EXPLORING BEST SOIL CONSERVATION PRACTICES USING THE TOLERABLE SOIL LOSS LIMIT IN CENTRAL HIGHLAND OF ETHIOPIA: A CASE STUDY OF ANDIT TID WATERSHED

MSc. Thesis

Tilahun Getachew Abebe

June 2024

Debre Berhan, Ethiopia

EXPLORING BEST SOIL CONSERVATION PRACTICES USING THE TOLERABLE SOIL LOSS LIMIT IN CENTRAL HIGHLAND OF ETHIOPIA: A CASE STUDY OF ANDIT TID WATERSHED

A Thesis Submitted to the Department of Natural Resources Management, College of Agriculture and Natural Resources Science, School of Graduate Studies

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In Partial Fulfillment of the Requirements for the Degree of Master Science (MSc) in Soil and Water Conservation

Tilahun Getachew Abebe

Advisors: Tesfaye Mebrate (Ph.D.)
Estifanos Lemma (Ph.D.)
Tesfa Worku (Ph.D.)

June 2024

Debre Berhan, Ethiopia

SCHOOL OF GRADUATE STUDIES

COLLEGE OF AGRICULTURE AND NATURAL RESOURCE SCIENCE

DEBRE BERHAN UNIVERSITY

APPROVAL SHEET-I

This is to certify that the thesis entitled "**Exploring Best Soil Conservation Practices Using the Tolerable Soil Loss Limit in Central Highland of Ethiopia: A Case Study of Andit Tid Watershed**", which was submitted in partial fulfillment of the requirement for the degree of Master Science Natural Resource Management with specialized in Soil and Water Conservation of the Graduate Program of the Department of Natural Resource Management, College of Agriculture and Natural Resource Science, Debre Berhan University, is a record of original research carried out by ***Tilahun Getachew Abebe (ID No. DBU1500166*)** under my supervisors No part of the thesis has been submitted for any other degree or diploma.

The assistance and help received during the course of this investigation have been duly acknowledged. Therefore, I recommend that it be accepted as fulfilling the thesis requirements.

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Name of Major Advisor	Signature	Date

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APPROVAL SHEET-II

We, the undersigned members of the Board of examiners of the final open defense by ***Tilahun Getachew Abebe,*** have read and evaluated the this entitled "**Exploring Best Soil Conservation Practices Using the Tolerable Soil Loss Limit in Central Highland of Ethiopia: A Case Study of Andit Tid Watershed**"**,** and examined the candidate. This is therefore to certify that the thesis has been accepted in partial fulfillment of the requirement for the degree of Master of Science in ***Soil and Water Conservation.***

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Name of Chairperson	Signature	Date
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Name of Major Advisor	Signature	Date
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Name of Internal Examiner	Signature	Date
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Name of External Examiner	Signature	Date

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Tilahun Getachew Abebe

June 2024

DEDICATION

This work is dedicated to loving memory to my parents. I extend my heartfelt wishes for long life and good health to my mother, Enani Alemayehu. To my father, Priest Getachew Abebe, who passed away while I was pursuing my MSc program, I offer my sincerest prayers. May the Creator grant him eternal rest in the embrace of Abraham, Isaac, and Jacob in a serene paradise.

STATEMENT OF THE AUTHOR

I declare that this thesis entitled "**Exploring Best Soil Conservation Practices Using the Tolerable Soil Loss Limit in Central Highland of Ethiopia: A Case Study of Andit Tid Watershed**" is my genuine work and all sources of the materials used for this thesis have been profoundly acknowledged. The thesis has been submitted in partial fulfillment of the requirements for Master science (MSc) in **"Soil and Water Conservation"** to the graduate studies of college of Agriculture and Natural Resource Science, Debre Berhan University by **Mr. Tilahun Getachew Abebe *(ID No. DBU1500166*)** and it is deposited at the University library to be made available for users under the rule of the library. I intensely declare that this thesis is not submitted to any other institution anywhere for the award of any academic degree, diploma or certificate.

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Name: Mr. Tilahun Getachew Abebe **Signature: _________________**

Place: College of Agriculture and Natural Resource Sciences, Debre Berhan University.

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ACRONYMS AND ABBREVIATIONS

Ao	Semivariogram Range
ASE	Absolute Standardize Error
C	Partial sill
Co	Nugget Value
BD	Bulk density
BL	Baseline Scenario
BSCPs	Best Soil Conservation Practices
CN	Curve Number
DBARC	Debre Berhan Agricultural Research Center
DEM	Digital Elevation Model
ERDAS	Earth Resource Data Analysis System
FAO	Food and Agriculture Organization
GIS	Geographic Information System
GPS	Geographic Positioning System
GT	Grass Strip Scenario
HRU	Hydraulic Response Unit
InVEST	Integrated Valuation of Ecosystem Services and Tradeoff
K	Soil Erodibility
Ks	Hydraulic Conductivity
LULC	Land Use and Land Cover
MUSLE	Modified Universal Soil Loss Equation
NGOs	Non-Governmental Organizations
NSE	Nash-Sutcliffe efficiency
OC	Organic Carbon
OK	Ordinary Kriging
OLI-TIRS/C2/L2	Operational Land Imager and Collection 2 Level-2
PBIAS	Percent Bias
RMSE	Root Mean Square Error
RMSSE	Root Mean Square Standardize Error
RSR	Observation Standard deviation ratio
RUSLE	Revised Universal Soil Loss Equation

SCRP	Soil Conservation Research Program
SCS	Soil Conservation Service
SDR	Sediment Delivery Ratio
SLSUBBSN	Average slope length
SUFI	Sequential Uncertainty Fitting
SWAT	Soil and Water Assessment Tool
SWAT-CUP	SWAT -Calibration and Uncertainty Program
SWC	soil and water conservation
TSLL	Tolerable Soil Loss Limit
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation
GDP	Gross Domestic Product
SSB	Stone/Soil bund Scenario
SSB & GT	Stone/Soil Bund and Grass Strip Scenario
SSB & RF	Stone/Soil bund and Reforestation Scenario
SOM	Soil Organic Matter
SRTM	Shuttle Radar Topography Mission
SW	Sub Watershed
TSLL	Tolerable Soil Loss Limit
USGS	United States Geological Survey
WLRC	Water and Land Resource Center

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ABSTRACT

Soil erosion presents a significant challenge in Ethiopia. In response, Ethiopia has undertaken ongoing watershed development campaigns. Scholars are actively engaged in estimating erosion rates, identifying hotspot areas, and assessing the effectiveness of implemented and potential soil and water conservation measures to reduce erosion. This study contributes to these efforts by focusing on tolerable soil loss estimation, identifying erosion hotspot areas, and exploring best Soil Conservation practices (BSCPs) to reduce erosion rates to/ or below tolerable soil loss limits (TSLLs). To achieve these objectives,40 composite soil samples were collected from the study watershed and subjected to laboratory analysis to determine the soil texture, bulk density, pH and organic carbon (OC) content indicators for assessing the TSLL and predicting soil and water assessment tool (SWAT) database parameters. The SWAT model, coupled with the SWAT Calibration and Uncertainty Procedures (SWAT-CUP), was utilized for simulation, sensitivity analysis, calibration, and validation using streamflow and sediment yield data. The calibrated SWAT model was used to assess soil erosion hotspot areas and evaluated the effectiveness of the selected BSCPs: soil and/or stone bund (SSB), grass strip (GT), reforestation (RF), soil and/or stone bund and grass strip (SSB and GT) and soil and/or stone bund and reforestation (SSB and RF). The results revealed that 49.33%, 32.49%, 13.87%, and 4.31% of the area exhibited TSLL values of 12.5, 10.0, 7.5, and 5 t ha^{-1}yr^{-1}, respectively, with 22.9% of the area showing soil loss rates below the TSLL. Furthermore, varying degrees of erosion above the TSLL were observed, with sub watershed SW-12 experiencing the highest erosion rate (47 tha^{-1}yr^{-1}) and sub watershed SW-2 experiencing the lowest (7.8 t ha^{-1}yr^{-1}). Among the evaluated BSCPs, SSB + RF demonstrated the greatest erosion reduction effectiveness at 76.6%, followed by SSB + GT, SSB, RF, and GT, with erosion reduction effectiveness values of 61.7%, 60.0%, 43.3%, and 13.9%, respectively. Based on these findings, SSB + RF is recommended for erosion reduction to or below the TSLL, with implementation priority given to sub watersheds SW-12, SW-10, SW-3, SW-2, and SW-5, which are ranked in descending order of erosion rate severity. During implementation, emphasis should be placed on reforestation of plant species of high ecological importance.

Keywords: Best soil conservation practices, hotspot area, priority sub watersheds, scenarios, SWAT, tolerable soil loss.

1. INTRODUCTION

1.1. Background and Justification

Soil erosion is a pervasive and formidable challenge in the realm of global land degradation and has a profound impact on nations across the globe, with Ethiopia being no exception. In this diverse landscape, characterized by its rich agricultural heritage and vital ecosystems, soil erosion poses a significant threat, not only depleting but also ultimately resulting in the complete loss of fertile soils (Aiello et al., 2015). Although all forms of erosion are problems, sheets and rills are dangerous because they are unnoticed or disregarded by landowners (Hurni, 1983a). These erosional processes are prevalent throughout the country and are coupled with gully erosion in the highland agroecology and with wind erosion in the rift valley area of Ethiopia, as water, wind, and gravity are the primary agents (Nyssen et al., 2004). Eroded materials can be transported over considerable distances, and once the erosive forces lose their material transport carrying capacity, deposition occurs, which is the third phase of erosion, i.e., deposition (Morgan, 2005).

The rate of soil erosion is affected by a multitude of factors. These include the erosivity of the eroding agent, the geomorphological characteristics of the watershed area, soil erodibility, land use type, and various management practices (Aiello et al., 2015; Blanco & Lal, 2008; Desta et al.,2017; Mitiku et al., 2006; Morgan, 2009). Additionally, anthropogenic influences such as tillage systems, overgrazing, deforestation, overcultivation, poorly designed soil and water conservation measures, and inadequate road design also significantly contribute to soil erosion rates (Foster, 1972; Kuznetsov et al., 1998). The current pressure from population growth, driven by the need to generate income through conventional agriculture and urban expansion, further compounds these challenges (Joshi et al., 2016; Pimentel, 1993; Sinha & Joshi, 2012).

The erosion process has both on-site and off-site impacts. Erosion below the threshold level of an area is essential for soil formation unless it becomes more rapid and greater than the tolerable soil loss limit of the area (Blanco & Lal, 2008). It depletes soil fertility and reduces crop productivity while also reducing soil depth within eroded areas. Furthermore, erosion can cause damage to infrastructure, siltation of reservoirs, and contamination of water bodies located far from the erosion site (Belasri & Lakhouili, 2016; Mitiku et al., 2006; Morgan, 2005, 2009). Erosion poses significant social, economic, political, and environmental challenges in developing countries such as Ethiopia (Ananda & Herath, 2003). For example, in Ethiopia, 85% of the population depends on agriculture, a sector contributing 50% of the GDP, employing 85% of the workforce, accounting for 90% of exports, and supplying 70% of industrial inputs (Atsbaha & Tessema, 2012; Wakolbinger et al., 2016). Land degradation due to rapid population growth exacerbates soil erosion issues.

Severe soil erosion necessitates the implementation of soil and water conservation (SWC) and environmental restoration measures to minimize its impacts and enhance productivity by improving soil fertility, depth, and nutrient cycling (Adimassu et al., 2019). SWC measures can transform and restore the environment by addressing erosion factors, including decreasing slope length, reshaping slope steepness, reducing runoff volume and speed, improving soil cover, and consequently increasing soil organic matter (SOM) and water holding capacity (Huffman et al.,2013). Ethiopia began implementing soil and water conservation measures through campaigns in the 1970s and 1980s, primarily targeting highland areas to address soil erosion and increase crop production (Herweg & Ludi, 1999). Since then, recommended SWC structures such as soil bunds, stone bunds, stone-faced soil bunds, graded Fanyaa juu, hillside terraces, bench terraces, waterways, cutoff drains, trenches, micro basins, and half-moons have been widely implemented across Ethiopia (Gebrernichael et al., 2005; Tesfaye et al., 2019). Most SWC initiatives have focused on degraded areas with limited production potential. Combatting land degradation through investment in SWC is crucial for achieving sustainable land management (Hurni et al., 2010). These implementations were also assisted by different nongovernmental organizations (NGOs) (Meresa et al., 2023; Strohmeier, 2016; Tefera & Sterk, 2010; Walie, 2016).

The government of Ethiopia, with close collaboration with the Institute of Geography at the University of Bern (Switzerland) and the Ethiopian Minister of Agriculture, soil and water conservation department, established seven soil conservation research program watersheds in different parts of the country, representing various agroecology, including Afdeyu, which is located in Eritrea (Herweg & Ludi, 1999). The primary purpose of these watersheds is to monitor soil erosion and identify critical factors to inform the construction of effective soil and water conservation measures. The Andit Tid watershed, which is located in the North Shewa Zone, Amhara region, is one of these learning and monitoring watersheds and represents the highland parts of the country (Herweg & Ludi, 1999). Several studies have been conducted in watersheds, including studies aimed at assessing erosion hotspot areas and erosion rates within watersheds (Desalegn et al., 2018; Yohannes & Soromessa, 2018).

1.2. Problem Statement

The Andit Tid watershed experiences significant soil erosion due to its steep topography, high rainfall, and extensive land cover changes (Desalegn et al.,2018; Hurni,1985; Yohannes & Soromessa, 2018). Additionally, the watershed is characterized by traditional farming practices and overgrazing, which further contribute to erosion issues. Scholars have consistently highlighted the severity of soil erosion in this watershed over time. For instance, Yohannes & Soromessa, (2018) reported soil loss ranging from 10 to 864 t ha^{-1} yr^{-1}, with more than 85% of the area affected by losses exceeding 60 t $ha^{-1}yr^{-1}$. Similarly, Desalegn et al., (2018) reported an average annual soil loss rate of 22.3 t $ha^{-1}yr^{-1}$, indicating an acute erosion problem in the watershed.

Despite various scholarly research efforts addressing different objectives within the watershed, there remains limited concrete evidence regarding the effectiveness of interventions, with little consideration given to establishing a tolerable soil loss limit (Desalegn et al., 2018; Gessesse et al.,2017; Tegenu Ashagrie, 2009). Since its establishment in 1981, the Andit Tid watershed has been monitored by the Soil Conservation Research Program (SCRP) and the Water and Land Research Center (WLRC) project with the focus of stream flow, weather, and suspended sediment-related data collection, with identification of critical factors for effective soil and water conservation measures. However, currently monitored by the Debre Berhan Agricultural Research Center (DBARC) with less emphasis on developing practical solutions to mitigate erosion rather collection and analysis of weather, stream flow and sediment yield data of the watershed, it exposed for sever erosion though (Desalegn et al., 2018). This ongoing erosion problem underscores the urgent need for effective intervention strategies in the watershed.

Although on-ground evaluation of soil and water conservation measures is difficult in terms of time and cost, Herweg & Ludi, (1999) attempted to evaluate the effectiveness of selected conservation measures in the Andit Tid watershed at the plot level on cultivated land with 24% slope steepness. This study reported up to 73% and 33% soil loss and runoff reduction effectiveness of grass strips, respectively. However, it is important to note that variations in slopes, land use, soil types, and complex long-term climate conditions were not considered. This limitation arises from the difficulty of managing these factors simultaneously and manually. As in the other subsequent studies conducted in watersheds by Desalegn et al., (2018) andYohannes & Soromessa (2018), the concept of a tolerable soil loss limit specific to watersheds was not incorporated in the study conducted by Herweg & Ludi, (1999).

Despite numerous research efforts in Ethiopia, watershed-based research approaches are crucial due to the country's rich diversity in agroecological, soil, rainfall, and geological characteristics. This approach enables the identification of watershed-level problems and the development of effective remedial solutions within a relatively short timeframe. It also facilitates engagement among communities, policymakers, and researchers in SWC and watershed development initiatives.

Hence, this study aimed to identify erosion hotspot areas, assess erosion rates, and establish a tolerable soil loss limit for the watershed. Furthermore, this study seeks to evaluate the effectiveness of individual and integrated soil and water management practices in reducing soil erosion to a level that meets or falls below the tolerable soil loss limit of the watershed. The findings of this research are anticipated to provide significant contributions to sustainable land management and conservation endeavors in the region.

1.3. Research Objectives

1.3.1. General Objective

The aims of this study were to identify erosion hotspot areas and best soil conservation practices for soil loss, considering tolerable soil loss limits at the sub watershed level in the central highlands of Ethiopia.

1.3.2. Specific Objectives

The specific objectives of the study to:

1. Determine the tolerable soil loss limit at the sub watershed level.
2. Identify erosion hotspot areas of the Andit Tid sub watershed and
3. Identify the best soil conservation practices for erosion hotspot areas

1.4. Research Question

To meet the research objectives and test the adjusted hypothesis, the following research questions will be addressed.

1. How is the trend of erosion hotspot areas within the watershed located?
2. Is the erosion rate within the watershed exceeding the established tolerable limit?
3. What are the best soil conservation practices that can reduce soil loss within a watershed to a level that meets or falls below the tolerable soil loss limit?

