., Wolf, F., Filipponi, F., Karger, D. N., ... & Eisenhauer, N. (2020). Global vulnerability of soil ecosystems to erosion. *Landscape ecology*, *35*, 823-842.

Habtamu, G., Tsegaye, M., & Melesse, A. (2020). Soil erosion estimation using the Revised Universal Soil Loss Equation in Ethiopia. *Soil Science SocietyHurni, H. (1993). Soil erosion and conservation in Ethiopia: A review. Journal of Soil and Water Conservation, 48(4), 207-215.

Hansen, M.C., et al. (2013). High-resolution global maps of 21st-century forest cover change. *Science*, 342(6160), 850–853.

Hurni, H. (1993). Soil erosion and conservation in Ethiopia: A review. Journal of Soil and Water Conservation, 48(4), 207–215.

Issaka, S., & Ashraf, M. A. (2017). Impact of soil erosion and degradation on water quality: a review. *Geology, Ecology, and Landscapes*, *1*(1), 1-11.

Kanianska, R. (2016). Agriculture and its impact on land-use, environment, and ecosystem services. *Landscape ecology-The influences of land use and anthropogenic impacts of landscape creation*, 1-26.

Klein, A., van der Meer, F., & Heuvelink, G. (2016). Atmospheric correction in remote sensing. Springer.

Lautze, S., Aklilu, Y., Raven-Roberts, A., Young, H., Kebede, G., & Leaning, J. (2003). Risk and vulnerability in Ethiopia: Learning from the past, responding to the present, preparing for the future. *Report for the US Agency for International Development. Addis Ababa, Ethiopia*.

Liu, X., Chen, X., & Xu, Y. (2012). Application of GIS and RUSLE model for soil erosion risk assessment in the mountain areas of China. Journal of Environmental Management, 112, 1-12.

Luvai, A., Obiero, J., & Omuto, C. (2022). Soil loss assessment using the revised universal soil loss equation (RUSLE) model. Applied and Environmental Soil Science, 2022(1), 2122554.

Mahmood, S. (Ed.). (2024). Soil Erosion: Risk Modeling and Management. BoD–Books on Demand.

Mekonnen, Y., Sileshi, Z., & Haile, M. (2021). Topographic and climatic factors in soil erosion in Ethiopia. Geomorphology, 185(3), 98–113.

Mirzabaev, A., Sacande, M., Motlagh, F., Shyrokaya, A., & Martucci, A. (2022). Economic efficiency and targeting of the African Great Green Wall. *Nature Sustainability*, *5*(1), 17-25.

Moore, I.D., & Wilson, J.P. (1992). Length-slope factors for the Revised Universal Soil Loss Equation: Simplified method of estimation. *Journal of Soil and Water Conservation*, 47(5), 423–428.

Morgan, R.P.C. (2005). *Soil Erosion and Conservation*. 3rd ed. Blackwell Publishing.

Mosissa, D. (2019). Soil and water conservation practices and its contribution to small holder farmers livelihoods in northwest Ethiopia: a shifting syndrome from natural resources rich areas. *Mod Concep Dev Agrono*, *3*(5), 362-371.

Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models. Journal of Hydrology, 10(3), 282–290.

Nearing, M.A. (1997). A single, continuous function for slope steepness influence on soil loss. *Soil Science Society of America Journal*, 61(3), 917–919.

Nyssen, J., Poesen, J., & Deckers, J. (2009). The effectiveness of soil conservation measures to reduce erosion in a semi-arid environment: Case study from the Ethiopian Highlands. Land Degradation & Development, 20(4), 307-318.

Owens, P. N. (2020). Soil erosion and sediment dynamics in the Anthropocene: a review of human impacts during a period of rapid global environmental change. *Journal of Soils and Sediments*, *20*, 4115-4143.

Panagos, P., Ballabio, C., & Borrelli, P. (2015). Rainfall erosivity and soil erosion in Europe: An assessment based on RUSLE, historical data, and geospatial tools. Journal of Hydrology, 528, 535-544.