1.5. Significance of the study

Effective management of natural resources, particularly through the adoption of soil and water conservation measures, necessitates a thorough evaluation of erosion rates and the maximum permissible soil loss rate within the watershed. This evaluation helps ascertain the extent of erosion impact, pinpoint areas most susceptible to erosion, and determine the severity of erosion, thereby guiding the prioritization of mitigation efforts. Moreover, it aids in identifying optimal management practices to curb soil loss and maintain it within acceptable limits.

Consequently, this study provides crucial insights to various stakeholders, such as students, farmers, researchers, agricultural authorities, nongovernmental organizations (NGOs), and policymakers. With this information, stakeholders can take proactive steps toward addressing erosion and promoting watershed restoration. Furthermore, this study serves as a reference point for stakeholders, facilitating the assessment of erosion severity vis-à-vis the maximum allowable soil loss rate and the selection of suitable best soil conservation practices (BSCPs) tailored to the country’s needs.

In addition to environmental benefits, the implementation of these measures enhances the fertility and productivity of the watershed. It also contributes to the socioeconomic development of the community by fostering sustainable land management practices.

1.6. Scope of the Study

This study focused on the biophysical aspects of watershed characteristics rather than socioeconomic factors due to time and budget constraints.

2. LITRATURE REVIEW

2.1. Soil Erosion Definition

Soil erosion refers to the process by which soil is displaced from its original location by various erosion agents, including water, wind, glaciers, or gravitational pull (Morgan, 2009). This process involves three distinct phases: detachment, transport, and deposition. Detachment and transport are responsible for the disintegration and movement of soil particles, while deposition occurs when the erosive agent loses the energy required to carry and transport these particles (FAO,2019). Two main types of erosion, geological and accelerated, are distinguished based on their underlying nature (Sharma & Singh, 2019). Geological erosion occurs naturally at a rate equivalent to soil formation, whereas accelerated erosion results from anthropogenic factors and occurs at a rate faster than soil formation (Humberto & Rattan, 2008)

Among the various types of erosion, water erosion is the most prevalent and severe worldwide (Humberto & Rattan, 2008). This process involves the disintegration of soil particles from the soil mass, known as splash erosion, caused by the impact of raindrops and the force exerted by flowing water. The detached soil particles are then washed away by flowing water, forming a thin layer of sheet erosion over the surface. As the runoff volume increases, the runoff becomes concentrated, leading to the formation of rill and gully erosion, which are more severe forms of water erosion. Ultimately, when flowing water loses its ability to transport soil particles or encounters surface barriers such as vegetation or conservation measures, deposition occurs in the third phase of erosion (FAO, 2019).

2.2. Causes of Soil Erosion in Ethiopia

Anthropogenic factors such as rapid population growth, cultivation on steep slopes, deforestation, and overgrazing are the primary drivers of soil erosion in Ethiopia (Desta et al., 2017). Hawando, (1997) highlights the exceptionally high population growth in the Ethiopian highlands, outstripping available productive land. Consequently, to meet basic needs, the population extensively cultivates every available piece of land, resulting in severe erosion. Additionally, factors such as topography, soil type, intense rainfall, and poor land management practices contribute to the formation of erosive runoff, particularly in the northern and central highlands of Ethiopia (Dubale, 2001). Similarly, (Amede et al., 2001) underscores the depletion of vegetation cover and increased farming on steep slopes due to population growth, leading to elevated levels of soil erosion in the Ethiopian highlands. The mountainous and hilly terrain, coupled with heavy rainfall and limited vegetation cover, further exacerbates erosion in these regions (Esser et al., 2022)

Consistent with these findings, cultivation on steep slopes, intensified farming practices without fallowing, inadequate implementation of conservation measures, lack of land ownership, deforestation, overgrazing, utilization of crop residue for animal feed and fuel, and heavy rainfall are identified as major contributors to soil erosion (Adimassu et al., 2014; Gashaw et al., 2014). The complex interplay of these factors underscores the multifaceted nature of soil erosion in Ethiopia, as shown below (Figure 1).

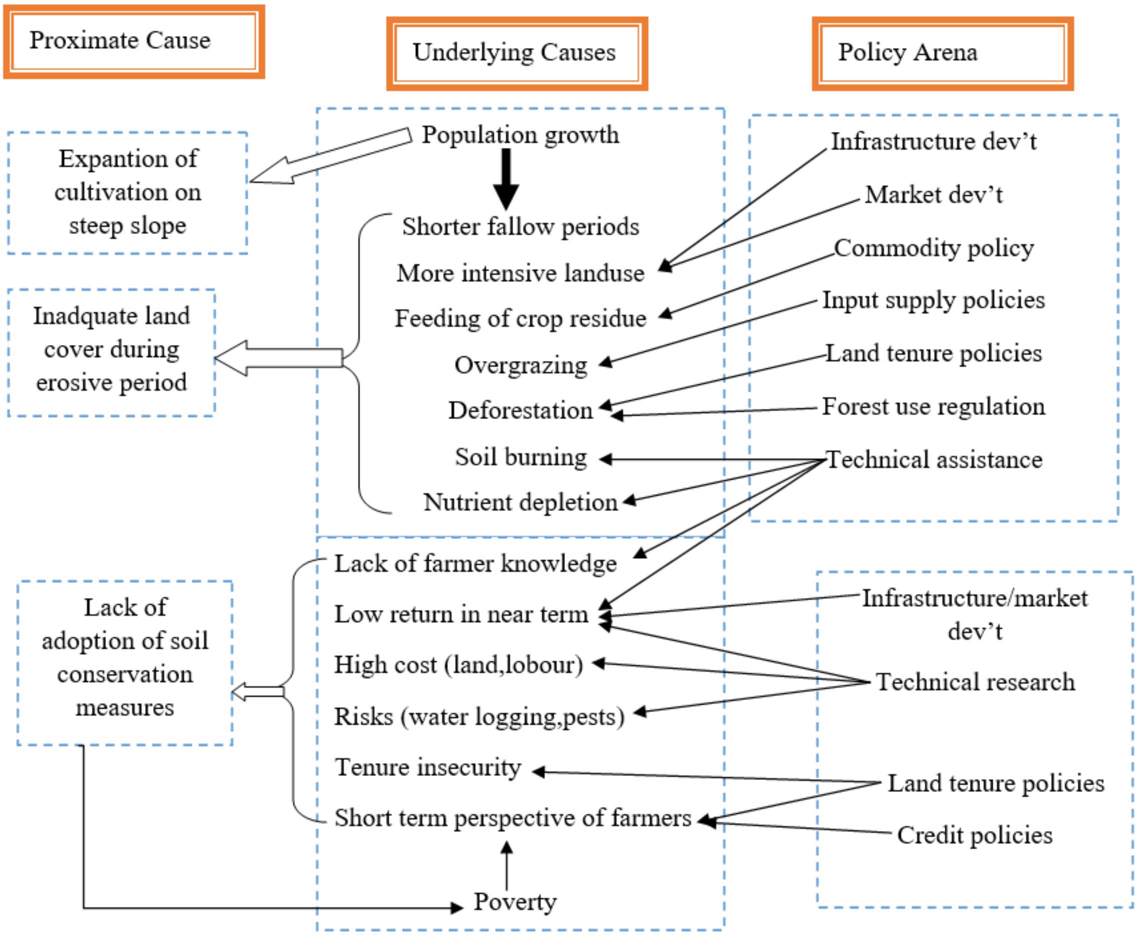


Figure 1. Causes of soil erosion adopted from adapted from Desta et al. (2017)

2.3. Extent of Soil Erosion in Ethiopia

Soil erosion is a critical issue in Ethiopia, particularly in its highland regions (Hurni, 1985). Recent estimates indicate a mean soil loss rate for Ethiopia of 16.5 t ha^{-1} yr^{-1}, with maximum rates reaching 200 t ha^{-1} yr^{-1} in steep slope areas (Haregeweyn et al., 2015). The central and northern highlands are disproportionately affected by erosion compared to the southern regions of the country (Gashaw et al., 2018). This disparity can be attributed to the fact that the Ethiopian highlands cover 50% of the nation's landmass and provide habitation for 90% of its population, as well as sustenance for 60% of the country's livestock (Hurni et al., 2010). Consequently, the overpopulation and mismanagement of these steep and mountainous lands render the northern and central highlands particularly susceptible to severe erosion (Dubale, 2001), resulting in average soil loss rates ranging from 20 to 80 t $ha^{-1}yr^{-1}$ (Adimassu et al., 2014).

On the other hand, Tamene et al., (2022)conducted a meta-analysis of over 170 peer-reviewed scientific papers and reported erosion rates in Ethiopia ranging from 0 to 220 t $ha^{-1}yr^{-1}$, with an average gross erosion rate of 38 t $ha^{-1}yr^{-1}$. This finding aligns with (Hurni, 1983a)the findings of , who reported 42 t $ha^{-1}yr^{-1}$ on cultivated land and 70 t $ha^{-1}yr^{-1}$ on unproductive land. Erosion rates tend to increase with altitude due to population pressure, high erosivity potential, and increased rainfall distribution. Similarly, Tamene et al., (2022) observed higher erosion rates in moist agroecological zones than in arid zones. The wide range of erosion rates underscores Ethiopia's diverse spatiotemporal dynamics of erosion-controlling factors, particularly in agroecological zones, which result from the combined influences of rainfall and altitude.

Table 1. Agroecological zone-based soil erosion extent in Ethiopia (Tamene et al., 2022)

Agroecological zone	Estimated soil loss rate ± Standard error (t $ha^{-1}yr^{-1}$)
Moist	57.0 ± 4.8
Sub moist	23.6 ± 2.7
Sub humid	29.0 ± 4.1
Arid	28.3 ± 6.5
Semiarid	42.0 ± 6.7
Humid	42.8 ± 15.2

2.4. Impact of Soil Erosion on Agricultural Productivity in Ethiopia

Soil erosion has both onsite and offsite effects, impacting the immediate area where erosion occurs as well as the surrounding environment. Onsite effects include the redistribution of soil within the field, soil removal, breakdown of soil structure, a decrease in soil organic matter content and nutrients, a reduction in cultivable soil depth, and diminished soil fertility (Morgan, 2005). This reduction in soil fertility is considered a significant consequence of water–soil erosion, which directly affects agricultural output (Tamene & Vlek, 2008). The loss of topsoil and breakdown of soil aggregates can alter soil quality, structure, stability, and texture, ultimately weakening the soil structure and changing its characteristics (Nekir, 2019). Globally, approximately 2.6 billion people rely on agriculture, making soil erosion a critical issue with widespread implications (Mitiku et al., 2006).

The offsite effects of erosion also occur through sedimentation downstream, reducing the capacity of rivers and drainage ditches, increasing the risk of flooding, and obstructing canals. This sedimentation can also impair the capacity of hydroelectric power and irrigation dams and contribute to environmental pollution (Morgan, 2005). In Ethiopia, soil erosion and nutrient loss result in annual losses of approximately $106 million, exacerbating poverty and food insecurity, particularly in rural areas (Nekir, 2019; Tadesse et al., 2017). Unless managed properly, soil erosion in the highlands could lead to a 30% reduction in land productivity and a decrease of US$21 in agricultural sector value added per capita per annum by 2030 (Nekir, 2019). Addressing soil erosion is therefore crucial for sustainable land use and agricultural development in Ethiopia and beyond.

2.5. Erosion Hot-Spot Areas

Erosion hotspot areas are regions within a catchment characterized by the highest erosion rates and sediment transport capacities (Betrie et al., 2011). Similarly, Mitiku et al.,(2006) defined erosion hotspot areas as parts of the landscape significantly affected by erosion, often identifiable by visible erosion features such as rills and gullies. These areas are particularly susceptible to erosion due to mismanagement of erosion-controlling factors such as land cover, topography, and soil and water management practices. Furthermore, regions in which the erosion rate exceeds the maximum erosion potential are classified as erosion hotspot areas (Hurni, 1983a).

In Ethiopia, the rate of soil formation varies from 2 to 22 t $ha^{-1}yr^{-1}$ (Hurni,1983a). Consequently, areas experiencing soil loss exceeding the average soil formation rate are classified as erosion hotspot areas requiring urgent intervention (Gashaw et al.,2021). Extensive research has been conducted in highland areas of Ethiopia to identify erosion hotspot areas, enabling the prioritization of site-specific management practices (Gashaw et al.,2021).

2.6. Tolerable Soil Loss Limit (TSLL)

The tolerable soil loss limit (TSLL) refers to the maximum allowable rate of soil erosion that still maintains soil fertility and ecological quality (Stefano et al., 2000; Stefano & Ferro, 2016). According to (Xingwu et al., 2012), it represents the highest rate of soil erosion that can be sustained economically and indefinitely while ensuring high crop productivity. The TSLL serves as a crucial criterion for determining the necessity of implementing soil conservation measures to preserve watershed fertility and ecological integrity (Liu, 2009).

Two key factors influencing TSLL are soil thickness and vulnerability to erosion (Xingwu et al., 2012). Often, the TSLL is compared with the soil formation rate to assess watershed erosion vulnerability, with the difference between soil formation and erosion rates indicating erosion susceptibility (Centeri, 2016). In the Ethiopian highlands, the TSLL has been estimated to range from 2 to 22 t $ha^{-1}yr^{-1}$ (Hurni, 1985). Scholars have employed various methods to estimate the TSLL of watersheds, highlighting its importance in guiding the implementation of soil and water conservation measures (Bagarello et al., 2010; Mandal & Sharda, 2011; Stefano et al., 2023). Establishing TSLL is essential for developing effective guidelines for soil and water conservation technologies (Gangcai et al., 2009).

2.7. Best Erosion Controlling Practices (BECPs)

Watershed management practices involve the strategic implementation of best soil conservation practices (BSCPs) aimed at curbing soil erosion and sediment transport (Betrie et al., 2011). BSCPs encompass a range of physical, chemical, structural, or managerial techniques designed to mitigate soil erosion while concurrently enhancing soil and water quality while ensuring economic viability (Zhao et al., 2022). Many of these practices are established norms recognized for their dual benefits of environmental stewardship and economic sustainability (Zhao et al., 2022). Erosion prevention BSCPs aim to minimize soil movement, while sediment control BSCPs work to intercept soil particles in runoff before they can escape the site or enter waterways (Uniyal et al., 2020). With careful design and implementation, certain BSCPs can fulfill both functions, such as grassed waterways and filter stripes, which not only filter runoff but also divert it away from vulnerable areas. A diverse array of BSCPs exist, spanning structural, biological, agricultural, and channel conservation practices (Uniyal et al., 2020). Agricultural and structural BSCPs are predominantly employed to mitigate soil loss on croplands, specifically by targeting erosion and nutrient runoff (Uniyal et al., 2020). The selection of BSCPs necessitates a comprehensive understanding of the target area, including factors such as land use, soil type, topography, and erosion risk levels (Selassie & Belay, 2013). Additionally, BSCPs selection should align with agro-ecological suitability, utilize local resources, and enjoy familiarity among development agents and farmers (Hurni, 1983).

In the Ethiopian Highlands, stone/soil bunds, reforestation, and filter strips have emerged as the most widely adopted conservation practices (Adimassu et al., 2014). Consequently, BSCPs such as soil/stone bunds, filter strips, and reforestation products hold promise for implementation in the Rib watershed. To evaluate the efficacy of BSCPs, the SWAT model incorporates adjustments to SWAT parameters, reflecting the impact of these practices on simulated processes (Briak et al., 2019). This modeling approach enables the assessment of the effectiveness of BSCPs in reducing sedimentation, as demonstrated in recent studies in our country (Gashaw et al.,2021).

2.8. SWAT Model Description

The Soil and Water Assessment Tool (SWAT) is a sophisticated, semi distributed model developed in the 1990s to comprehend the intricate impacts of agricultural practices on water, sediment, and agricultural chemical contaminants within vast and diverse watersheds (Arnold et al., 2012). Its unique capabilities enable it to provide estimations at both the sub watershed and HRU levels. HRUs are delineated areas within subbasins characterized by distinct land cover, soil types, and slope configurations (Betrie et al., 2011). This hierarchical approach enhances model accuracy by providing a more detailed physical representation of the watershed.

The ability of the model to categorize subbasins into HRUs not only improves accuracy but also enhances the ability to provide a comprehensive physical description. The values obtained from individual HRUs are aggregated to provide a holistic overview of the watershed (Betela, 2015). However, to effectively utilize the SWAT model, diverse spatial and temporal data are essential. Basic information such as topography, land use, soil, and climate is required for model setup and operation. Without these inputs, SWAT cannot accurately estimate water, sediment, and nutrient dynamics. Additionally, measured hydrological, sediment, and nutrient data are invaluable for calibrating and validating the model (Dibaba et al., 2021; Dibaba & Ebsa, 2022).

SWAT employs the Soil Conservation Service (SCS) curve number (CN) method to simulate surface runoff (Bewket, 2007). This method, which is renowned for its computational efficiency, predicts runoff for a given rainfall event based on land use characteristics, soil properties, and hydrological conditions (USDA, 1972). Equations 1 and 2 define surface runoff under the SCS CN method:

$$Q_{sur} = \frac{(R_{daily} - 0.2S)^2}{(R_{daily} + 0.8S)} \; if \; and \; only \; if \; R_{daily} > 0.2S \; unless \; Q_{sur} = 0 \qquad \text{Eq- 1}$$

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \qquad \text{Eq- 2}$$

where Q_{sur} is the surface runoff, R_{daily} is the daily rainfall, S is the surface retention parameter (mm), and CN is the curve number.

For sediment yield prediction, SWAT relies on the modified universal soil loss equation (MUSLE) model, an extension of the universal soil loss equation (USLE) developed by Wischmeier & Smith, (1978) based on rainfall data to estimate soil loss from a watershed. Unlike the USLE, the MUSLE influences runoff rather than solely relying on rainfall, resulting in more accurate sediment yield predictions (Smith & Wischmeier, 1962). Equation 3 also describes the MUSLE model:

$$SY = 11.8 * (Q_{sur} * q_p * A)^{0.56} * K * C * LS * P * F \qquad \text{Eq- 3}$$

$$q_p = \frac{\alpha_{tc} * Q_{sur} * Area}{3.6 * t_c} \qquad \text{Eq-4}$$

where SY is the sediment yield (tone); A is the area (ha); K, C, LS & P are the soil erodibility, crop, slope and management factors of the USLE; F is the percentage of the stoniness accounting factor; α_{tc} is the daily rainfall that occurs at a time of concentration; $Area$ is the subbasin area (km^2); and t_c is the time of concentration.

The versatility of the SWAT model extends to predicting the impacts of various soil and water management strategies, allowing for the assessment of different management alternatives through parameter adjustments (Gashaw et al., 2021)

3. MATERIALS AND METHODS

3.1. Study Area Description

The study was conducted in the Andit Tid watershed, which is located approximately 180 km northeast of Adis Ababa and approximately 50 km northeast of Debre Berhan, the capital city of the North Showa Zone. Geographically, it is located at 39°43’ E and 9°48’ N. The watershed has an altitude range of 3029-3525 meters above sea level. The Andit Tid watershed covers 477.7 ha. The watershed drains to the west, which makes it part of the Blue Nile Basin. The large escarpment that separates the Awash plain from the Shewa Plateau also bounds the watershed from the east side (Tegenu Ashagrie, 2009). The slope of the watershed ranges from 0-8% to >60%, with the area coverage of 5.02% to 3.24%. The area with a slope of 30-60% covers 49.01% of the watershed, followed by 15-30%, which covers 31.63% of the watershed area.

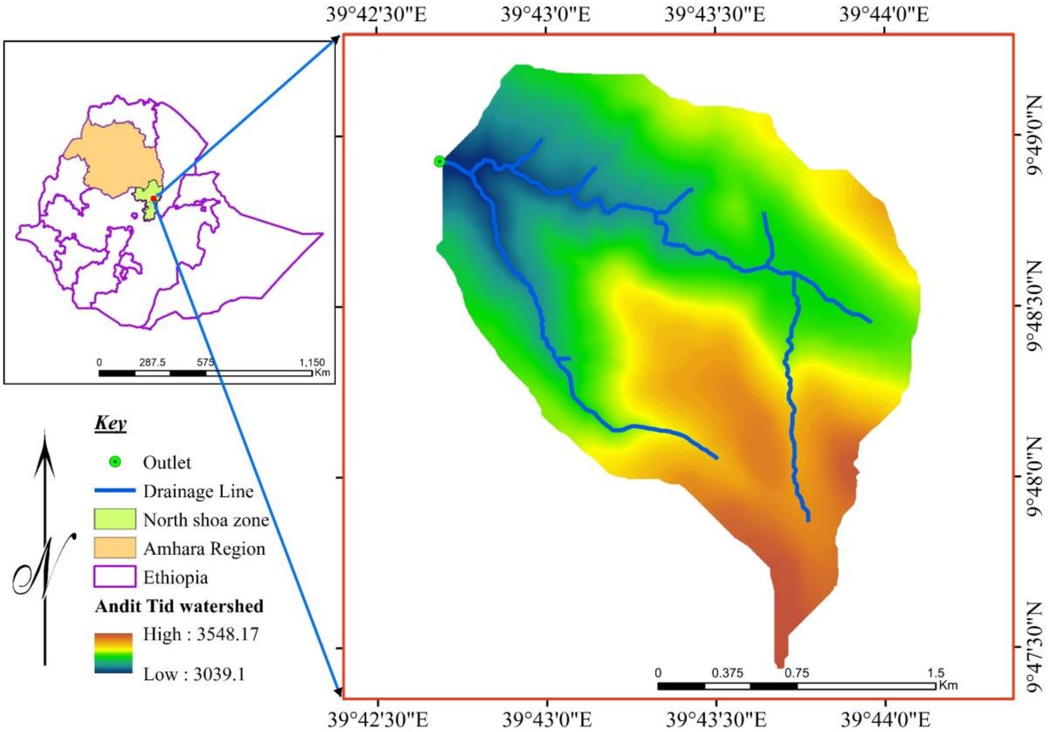


Figure 2. Location of Andit Tid watershed in the Central Highlands of Ethiopia area

The area receives 1360-1940 mm of annual rainfall, with an average rainfall of 1630mm. The watershed experiences a bimodal rainfall pattern, with a shorter rainy season from March to May and a longer rainy season from July to October (Figure 3). This difference in rainfall distribution, coupled with its altitudinal difference, caused the watershed to have

Moist Highland (24.5%) and Wurch (75.5%) agroecology. The two main rivers, Wadyat and Gudibado, drain the catchment to the west and confluence at a distance of approximately 150 m above the stream flow gage station, which is installed at the highway bridge crossing the main river. Both rivers arise from the upper portion of the watershed, which is covered by grass species. The average minimum and maximum temperatures of Andit Tid watershed is 7.50°C and 17.62°C, respectively.

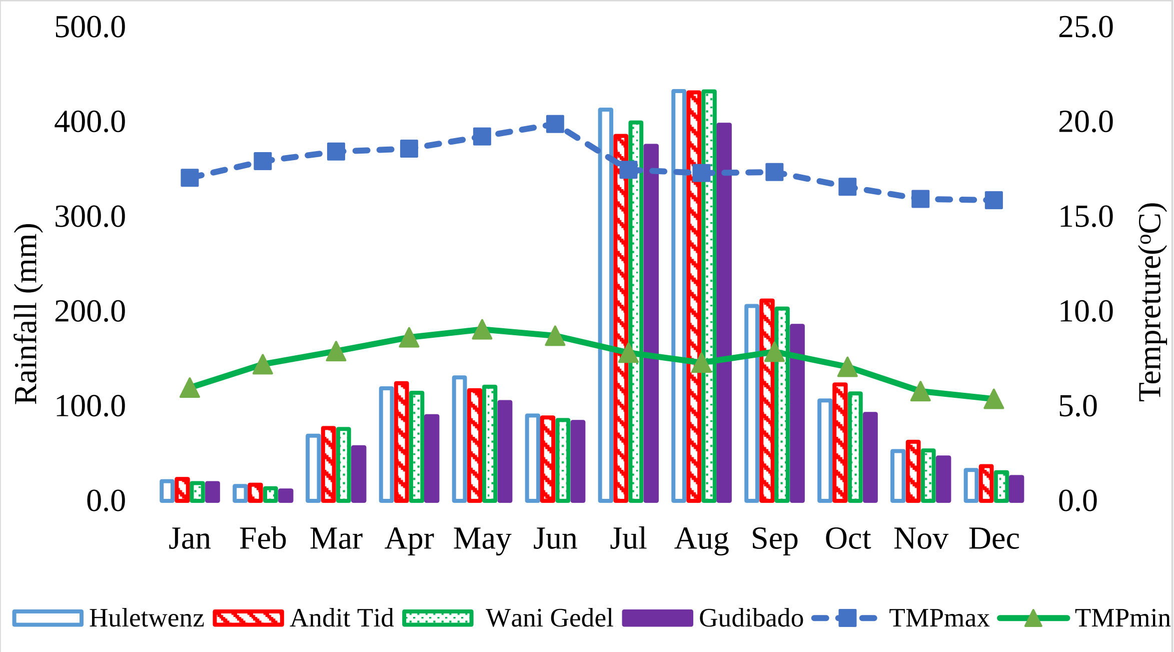


Figure 3. Temporal distribution of rainfall and temperature within the study area

Tertiary volcanic rocks, such as rhyolite, trachites, tuffs and basalts, are the parent materials for the development of soil in the area. Humic and ochric Andosols, which cover 66% of the watershed, are important soil types in terms of quality and extent, especially in the upper part of the watershed, followed by Regosols (32%), Fluvisols (1%) and Lithosols (1%)(WLRC, 2024).

Cultivated land (56.05%), shrub/bushland (11.5%), forestland (7.28%), and grassland (25.18%) are the main land uses of the watershed. Cereal crops are commonly cultivated in areas where the dominant crop is rare. Wheat, linseed, peas and beans are also common cultivated crops. According to Tegenu Ashagrie Engda, (2009), the productivity of this area is decreasing due to the increase in land pleasure and the resulting decrease in fallowing time as well as the use of natural fertilizers such as animal manures for fuel. This leads to farmers having limited income and being unable to buy fertilizers to improve land productivity. The area follows a mixed crop-livestock farming system with the main reared animals being cattle, sheep, donkeys, horses, and hens, while lentils, Faba bean, and barley are the main cultivated crops (Gessesse et al., 2017; Herweg & Ludi, 1999).

3.2. Study Design

The general methodology of this study relies on primary and secondary data collected from the field, websites, and different organizations. The analysis of these data was conducted in a way that generated information to meet the research objectives. The data collection data quality check and filling of missing data; development of soil and water conservation measure scenarios; adjustment of the model setup, simulation, sensitivity analysis, calibration and validation; and analysis of the results to achieve the objectives were performed. The general framework of the study is displayed in the following flow chart.

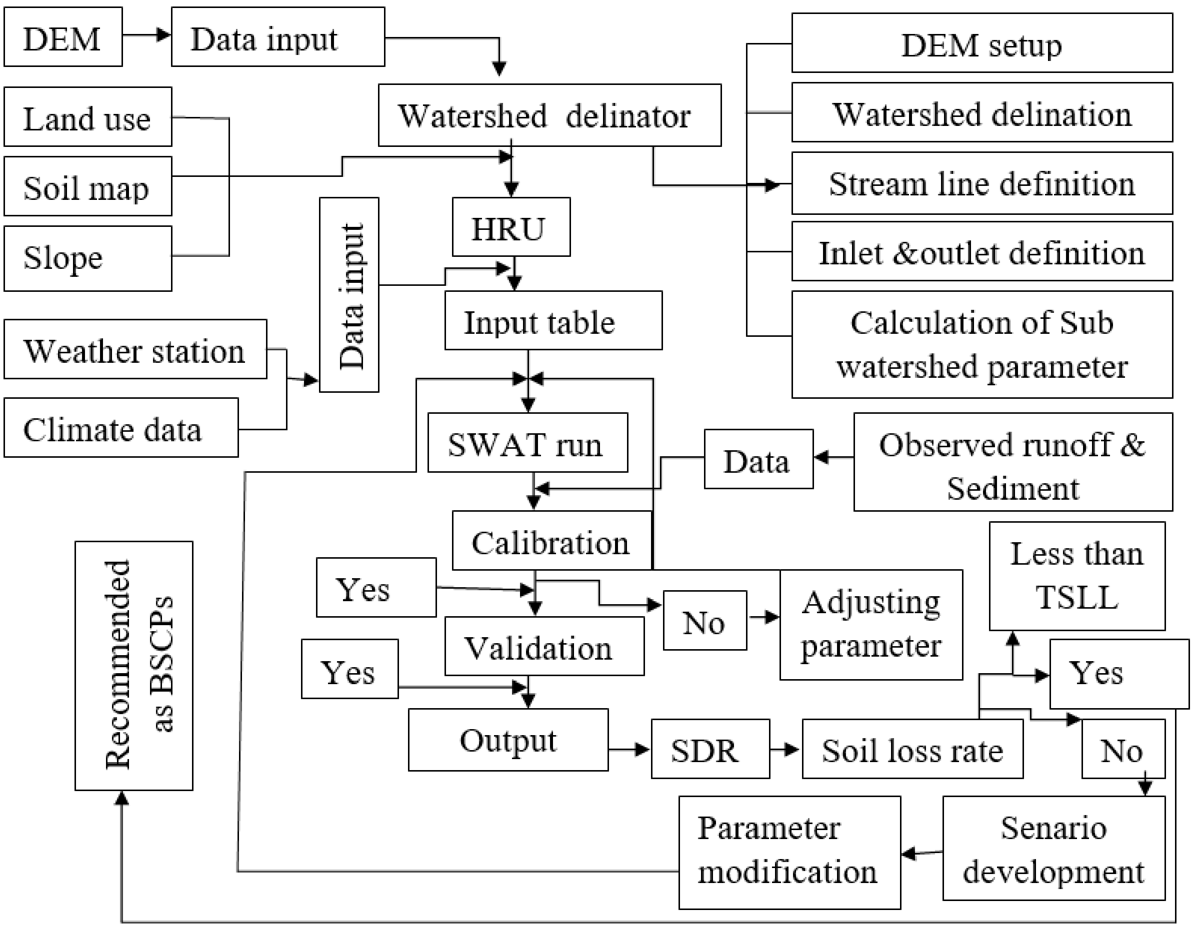


Figure 4. The conceptual framework of the study

3.3. Assessment of the Tolerable Soil Loss Limit (TSLL)

3.3.1. Soil Sampling and Analysis

Although various frameworks have been developed by different scholars such as Duan et al., (2017) and Xingwu et al., (2012) to estimate Tolerable Soil Loss Limit (TSLL), this study utilized the biophysical model outlined by (Mandal & Sharda, 2011). This model was selected because of its comprehensive consideration of key soil properties that have a function related to soil erosion (Ahmed, 2019). These soil properties include saturated hydraulic conductivity, soil erodibility, soil organic matter content, soil bulk density, and soil pH.

To assess soil properties across the watershed, a total of 40 composite soil samples were systematically collected using an auger for analysis of soil texture, organic matter content, soil pH, and hydraulic conductivity. The sampling points were strategically located based on the land use type, which was categorized into three slope positions: lower, middle, and upper. The spacing between sampling points was determined by the variability of soil observed during field assessments within each specific land use type. Soil samples were then collected at a depth of 0-20 cm from the left corner, center, and right corner of each categorized slope position. From each categorized slope position, one kilogram (kg) of composite soil sample was carefully collected, labeled, and securely packaged in plastic bags for transportation to the laboratory. Additionally, undisturbed soil samples were collected from the central location of each slope position within the categorized land use type using a core sampler (5 cm diameter × 5 cm height) for bulk density analysis. About 40 soil depth data were also collected simultaneously at the location of central topographic position within the identified land use category through excavation of soil pits (Figure 5). The soil depth excavated until 150 cm depth unless the bedrock was not found minor of this depth. All sampling points were accurately geo-referenced using handheld Global Positioning System (GPS) devices to ensure precise spatial data. Subsequently, the collected soil samples were analyzed at the Debre Birhan Agricultural Research Center (DBARC) soil laboratory. Prior to analysis, the samples were air-dried at room temperature, ground, and sieved to separate particles larger than 2 mm for texture and pH analysis and particles larger than 0.5 mm for organic carbon analysis(Jones, 2001).

Bulk density (BD) was evaluated using the core method (Blake, 1965). The core soil samples were oven-dried at 105°C for 24 hours until a consistent weight was reached. The weight of the dried soil was then divided by the volume of the core sampler to calculate the bulk density (ICARDA, 2013). To determine the soil particle size distribution, the hydrometer method was employed, leveraging the differential settling velocities of particles within a water column (Bouyoucos,1962). Soil pH was measured using a pH meter with a combined electrode in a water suspension with a 1:2.5 (w/v) ratio (Thomas, 1996). The soil organic carbon content was determined following the method outlined by Walkley & Black,(1934). All analyses followed the procedures outlined in the soil laboratory manual (ICARDA, 2013). The laboratory results for bulk density, organic carbon, and pH were directly incorporated into every aspect of the study.