Panagos, P., Borrelli, P., & Meusburger, K. (2015). Soil erosion in Europe: Major drivers, challenges, and policy recommendations. Environmental Science & Policy, 55(3), 53–64.

Panagos, P., Borrelli, P., Meusburger, K., & Ballabio, C. (2015). Rainfall erosivity and soil erosion risk in Europe: A synthesis. European Soil Bureau Research, 112, 118–128. https://doi.org/10.1016/j.ecolind.2015.05.015Renard, K. G., & Foster, G. R. (1983). Soil erosion and conservation practices. Soil Conservation Society of America.

Poesen, J., et al. (2003). Gully erosion and environmental change: Importance and research needs. *Catena*, 50(2–4), 91–133.

Renard, K. G., & Foster, G. R. (1983). The Revised Universal Soil Loss Equation (RUSLE) and its application in soil erosion studies. Journal of Soil and Water Conservation, 38(3), 232–239.

Renard, K.G., et al. (1997). *Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE)*. USDA Agriculture Handbook 703.

Rupesh, S. (2017). Soil erosion and sedimentation: Impact on water reservoirs. Water Resources Management, 31(9), 2909–2921. https://doi.org/10.1007/s11269-017-1768-4

Sadeghi, S. H., & Haghparast, S. (2017). Assessment of soil erosion risk using GIS and RUSLE model: A case study in the semi-arid region of Iran. Environmental Earth Sciences, 76(9), 322-331.

Tadesse, M., Kassa, B., & Berhanu, A. (2018). Deforestation and soil erosion in Ethiopia's highlands. Environmental Conservation, 44(1), 50–58.

Tegegne, A. (2014). Farmer perceptions on soil erosion in Ethiopia: A review. Land Degradation and Development, 25(6), 504–517.Teshome, S., & Desta, B. (2019). Soil erosion and conservation practices in the Lake Koka watershed. Journal of Soil Science and Environmental Management, 25(6), 58–65.

Tsegaye, B. (2019). Effect of land use and land cover changes on soil erosion in Ethiopia. *International Journal of Agricultural Science and Food Technology*, *5*(1), 26-34.

UN (2015). Transforming our World: The 2030 Agenda for Sustainable Development. United Nations General Assembly.

UNCCD (2017). Achieving Land Degradation Neutrality. United Nations Convention to Combat Desertification.

Vanacker, V., et al. (2005). Controlling factors of erosion patterns in a degraded mountain environment: The geomorphic and hydrologic impacts of land cover change in the Andes of southern Ecuador. *Earth Surface Processes and Landforms*, 30(3), 231–249.

Yigezu Wendimu, G. (2021). The challenges and prospects of Ethiopian agriculture. *Cogent Food & Agriculture*, *7*(1), 1923619.

Yimer, F., Tadesse, F., & Tesfaye, H. (2015). The socioeconomic impact of soil erosion in rural Ethiopia. African Journal of Agricultural Economics, 23(4), 92–105.

Zeleke, G., & Hurni, H. (2001). Land degradation in the Ethiopian highlands: A review of the environmental problems and strategies for sustainable land management. Agriculture, Ecosystems & Environment, 84(2), 141–155.

Zerihun, W., Tadesse, T., & Girmay, G. (2016). Farmers' perceptions of soil erosion and its impact on land productivity in Ethiopia. Environmental Science and Policy, 62, 101–109.Zewdu, D., Belay, A., & Berhanu, G. (2021). Sedimentation and soil erosion in the Lake Koka watershed. Hydrological Processes, 35(3), 276–290.

Zhang, Q., & Wang, C. (2020). Natural and human factors affect the distribution of soil heavy metal pollution: a review. *Water, air, & soil pollution*, *231*, 1-13.

Zhang, X.C., Nearing, M.A., et al. (2004). Soil erosion modeling: A review of new approaches and challenges. *Journal of Soil and Water Conservation*, 59(4), 191–199.