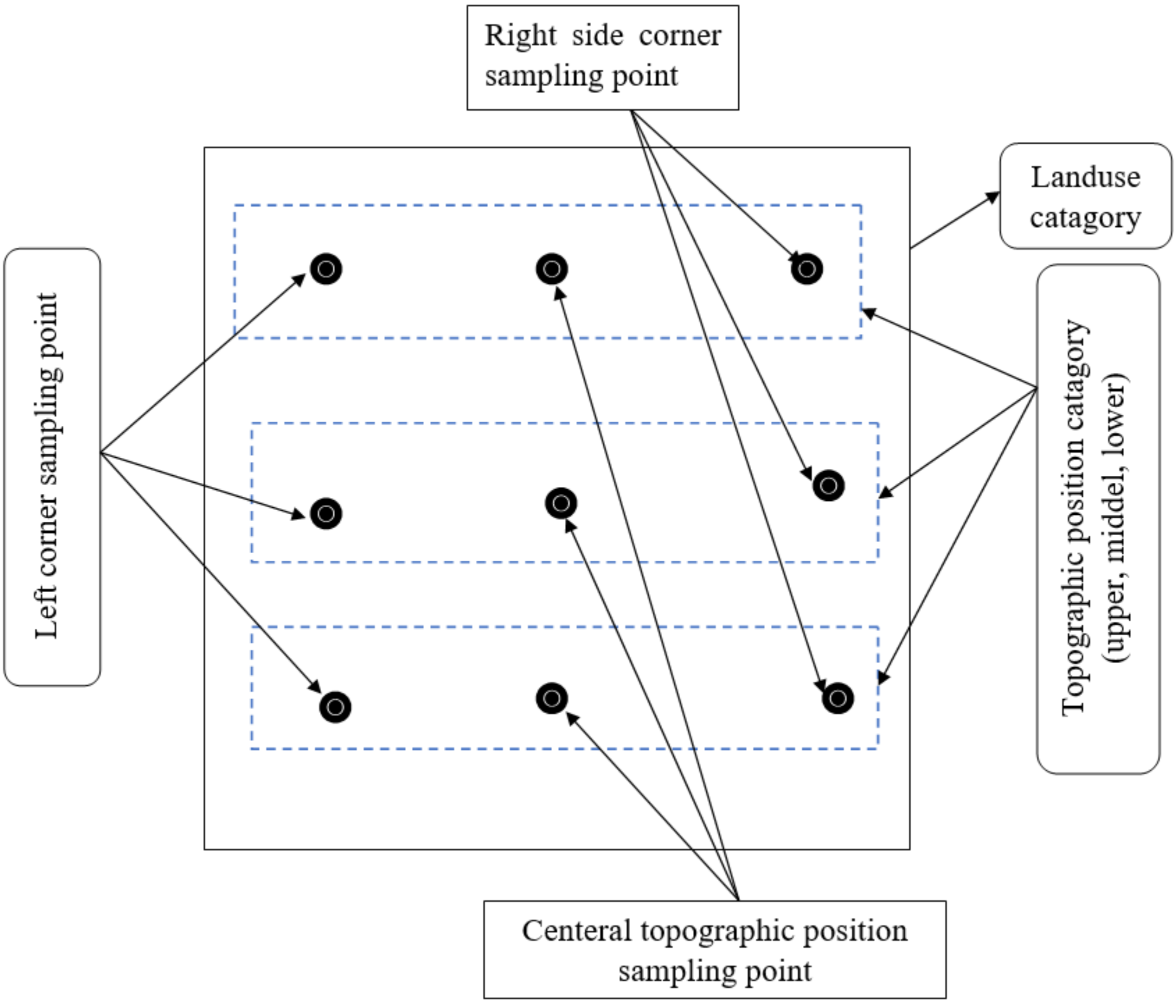


Figure 5. Schematic design of soil data sampling point

3.3.2. Soil Quality Indicator Factor Generation

The laboratory results for bulk density, organic carbon, and pH were directly incorporated into every aspect of the study.

3.3.2.1. Soil Erodibility (K)

The erodibility status of the soil was calculated using the equation below (Williams, 1995), as cited by (Wawer et al., 2005).

$$\mathbf{K_{USLE} = K_W = f_{csand} * f_{ci-si} * f_{orgc} * f_{hisand}} \qquad \text{Eq-5}$$

$$\left(\mathbf{f_{csand}} = (\mathbf{0.2 + 0.3 * exp}\left[-\mathbf{0.256 * m_s} * \left(\mathbf{1} - \frac{\mathbf{m_{sil}}}{\mathbf{100}}\right)\right]\right) \qquad \text{Eq-6}$$

$$\text{fcl} - \text{si} = \left(\frac{\mathbf{m_{silt}}}{\mathbf{m_c + m_{silt}}}\right)^{\mathbf{0.3}} \qquad \text{Eq-7}$$

$$\boldsymbol{f_{orgc}} = \left(\mathbf{1} - \frac{\mathbf{0.25} * \boldsymbol{orgc}}{\boldsymbol{orgc} + \boldsymbol{exp}[\mathbf{3.27 - 2.95} * \boldsymbol{orgc}]}\right) \qquad \text{Eq-8}$$

$$\boldsymbol{f_{hisand}} = \left(\mathbf{1} - \frac{\mathbf{0.7} * \left(\mathbf{1} - \frac{m_s}{100}\right)}{\left(\mathbf{1} - \frac{m_s}{100}\right) + \boldsymbol{exp}\left[-\mathbf{5.51 + 22.9} * \left(\mathbf{1} - \frac{m_s}{100}\right)\right]}\right) \qquad \text{Eq-9}$$

where $\mathbf{f_{csand}}$ is a factor that lowers the K indicator in soils with high coarse sand content and increases the erodibility factor for soils with little sand; $\mathbf{f_{ci\text{-}si}}$ is a factor that decreases the K value in soils with high organic carbon content; $\mathbf{f_{hisand}}$ decreases the K value for soils with extremely high sand content; $\mathbf{m_s}$ is the sand fraction content (0.05-2.00 mm diameter) [%]; **ms is** the silt fraction content (0.002-0.05 mm diameter) [%]; m_c is the clay fraction content (<0.002 mm diameter) [%]; and org_c is the organic carbon (SOC) content [%].

3.3.2.2. Hydraulic Conductivity (Ks)

Hydraulic conductivity refers to the soil's ability to allow water to flow or permeate through it with ease. This property is significantly influenced by factors such as soil bulk density, organic matter content, and texture. Moreover, there exists an inverse relationship between hydraulic conductivity and soil erodibility (Jadczyszyn & Niedÿwiecki, 2005). Given its importance in assessing a watershed's tolerable soil loss limit, hydraulic conductivity serves as a crucial input parameter.

To estimate hydraulic conductivity, the formula developed by Saxton & Rawls, (2006) was employed. This calculation method provides valuable insights into the soil's capacity to facilitate water movement, thereby aiding in the comprehensive analysis of soil erosion dynamics within the watershed.

$$K_s = 24\mathrm{exp}12.012 - 0.0755 * \mathrm{sand} + [-3.895 + 0.03671 * \mathrm{sand} - 0.1103 * \mathrm{clay} + 0.00087546\mathrm{clay}^2]/\theta_s \quad \text{Eq-10}$$

According to (Arisanty et al., 2022; Hillel, 2003)

$$\theta_s = \emptyset = 1 - \frac{BD}{PD} \quad \text{Eq-11}$$

where Ks is the saturated hydraulic conductivity (ms^{-1}), $\emptyset$ is the soil porosity, sand is the % sand proportion of the soil sample, clay is the % clay proportion of clay in the soil sample, BD is the bulk density, and the PD mineral particle density is 2.65 g cm^3.

The laboratory outputs of bulk density, organic carbon and soil pH were used directly for tolerable soil loss analysis.

3.3.3. Spatial Distribution Modeling of Soil Quality Indicator Parameters

The spatial distributions of the soil parameters (erodibility, organic carbon, hydraulic conductivity, bulk density and soil pH) were determined using ordinary kriging (OK) tech ique since it is the best balanced geostatistical predictor of spatial attributes for unsampled specific locations of random processes and has the ability to reduce the influence of outliers (Behera & Shukla, 2015). Using the OK, the predicted value of the soil parameter at an unsampled location ($Z'(x_o)$) was obtained using the measured value $Z(x_i)$, as given below.

$$Z'(x_o) = \sum_{i=1}^{n} \lambda_i \,.\, Z(x_i) \quad \text{Eq-12}$$

where λ_i is the kriging weight and i is the sampling number.

Prior to utilizing Ok for modeling the soil parameters, the data were subjected to a Shapiro-Wilker outlier test using R software version 4.3.3. An outlier, defined as an observation significantly deviating from others, can impact spatial interpolation performance (Yao et al., 2019). The identified outliers were redefined using the mean weighted method. A normal quantile–quantile plot was produced for individual parameters using Microsoft Excel 2019 to compare the data distributions with a standard normal distribution, providing another measure of normality. The data points closer to the line (45°) in the graph show a normal distribution (Mousavifard et al., 2013). Subsequently, descriptive statistics were computed for each soil quality parameter. Additionally, in accordance with OK requirements (Chabala et al., 2017), trend checkup and trend analysis removal were conducted alongside the normality test.

After the outlier and normality checkups, the data were subjected to OK, and a semivariogram was generated, which is a plot of semivariance as a function of the separation distance between two sampling locations, to show the status of spatial autocorrelation within the soil parameter data (Z. Liu & Wang, 2011; Saito et al., 2005). The semivariogram parameters included the following: the nugget value (C_0), which represents the residual variance of the sampling error together with the spatial variation that occurs over a distance much shorter than the minimum sample spacing and consequently cannot be resolved; the partial sill (C), which is the difference between the nugget variance and sill variance; and the sill variance (C_0 +C), which is the value that the semivariogram model attains at the range or at which the plotted points level off. The sill variance also represents the overall variability, which means that a larger sill variance indicates greater variability and vice versa (Nie et al., 2019; Xiao et al., 2016). The other examined semivariogram parameters are the range (A_0) and nugget-to-sill ratio ($C_0/(C_0 + C)$). The range is the distance over which the soil property values are correlated with each other or the distance at which the variogram level decreases (Tesfahunegn et al., 2011). On the other hand, the nugget-to-sill ratio indicates the spatial heterogeneity of the data as strong, moderate and weak spatial autocorrelation, with values of < 25%, 25-75% and > 75%, respectively (Cambardella et al., 1994).

To choose the best semivariogram model and evaluate how the model accurately predicts the soil quality indicator parameter at unsampled values, one-way cross-validation was applied (Chabala et al., 2017; Johnston et al., 2001). The indices absolute standard error (ASE), root mean square error (RMSE), and root mean square standard error (RMSSE), which indicate valid prediction standard errors if they are close to one, were estimated to validate the accuracy of interpolation during leave-one-out cross-validation(Chabala et al., 2017). A smaller RMSE indicates a better prediction, and the RMSSE indicates a valid prediction standard error if it is close to one. The indices are calculated as follows, where n is the number of soil sample points, Y_i' is the predicted value, y_i is the observed value (Chabala et al., 2017; Mousavifard et al., 2013, and Tesfay et al., 2022).

$$\mathrm{ASE} = \sqrt{\frac{1}{n}\sum_{\mathrm{i}}^{\mathrm{n}}[y_i' - (\sum_{i=1}^{n} y_i' \ /n)]^2} \quad \text{Eq-13}$$

$$\mathrm{RMSE} = \frac{1}{n}\sum_{i}^{n}\sqrt{(\mathrm{Y_i'} - \mathrm{y_i})^2} \quad \text{Eq-14}$$

$$\mathrm{RMSEE} = \sqrt{\frac{1}{\mathrm{n}}\sum_{\mathrm{i}}^{\mathrm{n}}(\mathrm{Y_i'} - \mathrm{y_i})^2} \quad \text{Eq-15}$$

3.3.4. Estimation of the Annual Soil Loss Tolerance

Various studies have assigned weights to soil quality indicators that are crucial for evaluating tolerable soil loss limits, considering their role in erosion control and soil quality enhancement. Mandal and Sharda (2011) reported these weights as 0.35 for hydraulic conductivity, 0.1 for bulk density, 0.25 for erodibility factor, 0.15 for organic carbon, and 0.15 for pH. Additionally, each parameter's laboratory output was transformed into a dimensionless score between 0 and 1 to compute the aggregate score for each soil sample. Various models have been devised by scholars to streamline this conversion process. For instance, Mcbratney & Odeh, (2006), as cited by Mandal & Sharda, (2011), used the joint membership function (JMF) of all attributes to develop four models.

For the optimum single ideal point (model 1), the ‘optimum point’

$$\mathrm{JMF\ (Y)} = \sum_{\mathrm{i=1}} \lambda_{\mathrm{i}}\,\mathrm{MF(x_i)} \quad \text{Eq-16}$$

For the optimum range ideal point (model 1) ‘optimum Range’;

$$\mathrm{MF(x_i\,)} = 1 \text{ if } (\mathrm{b_1} + \mathrm{d_1}) < \mathrm{x_1} < (\mathrm{b_2} - \mathrm{d_2}) \quad \text{Eq-17}$$

For the remaining asymmetry (model 3), ‘more is better;

$$\mathrm{MF(x_i)} = \left[\frac{1}{1+\left\{\frac{\mathrm{x_1 - b_1 - d_1}}{\mathrm{d_1}}\right\}^2}\right] \text{ if} \mathrm{x_i} < (\mathrm{b_1} + \mathrm{d_1}) \quad \text{Eq-18}$$

For asymmetric rights (model 4), ‘less is better’.

$$\mathrm{MF}(x_i) = \left[\frac{1}{1+\left\{\frac{x_1-b_2-d_2}{d_2}\right\}^2}\right] \quad \text{if } x_i > (b_2 - d_2 \qquad \text{Eq-19}$$

where Y is the membership function of all attributes, λ_i the weighting factor for the ith soil property x, b and d are model parameters for the lower crossover (b) and upper crossover (d) points, respectively. For instance, the study used the soil characteristics categorize ranking table, which was developed through these four models, to convert the soil laboratory results to dimensionless values (0 to 1).

Table 2. Unitless range score convertor matrix of soil attributes

Soil attribute		Categories					Model no.
		1	2	3	4	5	
Ks (cm/hr)	Range	0.5-1.0	1.0-2.0	2.3-3.5	3.5-5.0	>5.0	3
	Score	0.2	0.3	0.5	0.8	1	
BD (Mg m-3)	Range	<1.4	1.40-1.47	1.48-1.55	1.56-1.63	>1.63	4
	Score	1	0.8	0.5	0.3	0.2	
K factor	Range	<0.10	0.10-0.29	0.30-0.49	0.50-0.69	>0.70	4
	Score	1	0.8	0.5	0.3	0.2	
OC (%)	Range	<0.50	0.50-0.75	0.75-1.00	1.00-1.50	>1.50	3
	Score	0.2	0.3	0.5	0.8	1	
PH	Range	<5.0	5.0-5.5	5.5-6.0	6.0-6.5	6.5-7.5	4
		>9.0	8.5-9.0	8.0-8.5	7.5-8.0		
	Score	0.2	0.3	0.5	0.8	1	

NB. Ks; Hydraulic conductivity, BD; Bulk density, K; Soil erodibility, OC; Organic carbon, pH; Soil pH.

Using this unitless converted value and weight of each soil parameter, the aggregate score (Q) of the soil at each sampling point was generated using the formula below:

$$Q = \sum_{i=1}^{n} qiwi \qquad \text{Eq-20}$$

where Q = the status of the soil in terms of integrity (structural and functional), qi = the rating index of each parameter, and Wi = the weight factor of each parameter.

Following the determination of the status of the soil in terms of aggregate (Q), the soil was categorized into three soil groups: Q < 0.33, 0.33 < Q < 0.66, and Q > 0.66. These soil groups were matched with the corresponding soil depth of each sample point, and then a tolerable soil loss limit was obtained using the matrix developed by (USDA, 1999). Finally, the tolerable soil loss limit of the watershed is mapped and interrelated with the other factors for further analysis.

Table 3. Tolerable soil loss limit estimation matrix (Mandal & Sharda, 2011)

Soil depth(cm)	Annual soil loss tolerance (Mg ha^{-1} yr^{-1}		
	Group1 ($Q < 0.33$)	Group 2 ($0.33 < Q < 0.66$)	Group 3 ($Q > 0.66$)
0-25	2.5	2.5	7.5
25-50	2.5	5.0	7.5
50-100	5.0	7.5	10.0
100-150	7.5	10.0	12.5
>150	12.5	12.5	12.5

3.4. Surface Runoff and Sediment Yield Simulation

3.4.1. Model Selection

Currently, different models have been developed to assess and quantify the erosion rate and hotspot area of targeted areas, such as the RUSLE Renard et al.,(1997) and InVEST (NCA,2024). However, these models have no strong calibration or validation mechanism and do not allow for the evaluation and selection of best soil conservation practices that can reduce the erosion rate of an area below the tolerable soil loss limit; rather, they can estimate the erosion rate and identify and map erosion hot spot areas. On the other hand, the SWAT model was developed for alternative management decisions on soil and water-related issues Arnold et al., (2012), allowing the selection and mapping of suitable conservation measures Uniyal et al., (2020), and has a strong calibration and validation system that can train the model to the nature of the study watershed (Abbaspour, 2015).. Although data availability is the main challenge of the model Akoko et al., (2021), many scholars have used this model for erosion rate, hotspot area identification, stream flow assessment, and selection and evaluation of the best conservation measures that can effectively minimize the erosion problem and gain valuable output (Betrie et al., 2011; Dibaba & Ebsa, 2022; Gashaw, Bantider, et al., 2021). Therefore, this study used the SWAT model for this purpose.

3.4.2. SWAT Model Input

To estimate the sediment yield and identify erosion hotspot areas within the watershed, the SWAT model relies on both spatial and temporal data inputs. Spatial data, including digital elevation models (DEMs), land use/land cover, and soil data, are essential for understanding the physical characteristics of terrain and soil properties. Meanwhile, temporal data, encompassing parameters such as maximum and minimum temperature, precipitation, solar radiation, wind speed, and relative humidity, provide crucial information on climatic conditions over time. By integrating these spatial and temporal datasets, the SWAT model can effectively simulate erosion processes and identify vulnerable areas within watersheds.

3.4.2.1. Digital Elevation Model (DEM)

The digital elevation model (DEM) serves as a foundational layer in various aspects of watershed analysis, including watershed delineation, stream network identification, sub watershed generation, hydrological response unit (HRU) delineation, and slope mapping. It represents a critical spatial input for processing the SWAT model, providing essential data for characterizing the terrain. The SWAT model operates based on three key spatial features: watersheds, subwatersheds, and hydrological response units (HRUs). Initially, the model requires delineation of the watershed boundary, which is accomplished through an automatic watershed delineation interface using a digital elevation model (DEM) as input data. The watershed area is then subdivided into smaller sub watersheds based on specified threshold criteria, and each sub watershed is further divided into HRUs. For example, in our analysis, DEM data with a resolution of 2 meters were acquired from the Water and Land Resource Center (WLRC) to facilitate watershed delineation and generation of drainage patterns. From these DEM data, all necessary parameters related to drainage characteristics and slope were derived to inform SWAT model processing. The DEM was projected to have a projection of WGS_1984_UTM_Zone_37P before any process was conducted.

3.4.2.2. Land Use

Land use and land cover maps were essential data required for the SWAT model for the simulation of surface runoff and sediment yield in the area. This is because of its significant impact on surface runoff, erosion, and hydrological processes in nature. Therefore, high-resolution (10-meter) Sentinel-2 satellite images were obtained from the Copernicus Open Access Hub website (https://scihub.copernicus.eu/.) The image captured on January 23, 2023, was chosen for prioritization. This decision was based on the anticipation of minimal or zero cloud cover during these months and to mitigate significant disparities in the land cover reflectance dataset. (Leta et al., 2021). The Sentinel image was subjected to ArcGIS software version 10.5 for land use classification through supervised classification under the maximum likelihood classification algorithm. The land use accuracy assessment classifications were computed through the confusion matrix using a total of 69 on-ground geo-referenced collected sample data from each land use within the watershed. The classification was conducted repeatedly until it attained better classification accuracy.

3.4.2.3. Soil

The soil textural class map of the watershed was generated using the USDA textural class triangle (USDA, 2017) based on laboratory soil texture analysis results. Furthermore, the soil laboratory results, which provide crucial information on soil properties such as erodibility, hydraulic conductivity, organic matter content, bulk density, soil pH, and soil depth collected from the watershed, were utilized to predefine the SWAT model database.

3.4.2.4. Climate, Streamflow and Sediment Data

The Soil and Water Assessment Tool (SWAT) model relies on long-term climatic data for precise runoff and sediment yield simulation, including precipitation, temperature (both minimum and maximum), wind speed, solar radiation, and relative humidity. For this study, climate data spanning from 1995 to 2022 were obtained from the DBARC. Precipitation was continuously monitored using four rain gauges distributed across the watershed, while other climate variables were recorded at a single station located at the watershed outlet. Although temperature data were recorded at a single gauge near the outlet, ensuring continuous climate data collection posed challenges within the study watershed. To address this issue, the SWAT weather generator estimator tool was used to fill in missing data and format the climatic data in accordance with SWAT requirements. The tool was acquired from the official website of the Soil and Water Assessment Tool (SWAT) at https://swat.tamu.edu/software/. Subsequently, it was effectively utilized to complete and replace all missing data within the dataset. Additionally, observed runoff and sediment yield data are also required for the calibration and validation of SWAT software. For instance, daily stream flow and sediment yield data (2012-2022) were also obtained from the DBARC.

3.4.3. SWAT Model Setup

3.4.3.1. Watershed Delineation and HRU Generation

The delineation of the watershed commenced with the utilization of a DEM with a resolution of 2 meters, accessed from the Water and Land Resource Center (WLRC). After this, the delineation of sub watersheds, stream network definition, and identification of watershed inlets and outlets were carried out employing a designated threshold area of 10 hectares. The generation of sub watershed aids in categorizing the watershed into more manageable hydrologic units, facilitating the identification of erosion hotspot areas and prioritizing implementation strategies through comparative analysis. With a threshold area of 10 hectares, the delineated watershed spanned 477.7 hectares, comprising 15 sub watersheds. The area encompassing the installation sites for sediment and stream flow gauges was designated as the outlet for the watershed.

Further subdivision of the delineated watershed was performed to define the HRU, which represents areas with unique combinations of land use, soil type, and slope characteristics. HRUs are treated as individual units by the SWAT model for simulation purposes. During HRU definition, predefined land use and soil data from the crop and user soil databases were considered. The slope of the watershed was classified into five categories based on FAO guidelines (2006), ranging from 0-8% to greater than 60%.

Table 4. Slope gradient classes and its area coverage in the study watershed (FAO, 2006)

Slope (%)	Description	Area (ha)	Area (%)
0-8	Gentle	24.0	5.0
8-15	Slopy-Strongly slopy	53.0	11.1
15-30	Moderately steep	151.1	31.6
30-60	Steep	234.1	49.0
>60	Very steep	15.5	3.2

Multiple HRU options were utilized, employing a threshold of 15% for land use, soil, and slope to allow for the creation of multiple HRU units within a subbasin. This threshold was chosen to enhance the interpretability of streamlines by eliminating HRUs resulting from minor combinations of land use, soil, and slope. The 15% threshold for each criterion facilitated reasonable simulations of stream flow and sediment yield within the Andit Tid watershed, drawing inspiration from equivalent methodologies applied in the Blue Nile basin (Ayele et al., 2017; Gashaw et al., 2021; Lemma et al., 2019). Consequently, a total of 66 HRUs were identified within the study watershed. Subsequently, the HRU surface runoff and sediment yield were simulated for each subbasin using the Arc SWAT (2012) interface within the ArcGIS version 10.5 software environment.

3.4.4. Sensitivity Analysis, Calibration and validation

In addition to the model setup, the model was pushed to simulate the stream flow and sediment yield following the user guide of the SWAT model. The model simulation performance was also evaluated through sensitivity analysis, calibration and validation using statistical tools for evaluating the model performance in terms of the accuracy of the simulated data compared to the measured data (Moriasi et al., 2007, 2015).

3.4.4.1. Sensitivity Analysis

To identify, understand and control the influential factors that are able to govern the simulation of the hydrological process, a sensitivity analysis was conducted. This approach was used to speed up the calibration and validation process by reducing the number of parameters required for calibration (Abraham, 2006). This analysis considers approximately 11 parameters for stream flow and 10 parameters for sediment yield simulation within the range recommended by (Abbaspour, 2015).

Table 5. The recommended ranges of the considered sensitive parameters

Parameter Name	Description	Range
	Stream flow	
v_REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm).	0-500
v_ GW_DELAY.gw	Groundwater delay (days).	0-500
v_ RCHRG_DP.gw	Deep aquifer percolation fraction.	0-1
v_ GW_REVAP.gw	Groundwater "revap" coefficient.	0.02-0.2
v_ GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm).	0-5000
v_ ALPHA_BF.gw	Base flow alpha factor (days).	0-1
r _ CN2.mgt	SCS runoff curve number f	-0.1-0.1
r _ SOL_ AWC (..).sol	Available water capacity of the soil layer.	0-1
v_ CH_N2.rte	Manning's "n" value for the main channel.	-0.01-0.3
v_ CH_K2.rte	Effective hydraulic conductivity in main channel alluvium.	-0.01-500
v_ ESCO. Hru	Soil evaporation compensation factor.	0-1
	Sediment Yield	
v_ USLE_P. mgt	USLE equation support parameter	0-1
v_ USLE_ K ().sol	USLE equation soil erodibility (K) factor.	0-0.65
v_ CH_COV1.rte	Channel erodibility factor.	-0.05-0.6
v_ CH_COV2.rte	Channel cover factor.	-0.001-1
v_ SPCON. bsn	Linear parameter for calculating the maximum amount of sediment that can be retrained during channel sediment routing.	0.0001-0.01
v _ SPEXP. bsn	Exponent parameter for calculating sediment retrained in channel sediment routing.	1-1.5
v_ USLE_C{AGRC}. plant.dat	Min value of USLE C factor applicable to the land cover	0.003-0.5
v_ USLE_C{EUCA}. plant.dat	Min value of USLE C factor applicable to the land cover	0.001-0.5
v_ USLE_C{PAST}. plant.dat	Min value of USLE C factor applicable to the land cover	0.001-0.5
v_ USLE_C{RNGB}. plant.dat	Min value of USLE C factor applicable to the land cover	0.001-0.5

These parameters were identified based on the researcher's judgment and previous studies conducted in related agroecology (Admas et al., 2022; Gashaw et al., 2021; Lemma et al., 2019). The sensitivity analysis was conducted through SWAT CUP 2012 version 5.1.6.2 software using global sensitivity analysis, which allows changing each parameter at a time and gives the sensitivity of one parameter relative to the other with their statistical significance. The sensitivity rank was determined using *t*-statistics and *p* values of the parameters. A highly sensitive parameter is indicated by a higher absolute value and a p value close to zero (Abbaspour, 2015). The SWAT-CUP software was downloaded from the https://swat.tamu.edu/software/ link.

3.4.4.2. Model Calibration

Calibration involves adjusting a model's parameters to match specific conditions within a watershed, aiming to minimize simulation uncertainty (Arnold et al., 2012). It serves as a means of fine-tuning model parameters to align simulated data with observed data for corresponding seasons within an acceptable range of variance. Calibration can be carried out through trial and error or automated methods, with the latter offering greater accuracy and efficiency (Moriasi et al., 2007, 2015). This study employed a combined approach to calibration, utilizing both manual calibration assistance and automated techniques to expedite the process. Prior to calibration, the model's performance was assessed using default parameter values. Calibration was then conducted using monthly stream flow and sediment yield data from 2012 to 2018, adjusting and reconstructing sensitive variables within recommended ranges until improved simulation accuracy was achieved.

3.4.4.3. Model Validation

Validation is the technique of matching the simulated and field-measured results without altering the calibration parameters or a means of testing the calibration result without changing the parameter range obtained through the calibration process but with the other dataset recorded during the simulation period.(Arnold et al., 2012; Kefay et al., 2022) Validation was conducted following the SWAT-CUP guidelines Abbaspour, (2015) using monthly streamflow and sediment yield data from 2019-2022. Both graphical and statistical approaches were used to validate the results, similar to the results of calibration (Arnold et al., 2012; Moriasi et al., 2007, 2015).

3.4.4.4. Model Performance Evaluation

Model performance evaluation is the assessment of the model’s ability to perform a given task accurately not only with training data but also in real time with runtime data. The model simulation performance was evaluated using common evaluating statistical tools (Moriasi et al., 2007)(Moriasi et al., 2015). These indices are the Nash-Sutcliffe efficiency (NSE), which measures the residual and measured variance or the level of similarity between the simulated and observed datasets and ranges from $-\infty$ to 1. Values between 0 and 1 are acceptable for performance. The percent bias (PBIAS) shows the overestimation and underestimation of the model. A value of 0 is the optimal PBIAS, while a positive value indicates an underestimation of bias, and a negative value indicates an overestimation bias of the model. The root mean square error (RMSE)-observation standard deviation ratio (RSR) also reflects the magnitude of the error. A value of RSR closer to zero indicates better model performance, and vice versa. The other performance evaluation tool is the coefficient of determination (R^2), which indicates how well the model predicts the condition. An R^2 close to 1 indicates a better estimation of the model. The statistical tool calculations and acceptance limits were determined as suggested by (Moriasi et al., 2007, 2015).

$$NSE = \left\{1 - \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{mean}\right)^2}\right\} \qquad \text{Eq-21}$$

$$\text{PBAIS} = \left\{\frac{\sum_{1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right) * 100}{\sum_{1}^{n}\left(Y_i^{obs}\right)}\right\} \qquad \text{Eq-22}$$

$$\text{RSR} = \frac{\text{RMSE}}{\text{STD}_{obs}} = \left\{\frac{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}}{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{mean}\right)^2}}\right\} \qquad \text{Eq-23}$$

$$R^2 = \left\{\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{mean}\right) * \left(Y_i^{sim} - X^{mean}\right)}{\sqrt{\left[\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{mean}\right)^2\right]} * \sqrt{\left[\sum_{i=1}^{n}\left(Y_i^{sim} - X^{mean}\right)^2\right]}}\right\}^2 \qquad \text{Eq-24}$$

Table 6. Model performance metric (Moriasi et al., 2007, 2015)

Statistical tools	Performance rate			
	Very good	Good	Acceptable	Poor
R2	≥ 0.85	≥ 0.75	≥ 0.65	< 0.65
NSE	> 0.80	> 0.70	> 0.50	≤ 0.50
PBAIS (1) %	< ± 10	< ± 15	< ± 25	≥ ±25
PBAIS (2) %	< ± 15	< ± 30	< ± 55	≥ ±55
RSR	≤ 0.50	≤ 0.60	≤ 0.70	> 0.70

PBAIS(1)%; for stream flow, PBAIS(2)%; for sediment yield

Once the model underwent calibration and validation, the fitted values of the calibration parameters were rewritten to the SWAT database. Subsequently, the runoff and sediment yield simulations were rerun. The resulting sediment yield simulation served as the baseline scenario for the study. Hence, to ensure that the erosion hotspot area of the watershed was comparable to the tolerable soil loss limit, the simulated sediment yield of the watershed and sub watershed was converted to the soil loss rate of the watershed through the sediment delivery ratio method.

3.4.5. Sediment Delivery Ratio (SDR)

The SDR is the ratio that represents the amount of eroded material that is transported and reaches the catchment outlet relative to the total amount of detached/eroded materials from the entire area of the catchment. Hence, the sediment yield simulated for the watershed and sub watershed was converted to the soil loss rate using their relationship developed by Williams & Berndt, (1972) as cited by Zhang et al., (2015) for watersheds with areas of less than one square kilometer. Finally, the soil loss rate of the watershed was mapped.

$$Soil\ loss\ (t\ ha^{-1}yr^{-1}) = \frac{\text{sediment yield } (\text{t ha}^{-1}\text{yr}^{-1})}{(\text{SDR})} \qquad \text{Eq-25}$$

where $SDR = 0.3481 \ * (area\ of\ watershed(km^2))^{-0.211}$ Eq-26

After the soil loss rate of the watershed was compared with the tolerable soil loss limit of the watershed, the erosion hotspot areas of the watershed were identified.

3.5. Best Soil Conservation Practice Scenarios

The SWAT model has been widely applied throughout the world, including Ethiopia, to determine the best and most effective soil and water conservation measures for reducing sediment yield (Admas et al., 2022; Aysheshim, 2015; Briak et al., 2019; Gashaw et al., 2021). The first screening to evaluate soil and water conservation measures was conducted manually depending on the following field assessment criteria: agroecology, slope, soil depth, soil texture, and rainfall according to the soil and water conservation guidelines (Desta et al., 2005; Hurni et al., 2016). Hence, based on the background information stated in the area description section, three independent scenarios—grass strip scenario (Scenario GT), stone/soil bund (Scenario SSB), and reforestation (Scenario RF)—and two combined scenarios—soil/stone bund and grass strip (Scenario SSB &GT) and soil/stone bund and reforestation (Scenario SSB &RF)—were selected and evaluated against the baseline scenario (Scenario BL). The conservation measures that reduce soil loss to an extent below or equal to the tolerable soil loss limit of the watershed were categorized under the best conservation measures and mapped to their suitable area in the watershed, but the others were rejected from the implementation option.

3.5.1. Baseline Scenario (Scenario BL)

The BL scenario reflects the status of the watershed under the existing conditions. This means that the current erosion status of the watershed under the current status of implemented soil and water conservation measures and land use land cover status which affects the soil erosion status of the watershed. To capture those measures effect on the soil erosion resistance ability the key soil property that can control the erosion potential of the area; hydraulic conductivity, Bulk density, Soil erodibility, Soil PH, Soil organic carbon was analyzed through soil laboratory including soil depth was predefined with in SWAT database. For instance, the calibrated outputs of surface runoff and sediment yield were considered the baseline scenario.

3.5.2. Grass Strip Scenario (Scenario GT)

A grass strip is a strip of grass constructed along the contour across the slope to filter and trap the sediment carried out by the runoff. On the other hand, it checks the runoff velocity and reduces its volume by facilitating infiltration and thereby combatting the formation of rills and gullies (Desta et al., 2005; Hurni et al., 2016). Grass strips were selected for this study due to their effectiveness in the same watershed (Herweg & Ludi, 1999) and in different parts of Ethiopia (Dibaba et al., 2021; Gashaw et al., 2021) and the availability of different grass species in the study area. Grass strip represented in the SWAT model by 'FILTERW'. Hence, this scenario was evaluated by the SWAT model by changing the width of the filter strip (FILTERW) to 1 m for all agricultural land on slopes ranging from 0-15%. A width of 1 m was applied due to the suggestion of research conducted on the same watershed Herweg & Ludi, (1999), and the slope class limit was also limited due to the suggestion of scholars (Desta et al., 2005; Hurni et al., 2016).

3.5.3. Stone/Soil Bund Scenario (Scenario SSB)

A stone/soil bund is a bund constructed across a slope along a contour to trap runoff for infiltration as well as for supplying moisture to neighboring environments in seepage and infiltration zones (Amare et al., 2014; Desta & Adunga, 2012). A bund may be constructed using only soil and/or stone based on the availability of construction materials (Desta et al., 2005). The main objective of bunds is to reshape the topographic factors of slope length and steepness and thereby reduce the formation of runoff by providing time for infiltration (Hurni et al., 2016). Additionally, it enhances the physiochemical properties of soil, which are vital for the productivity of land (Desta et al., 2021). This parameter is appropriately represented in the SWAT model by the curve number (CN2), average slope length (SLSUBBSN), slope steepness (HRU_SLP) and USLE supporting practice factor (USLE_P). Hence, this scenario was evaluated by editing the slope length (the length that should be present between the bunds) on the HRU table depending on the slope of the area following the guidelines (Desta et al., 2005; Hurni et al., 2016). The CN2 values adjusted to 59 , by editing the management input table, as recommended by field experience (Gebremicheal, 2019; Hurni, 1985).

3.5.4. Reforestation (RF Scenario)

Reforestation is the practice of shifting erosion areas into forestland to minimize the erosion rate of the area by reducing overland flow and rainfall erosivity (Gashaw et al., 2020). The reforestation of vulnerable cropland has shown significant results in the highland area of Ethiopia (Betrie et al., 2011). Hence, this scenario was implemented by changing the vulnerable cropland to forest in the land use map of the watershed without parameter changes.

3.5.5. Soil/Stone Bund with Grass Strip (SSB & GT)

This scenario was evaluated by integrating the two scenarios at a time when the independent scenarios were unable to reduce the erosion to a rate below or equal to the tolerable soil loss limit.

3.5.6. Soil/Stone Bund with Reforestation (SSB & RF)

This scenario was evaluated by integrating the two scenarios at a time when the independent scenarios were unable to reduce the erosion to meet TSLL.

Table 7. Literature-based BSCPs and SWAT database change descriptions (Desta et al., 2005; Herweg & Ludi, 1999; Hurni, 2016; Lemma et al., 2019)

Scenarios	**Description**	**Parameters**	**Calibrated**	**Modified**
Scenario BL	Existing soil erosion condition of watershed			
Scenario SSB	Soil/Stone bund constructed across the slope at different interval depending on slope steepness	SLSUBBSN(.hru)		
		0-8% slope	76	23 m
		8-15% slope	46	13 m
		15-30% slope	15	8.9 m
		30-60% slope	9	4 m
		>60% slope	9	4 m
		HRU-SLP	a	0.75a
		CN2	78	59
Scenario GT	A strip of grass installed across the slope	FILTERW	0	1 m
Scenario RF	changing of cultivated land having slope >30% to forest	Land use change		
Scenario SSB & GT	Implementation of soil or stone bund and grass strip across the slope	Simultaneously, modifying the two scenarios parameter		
Scenario SSB & RF	Applying of soil/stone bund and reforestation scenarios simultaneously	Simultaneously, modifying the two scenarios parameter		

The sediment yield of the baseline scenario and the outputs of the BSCPs were compared with the tolerable soil loss limit and erosion severity classification, and the erosion reduction efficiency was generated accordingly.

4. RESULTS AND DISCUSSION

4.1. Tolerable Soil Loss Limit

4.1.1. Characteristics of Soil Properties

The bulk density of the Andit Tid watershed is 1.31 ± 0.17 g/cm^3, ranging from a minimum of 1.01 to a maximum of 1.74 g/cm3, with a hydraulic conductivity of 1.31 ± 0.41 cm/hr (Table 8). FAO, (2023) suggested that this bulk density is favorable for cultivation, root penetration, and development. Nonetheless, it reflects an increase of more than 50% compared to findings (0.68) in no conserved areas of the same watershed by Tadese & Shiferaw, (2024), although it aligns closely with a previous report (1.5 g/cm^3) in Laelay Mychew central Tigray (Lemma, 2013). The soil erodibility K factor of the Andit Tid watershed also ranges from 0.12 to 0.15 Mg h MJ^{-1} mm^{-1}, with an average of 0.13 ± 0.01 Mg h MJ^{-1} mm^{-1}, indicating low susceptibility to erosion (Ahmad et al., 2022). This finding aligns with reports by Desalegn et al., (2018) and Abebe & Woldemariam, (2024) in the same watershed and Ayigebire watershed, respectively, which share the same agroecology. However, this finding contrasts with the higher K factor values reported elsewhere (Addis & Klik, 2015; X. Liu et al., 2020).

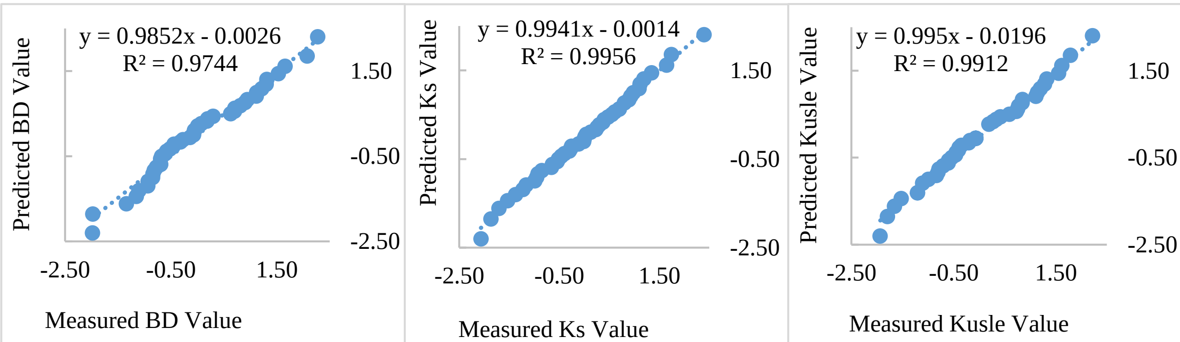
The average soil pH of the watershed stands at 5.26 ± 0.23, ranging from a minimum of 4.82 to a maximum of 5.82 (Table 10), indicating a strongly to moderately acidic nature (Negese, 2019). Currently, there is a decrease in soil pH compared to that in previous reports (5.52-6.19) (Yohannes & Soromessa, 2018). This decrease may be attributed to cation loss through erosion and leaching, intensive crop residue extraction for cattle feed, organic fertilizer application (Laekemariam & Kibret, 2021), and the expansion of *Eucalyptus* forests (Yimam et al., 2024). The organic carbon content in the watershed ranged from 0.72% to 6.30%, with an average of 3.47 ± 1.33%. Despite the presence of high organic carbon, there was significant variation among the sampling locations, which was five times greater than that in a previous report (0.14) by (Tadese & Shiferaw, 2024) on the same watershed. This variation could be due to land use changes and topographic factors accelerating organic matter depletion through runoff (Bot and Benites, 2005). Despite a slight improvement from previous reports (Yohannes & Soromessa, 2018), the organic carbon content remains lower than that in different parts of the Ethiopian highlands (Amare et al., 2013)

The soil quality indicators selected for the TSLL assessment exhibited both negative and positive skewness (Table 8), ranging from 0.005 for Ks to 0.32 for BD. pH and OC show negative skewness, while all others are positively skewed. Despite low skewness, all parameters demonstrate negative kurtosis, indicating lighter tails than the normal distribution. In terms of the coefficient of variation (Table 8), pH (4.35%), BD (12.64%), and Kusle (5.705) displayed low variability, while Ks (31.39%) and OC (38.41%) exhibited moderate to high variability (Wilding, 1985), as cited by (Addis & Klik, 2015)

Table 8. Descriptive statistics of the soil parameters

Parameters	Min	Max	Mean	SD	Skewness	Kurtosis	CV (%)
BD (g/cm^3)	1.01	1.74	1.35	0.17	0.32	-0.38	12.64
Ks ($cm\ hr^{-1}$)	0.46	2.30	1.31	0.41	0.005	-0.32	31.39
Kusle ($Mg\ h\ MJ^{-1}\ mm^{-1}$)	0.12	0.15	0.13	0.01	0.16	-0.56	5.70
pH (pH scale)	4.82	5.82	5.26	0.23	-0.04	-0.29	4.35
OC (%)	0.72	6.30	3.47	1.33	-0.20	-0.35	38.41

The Q–Q plot of the parameters demonstrates a normal distribution, as indicated by the concentration of points along the line inclined at 45 degrees. This validates the use of kriging interpolation to generate a surface based on the observed sample data (Mcgrath & Zhang, 2003).



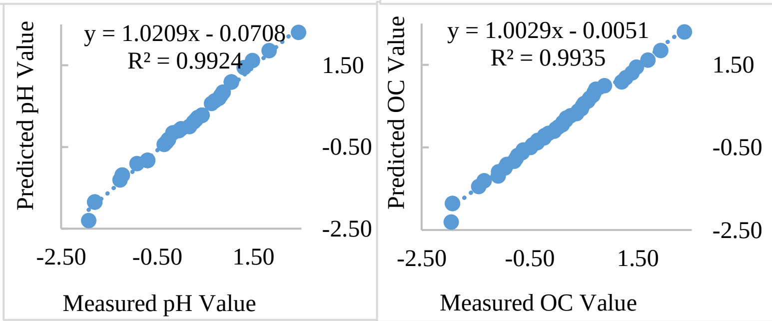


Figure 6. Q–Q plot of the soil parameters

All the soil parameters exhibited discernible trends during the trend analysis (Figure 1Figure 7). In the east–west direction, the green straight line representing Kusle shows no trend, while the upward curve (pH and BD) and slight downward curve (OC and Ks) indicate decreasing and increasing trends, respectively. Conversely, in the North–South direction, the downward blue curve (pH, OC, & Ks) and upward curve (Kusle & BD) suggest decreasing and increasing trends, respectively. This underscores the importance of applying trend removal analysis to enhance the accuracy of map predictions. Consequently, employing a first-order trend analysis tool for all parameters is necessary for trend removal.

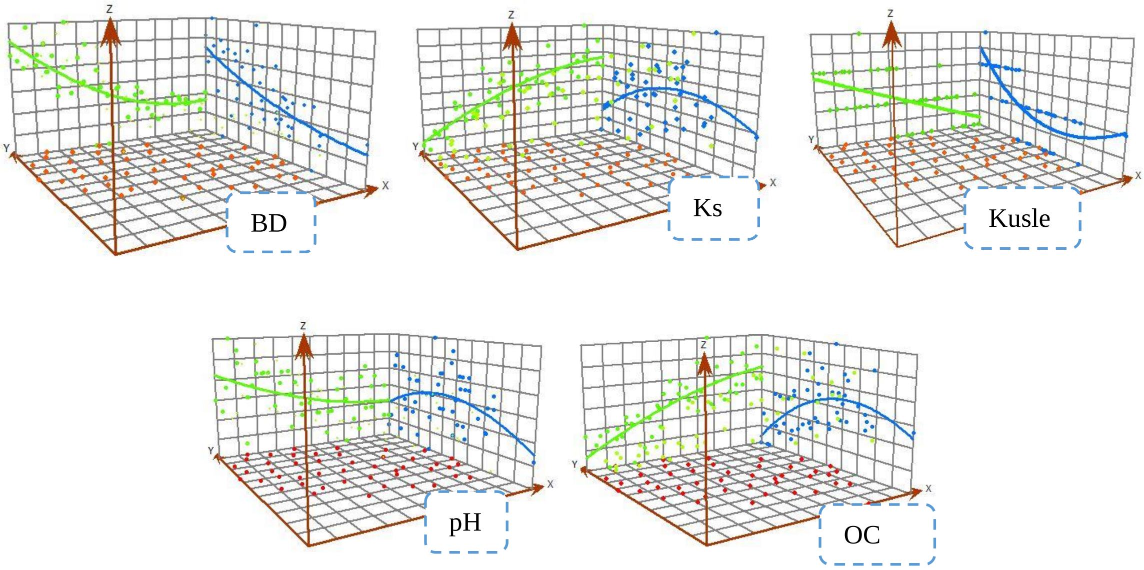


Figure 7. Trend analysis indicator diagram for the soil parameters

In the graph showing the comparison of predicted versus measured values (Figure 8), the relationship between the blue line and the straight line serves as a visual indicator of the confidence level in the accuracy of kriging predictions for various soil parameters, as discussed by (Johnston et al., 2001; Tesfay et al., 2022). Interestingly, the proximity of the blue line to the straight line varies across different parameters. Particularly noteworthy is the close alignment observed for parameters such as organic carbon (OC), Kusle, hydraulic conductivity (Ks), and bulk density (BD). However, it is worth noting a slight deviation in the case of soil pH, which is apparent in Figure 8.

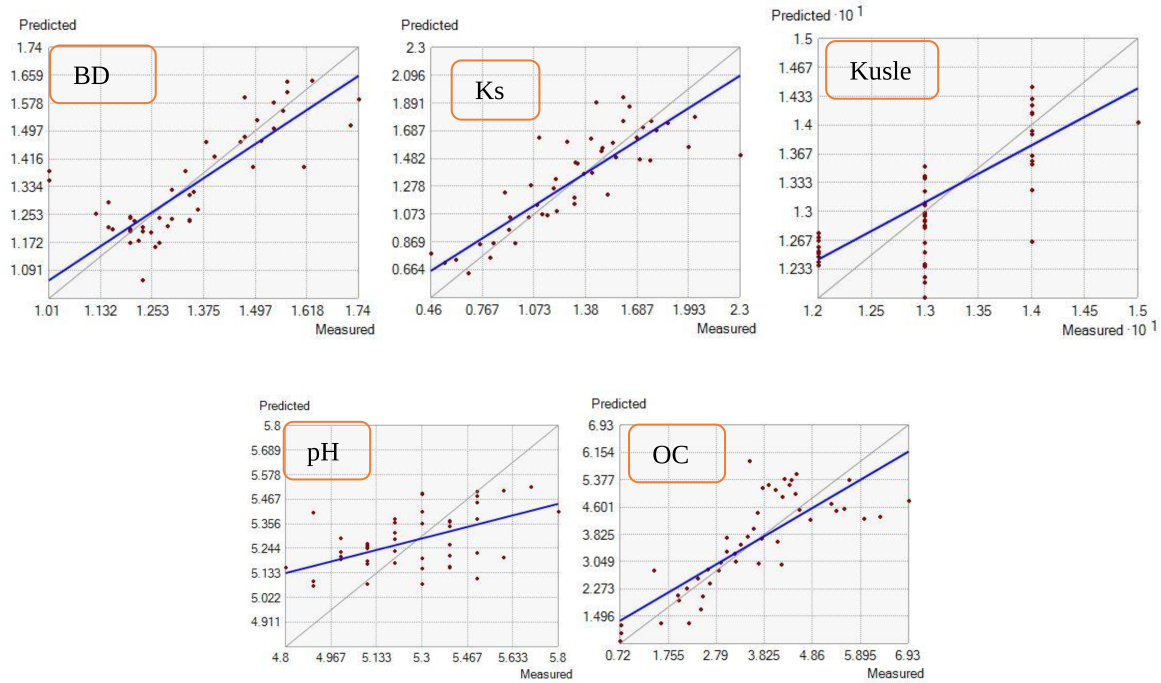


Figure 8. Measured and predicted values of soil parameters in the ordinary kriging model

The Gaussian and circular ordinary kriging interpolation models demonstrated superiority over other models, proving to be more reliable in predicting the spatial distributions of Ks and OC (Gaussian) and pH and Kusle and BD (circular). The Nugget/Sill ratio ranged from a minimum of 2.78% (BD) to a maximum of 36.59% (Kusle) (Table 9). According to Cambardella et al., (1994), BD and OC exhibit strong spatial dependency, while the rest show moderate spatial dependency. The range of spatial dependency varies from a minimum of 458 m (BD) to a maximum of 1839 m (pH). All the parameters exhibit RMSEs close to zero, except for OC, which is 0.88 and close to one RMSSE (Table 9). This cross-validation result indicates that the model fits the dataset of the parameter very well in an unbiased manner (Mousavifard et al., 2013; Tesfay et al., 2022).

Table 9. The optimal parameters for semivariogram and cross-validation analysis

Parameters	Nugget	Sill	Nugget/sill	Range	RMSE	RMSSE	ASE
BD	0.00	0.01	2.78	458	0.11	1.10	0.10
Ks	0.02	0.06	27.27	793	0.23	0.86	0.26
Kusle	0.00	0.00	36.59	803	0.01	1.02	0.01
pH	0.02	0.06	34.38	1839	0.20	1.08	0.18
OC	0.03	0.13	23.08	1151	0.88	1.06	0.90

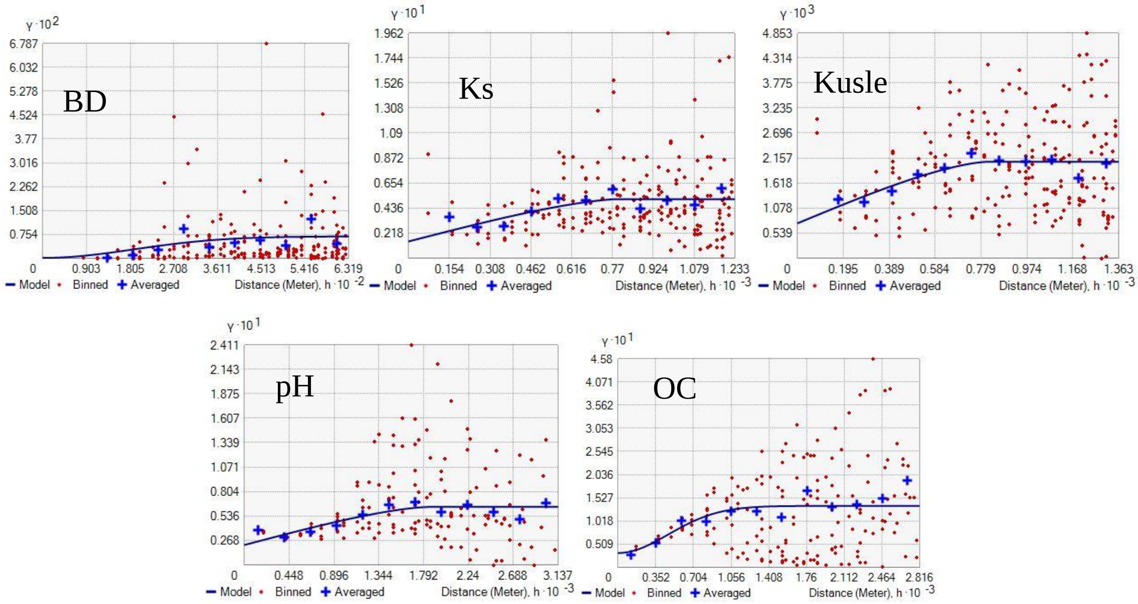


Figure 9. Semivariogram map of the soil parameters

4.1.2. Spatial Distribution of Selected Soil Quality Indicator

The spatial distribution of the soil quality indicator parameter (Figure 10) showed that greater bulk density was also observed in the northwestern region of the watershed, which was primarily attributed to the prevalence of *Eucalyptus* open forest and intensive cultivation practices. Both factors contribute to increased soil bulk density through the extraction of high amounts of organic matter and the formation of structureless soil (Amanuel et al., 2018; Amsalu, 2019). Conversely, a lower bulk density of 0.969 g/cm^3, as reported by Amanuel et al., (2018), was recorded in *Eucalyptus* forests in the Entoto area. This difference may be influenced by forest density and the duration since plantation, both of which affect soil density. According to Yimam et al., (2024), land covered with *Eucalyptus* for a longer duration exhibits lower soil bulk density, possibly due to greater organic matter accumulation from long-term litterfall and decomposition. Conversely, the southern and southeastern parts of the watershed display moderate to low bulk density compared to other areas. This is attributed to the presence of well-structured soil resulting from high organic matter derived from dense-bush and grasslands. These findings align with the results reported by (Amanuel et al., 2018; Buraka et al., 2022).

The lowest Ks values were observed in the northwestern areas of the watershed, where clay and clay loam soil textures prevail. In contrast, the central parts of the watershed, characterized by loam and sandy loam soil textures, fall into hydrologic soil groups B and A, respectively (Blanco & Lal, 2008). This distinction contributes to slightly higher Ks values in the central regions of the watershed, as noted by Wilding, (1985) and (Addis & Klik, 2015).

In the northwestern portion of the watershed, soil erodibility is notably greater, primarily due to intensive cultivation practices. This region lacks mechanisms to enhance its organic matter content, which plays a crucial role in soil structure improvement and erosion resistance, as suggested by (Tuji & Moges, 2022). Conversely, the southeastern sector of the watershed exhibits a lower soil erodibility potential. This can be attributed to its higher organic matter content derived from the presence of shrubs and grass species. However, areas covered by *Eucalyptus* forests within this region demonstrate elevated erodibility potential compared to the remaining cultivated, shrub, and grassland areas. This difference may stem from the slower decomposition of litter in the *Eucalyptus* forests, as indicated by (Yimam et al., 2024)

Spatially, strong acidity was noted in the northeastern section of the watershed. Conversely, the central, western, and southern parts of the watershed, extending from the outlet to the inlet, predominantly exhibited a pH range of 5.0-5.4. This distribution coincides with the undulating topography covering 52% of the watershed, featuring slopes greater than 30%. These terrain characteristics may contribute to the spatial pH gradient, in addition to other factors identified by (Laekemariam & Kibret, 2021; Tsui et al., 2004; Yimam et al., 2024).

In the southeastern region of the watershed, there is a notable presence of higher OC. This phenomenon arises from the dense coverage of shrub and grass species, characterized by a high decomposition rate of their residues. This finding aligns with a similar report by Buraka et al., (2022) in southern Ethiopia, where an OC content of 3.952% was observed. In contrast, the northwestern part of the watershed exhibited lower OC contents ranging from 0.72% to 2.38%. This discrepancy can be attributed to intensive cultivation practices in this area, which accelerate the loss of organic matter through tillage and the removal of crop residues for animal feed. Additionally, parts of this region are covered by open E*ucalyptus* forests, which contribute to lower litterfall. Notably, Amsalu, (2019) reported a higher OC content of 4.07% in *Eucalyptus* forests in the Entoto area. The variance may be due to differences in density per unit area, species types of *Eucalyptus*, and topography, as highlighted by (Buraka et al., 2022).

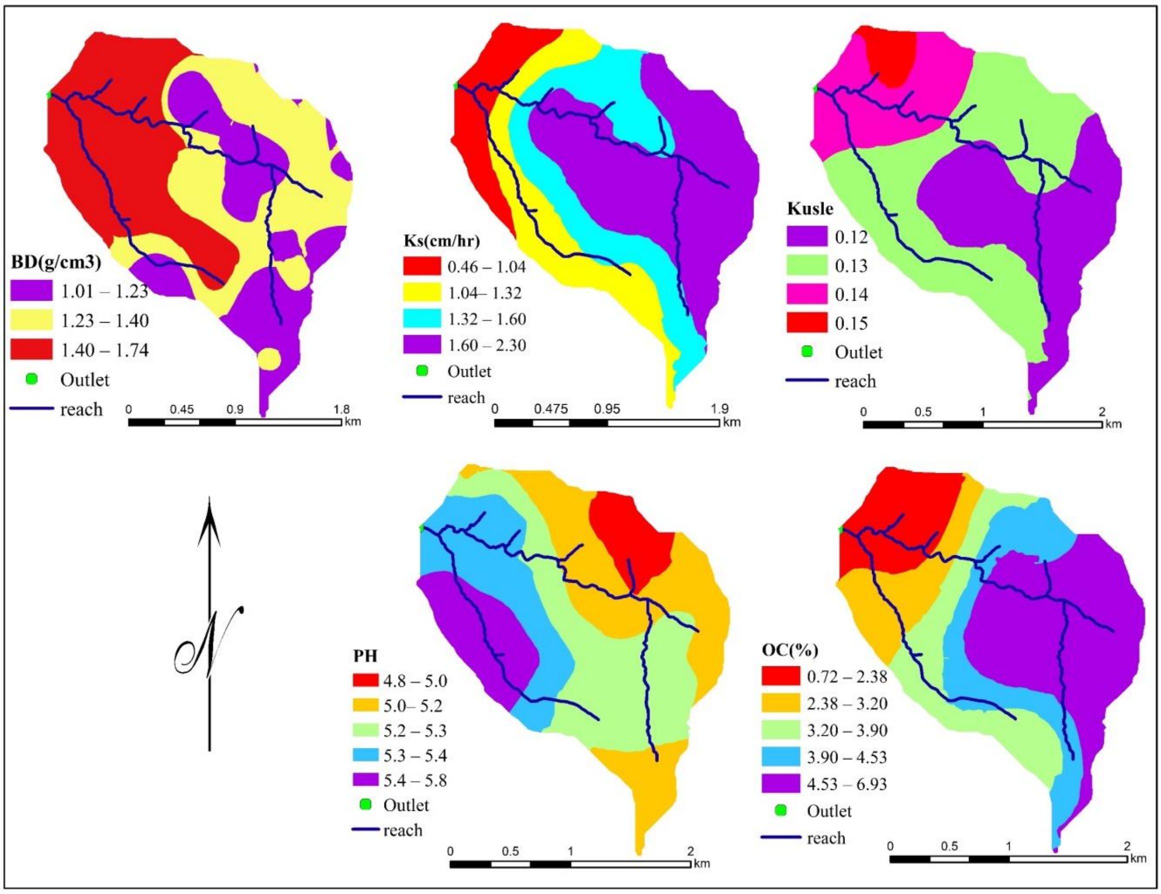


Figure 10. Spatial distribution of soil parameters

4.1.3. Soil Aggregate Group and Depth

The Andit Tid watershed exhibits two soil groups in terms of aggregation (Table 10): group two and group three, covering areas of 183.01 and 294.67 hectares, respectively. This finding is in line with a report conducted by Yeneneh et al., (2024) in the Suha watershed in the northwest highland of Ethiopia.

Table 10. Watershed soil aggregate scores with their respective soil group class

No.	Aggregate score(Q)	Group	Area (ha)	Area %
1	0.33-0.66	2	183.01	38.3
2	>0.66	3	294.67	61.7

A significant portion of the Andit Tid watershed, specifically 54.72%, is characterized by a soil depth ranging between 100 and 150 cm (Table 11). Moreover, 14.4% of the watershed area comprises soil depths exceeding 150 centimeters, indicating substantial variability in soil depth across the landscape. Conversely, there are smaller percentages of watershed areas with shallower soil depths: only 0.3% of the region features depths ranging from 10 to 15 centimeters, while 5.9% of the watershed features soil depths spanning from 25 to 50 centimeters. This distribution underscores the diverse soil profiles within the Andit Tid watershed, highlighting the importance of understanding and managing this variability for effective land use planning and soil conservation efforts.

Table 11. Soil depth status of the watershed

No.	Soil Depth (cm)	Av. Soil depth (cm)	Area (ha)	Area (%)
1	10-15	12.5	1.46	0.30
2	25-50	37.5	28.14	5.89
3	50-100	75	118.06	24.71
4	100-150	125	261.39	54.72
5	>150	175	68.65	14.37

4.1.4. Tolerable Soil Loss Limit (TSLL)

The mean annual tolerable soil loss limit (TSLL) of the watershed was estimated to be 10 t $ha^{-1}yr^{-1}$ (Table 12). This value is within the range reported by Hurni, (1983) (2-22 t ha^{-1} yr^{-1}) for all parts of Ethiopia. However, this value exceeds the reported soil formation rate of approximately 2 t ha^{-1} yr^{-1} in the Shoa area, which is within an altitudinal range greater than 3000 m a.s.l. (Hurni, 1983). The maximum TSLL was recorded in the southern and southeastern parts of the watershed, which are dominated by grassland and shrubland (Figure 11), while the minimum TSLL was observed in the northwestern part of the watershed, which encompasses SW2 and SW3, where sediment and surface runoff gauge stations are installed. This area is covered with *Eucalyptus* species, and a low soil formation rate is expected according to Hurni, (1983) coupled with low TSLL due to low organic matter and soil nutrient content, low pH, and high bulk density compared with those in areas covered with other tree species (Liang et al., 2016). In contrast, cultivated land exhibited a greater

TSSL than did the area covered by *Eucalyptus*. This could be attributed to active mechanical, biological and chemical destruction during plowing and cultivation (Hurni, 1988).

Table 12. The TSLL of the watershed with its area coverage

No.	TSLL	Area (ha)	Area %
1	7.5	19.6	4.1
2	8.8	110.0	23.0
3	10.0	51.3	10.7
4	11.3	217.1	45.4
5	12.5	79.8	16.7

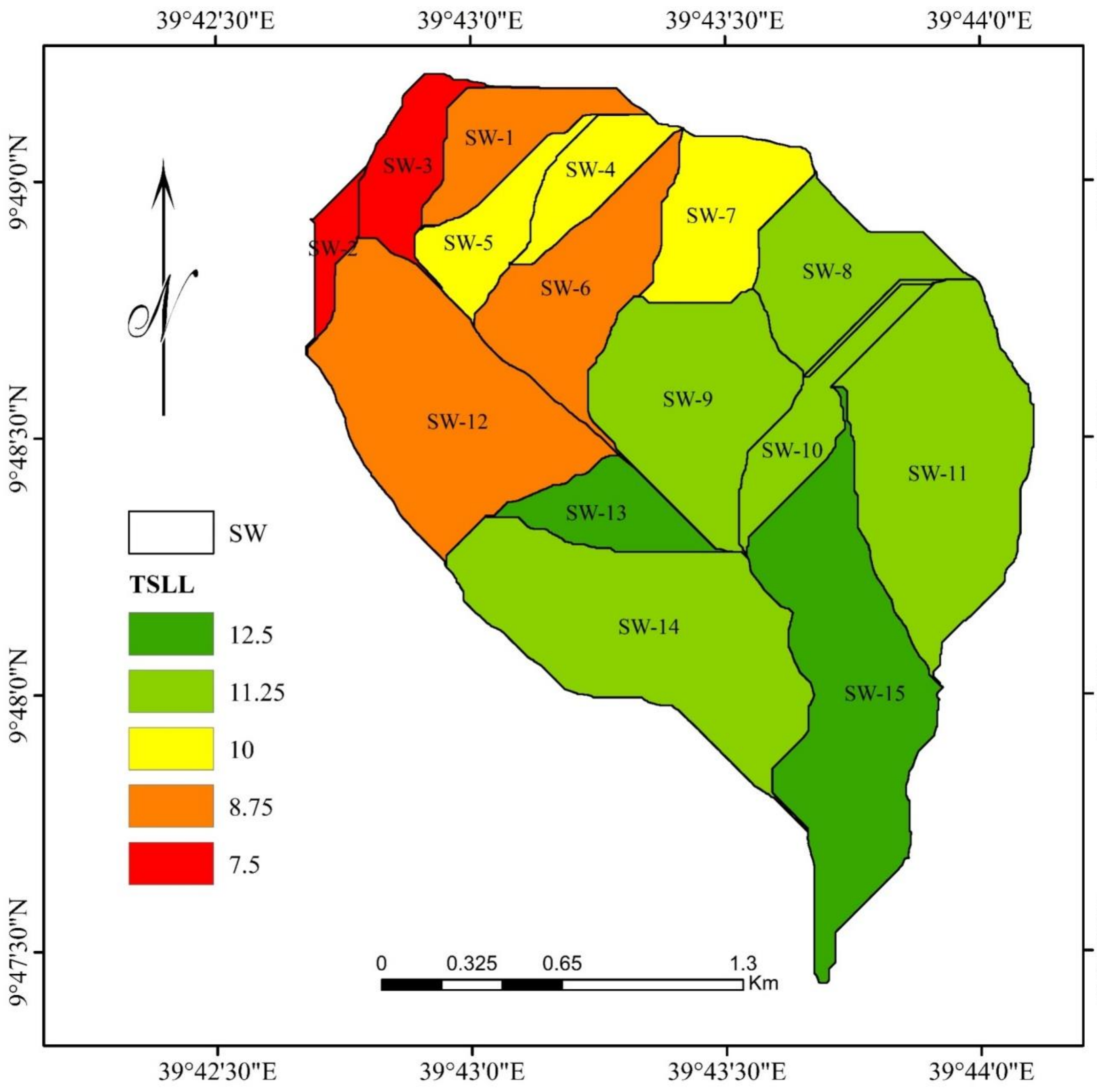


Figure 11. Spatial distribution of TSLL within the watershed

4.2. Erosion Hotspot Area

4.2.1. Land use and Soil Map of Andit Tid Watershed

4.2.1.1. Land use Map

Four dominant land use/land cover types were found in the Andit Tid watershed (Figure 12). A larger area of the watershed was covered by cultivated land, especially in the northern and southern parts of the watershed, accounting for 56.05% of the total area. The eastern and western parts of the watershed are dominated by grass (25%) and forest (7%), respectively.

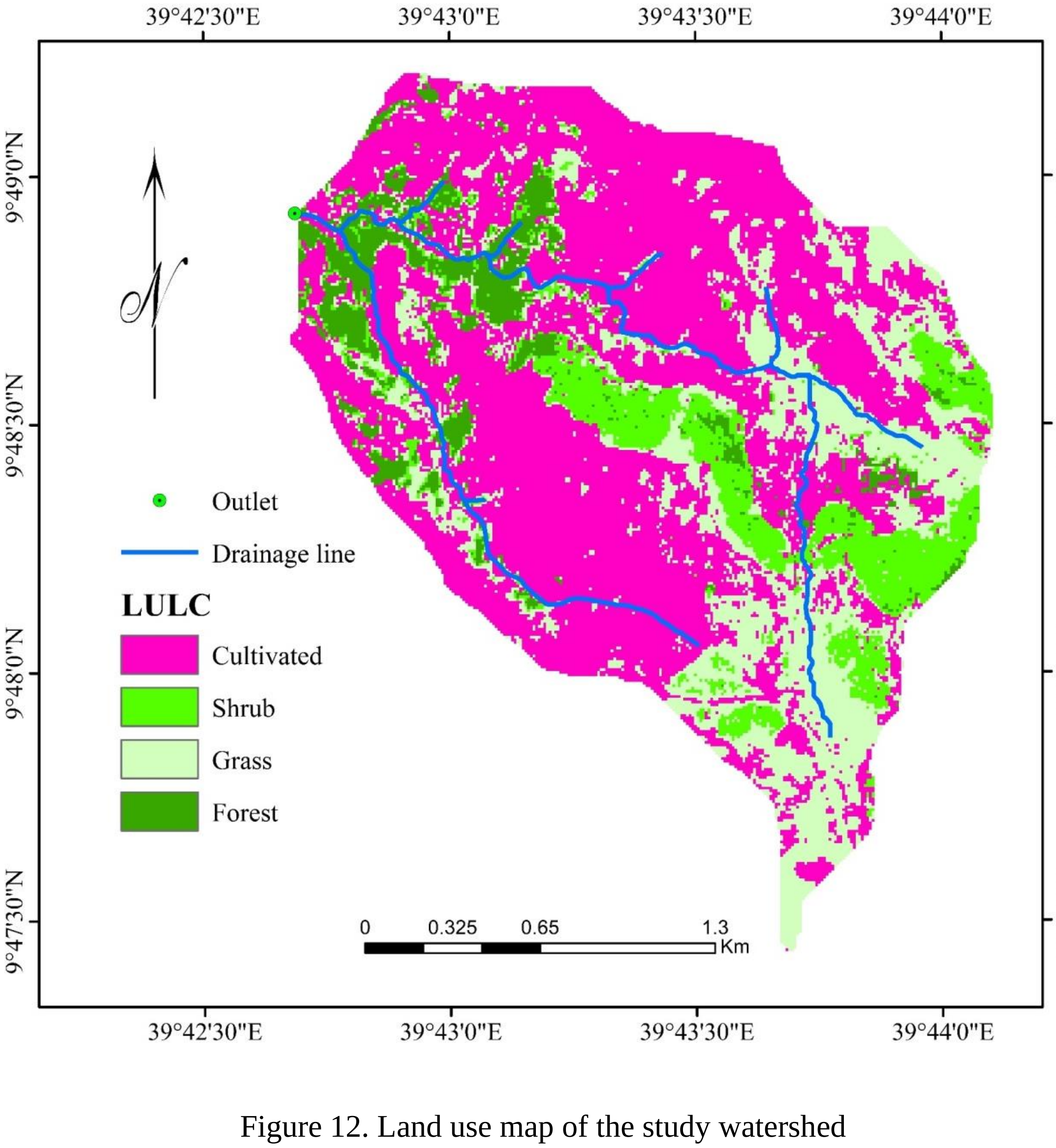


Figure 12. Land use map of the study watershed

Table 13. Description of major land use and land cover types of the study watershed (FRA, 2020; Tadese et al., 2021)

No.	LULC	Description
1	Forest land	Land covering over 0.5 hectares, they must be at least 2 meters tall, have a canopy cover exceeding 20%. Alternatively, the trees should have the potential to attain these thresholds naturally over time.
2	Shrub land	Land with shrubs or bushes should have a canopy cover or combined cover not exceeding 10%. These woody perennial plants should reach a height of 2 meters at maturity in their natural habitat.
3	Grass land	Land covered by permanent grass which are used for grazing purpose
4	Cultivated land	Land used for the purpose of crop production. It includes fallow land and homestead.

The accuracy of classification was assessed to be confident about how well the data fit the ground situation. Accordingly, an 89.9% overall accuracy and 82.6% kappa coefficient were obtained.

Table 14. Land use classification accuracy assessment confusion matrix (Monserud, 1990)

	Cultivated Land	Shrub Land	Grass Land	Forest Land	Row Total	User's Accuracy
Cultivated Land	**37**	0	1	0	38	97.4
Shrub Land	0	**2**	0	0	2	100.0
Grass Land	3	0	**11**	0	14	78.6
Forest Land	3	0	0	**12**	15	80.0
Column Total	43	2	12	12	**69**	
Producer's Accuracy	86.0	100.0	91.7	100.0		

Kappa coefficient=82.6 Overall Accuracy=89.9%

4.2.1.2. Soil Map

The dominant soil textural classes in the Andit Tid watershed are clay loam (32.14%), loam (46.2%), sandy clay loam (16.96%), and sandy loam (4.96%), as depicted in Figure 13. The spatial distribution revealed that the loam textural class prevailed in the northern and southern regions, while the eastern, western, and central regions were characterized by clay loam, sandy clay loam, and sandy loam, respectively.

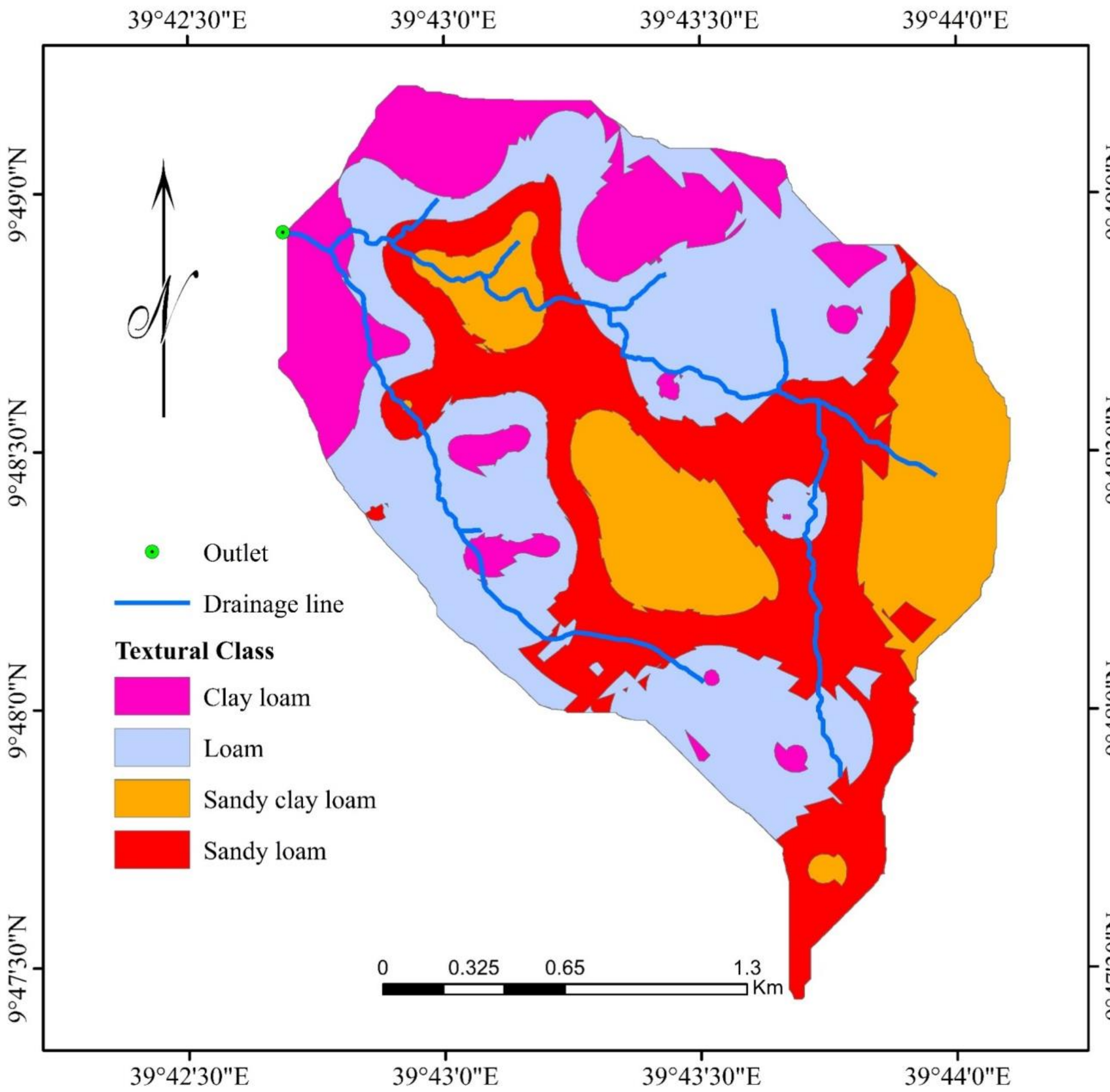


Figure 13. Soil map of the study watershed

Note: The map was generated by giving a numerical fixed value to the soil textural class.

4.2.2. Streamflow Simulation

4.2.2.1. Sensitivity Analysis

The sensitivity analysis results based on the stream flow parameters revealed that for the Eleventh parameters (Table 15), seven of the parameters were highly sensitive to the stream flow output, with sensitivity ranks of ALPHA_BF, ESCO, CH_N2, CN2, CH_K2, RCHRG_DP and SOL_AWC Table 15. In line with this result, Gashaw et al.,(2021) reported that the streamflow parameters ALPHA_BF, CH_N2, CN2, and CH_K2 were sensitive in a simulation test within the same agroecosystem zone. In addition, the parameters ESCO and SOL_AWC were also found to be highly sensitive to stream flow (Admas et al., 2022; Lemma et al., 2019). The parameters GWQMN, GW_DELAY, and GW_REVAP exhibited moderate sensitivity, while REVAPMN exhibited low sensitivity, as also supported by other studies (Betela, 2015; Gashaw et al., 2021; Tiki et al., 2016).

Table 15.Stream flow parameter sensitivity with their fitted values

Parameter Name	Fitted Value	t-Stat	P Value	Sensitivity Rank
v_ALPHA_BF.gw	0.39	9.13	0.00	1
v_ ESCO. Hru	0.10	-5.86	0.00	2
v_CH_N2.rte	0.30	-3.65	0.00	3
r_CN2.mgt	0.07	-3.62	0.00	4
v_CH_K2.rte	104.99	-3.03	0.00	5
v_RCHRG_DP.gw	0.03	-1.76	0.08	6
r_ SOL_ AWC (...).sol	0.05	1.44	0.15	7
v_GWQMN.gw	4150.00	0.66	0.51	8
v_GW_DELAY.gw	475.00	-0.50	0.62	9
v_GW_REVAP.gw	0.16	-0.47	0.64	10
v_REVAPMN.gw	1	0.11	0.91	11

where - v_ is the existing parameter value to be replaced by a given value and
r_: the existing parameter value is multiplied by (1+ given value).

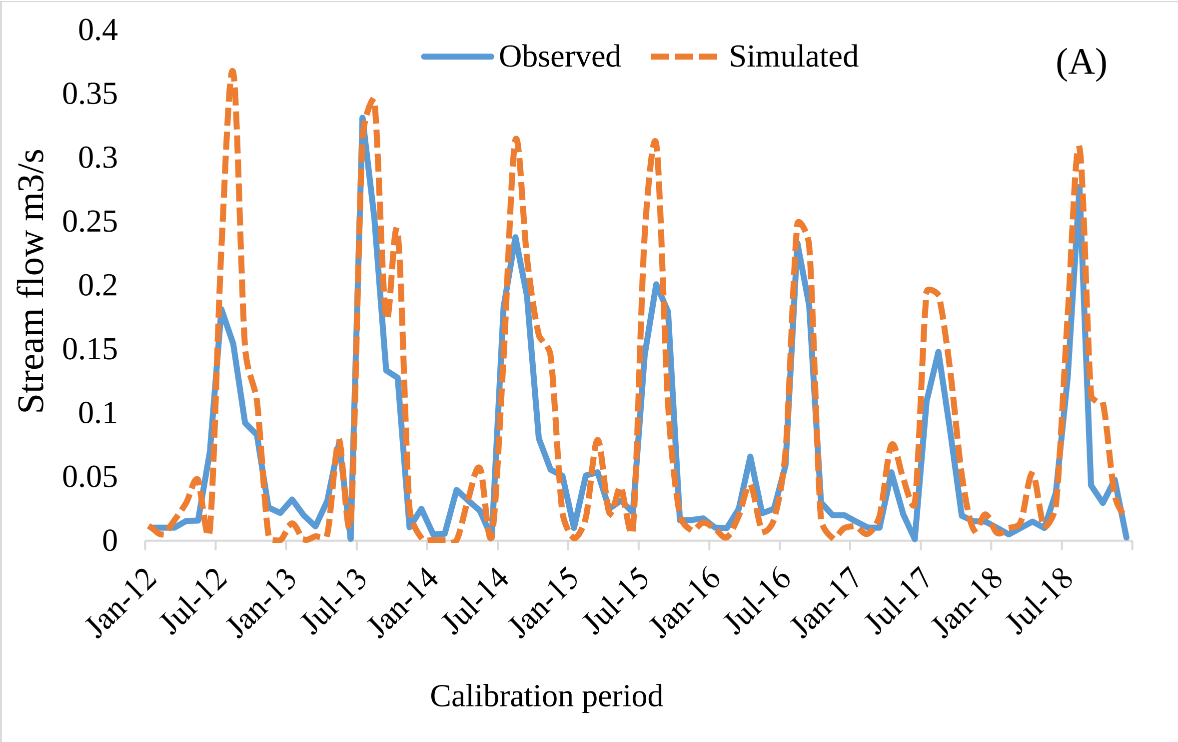
4.2.2.2. Calibration and Validation of Stream Flow

Following the completion of the sensitivity analysis, the calibration phase was initiated, wherein the model's parameters were adjusted to optimize its performance. Accordingly, an R^2 value of 0.84, an NSE value of 0.67, a PBIAS value of 29.5, and an RSR value of 0.56 were obtained (Table 16). This performance suggests that the simulation falls within an acceptable range (Moriasi et al., 2007, 2015). On the other hand, the validation phase, which was conducted following calibration, also revealed notable enhancements across all the statistical tools (Table 16). For instance, the R^2 increased to 0.87, indicating a closer fit between the simulated and observed data. The NSE improved to 0.73, reflecting a higher level of agreement between the observed and simulated values. Moreover, there was a decrease in the PBIAS to 20.5, suggesting a reduction in bias between the simulated and observed data, while the RSR decreased to 0.52, indicating improved model accuracy. These improvements were observed during the validation period, which shows the model's enhanced predictive capability.

Table 16. Calibration and validation results of the statistics for stream flow

Stream flow simulation	Model performance			
	R^2	NSE	PBIAS	RSR
Stream flow Calibration period (2012-2018)	0.84	0.67	-23.5	0.56
Stream flow Calibration period (2019-2022)	0.87	0.73	-20.5	0.52

The hydrograph of the streamflow simulation highlights an admirable alignment between the peaks and troughs of the simulated and observed streamflow patterns within the watershed (Figure 14). However, noticeable differences between the measured and simulated stream flows were observed. Such variations could occur from several sources, including potential inaccuracies in the recording of streamflow and weather data, as well as inherent limitations within the model itself that hinder its ability to fully capture the complexity of streamflow dynamics within the watershed. Although significant improvements have been made in refining the model's statistical performance during validation, slight deviations persist in the streamflow hydrograph across both the calibration and validation phases. The ongoing presence of these differences underscores the complex interaction between data precision, model reliability, and the inherent complexity of hydrological systems.



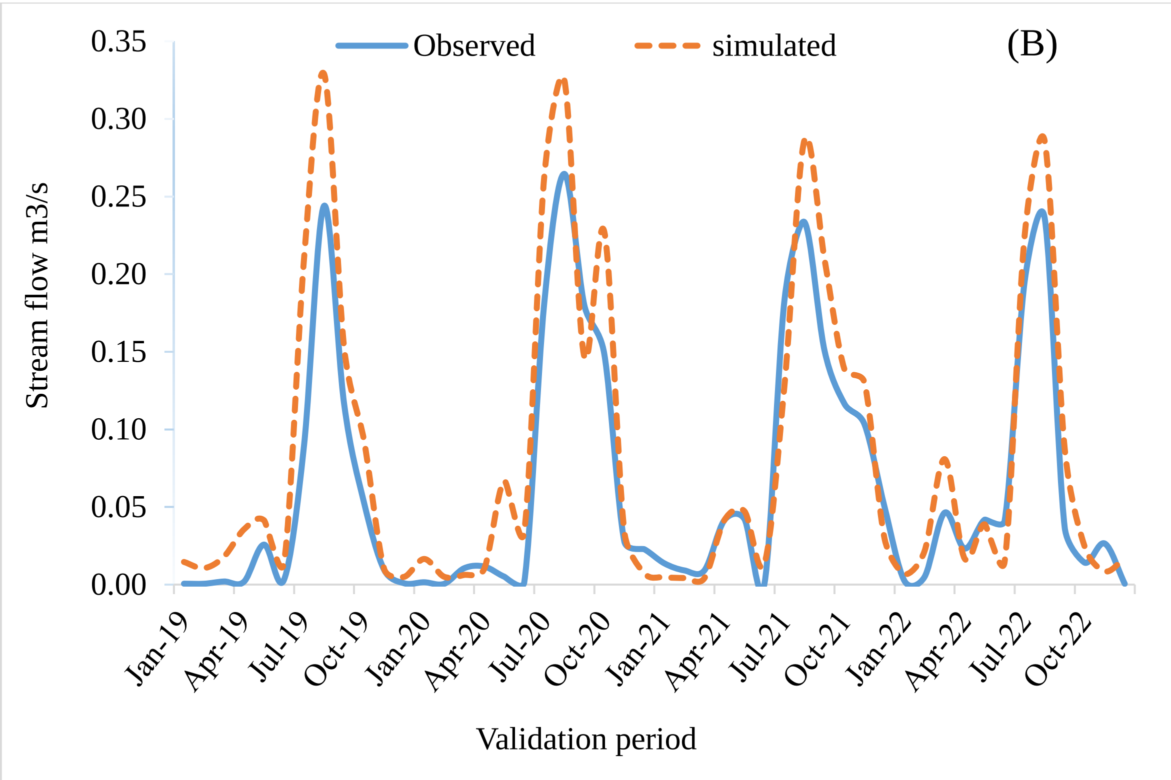


Figure 14. Stream flow hydrograph during the calibration (A) and validation (B) periods

4.2.3. Sediment yield simulation

4.2.3.1. Sensitivity Analysis

All ten sediment parameters considered for the sediment yield parameter sensitivity analysis exhibited varying degrees of sensitivity (Table 17). Among them, seven were found to be highly sensitive for sediment yield output, with the following sensitivity order: USLE_P, USLE_K, and USLE_C for cultivated land; CH_COV2; CH_COV1; USLE_C for *Eucalyptus* Forestland; and SPCON. Similar findings have been reported in various parts of Ethiopia (Admas et al., 2022; Betela, 2015; Zeberie, 2020). The USLE_C of cultivated land was more sensitive than that of other land use types in the watershed, followed by that of Eucalyptus forestland. Conversely, USLE_C for grassland and USLE_C for shrubland exhibited lower sensitivity to sediment yield output in the watershed. This finding contrasts with the results of Admas et al., (2022) and Gashaw et al., (2021) but aligns with the findings of (Lemma et al., 2019).

Table 17.Sediment yield parameter sensitivity with their fitted values

Parameter Name	Fitted Value	*t*-Stat	*P* Value	Sensitivity Rank
v _USLE_ P. mgt	0.01	-5.13	0.00	1
v _USLE_K (...).sol	0.02	-3.81	0.00	2
v _USLE_C{AGRC}. plant.dat	0.02	-2.28	0.02	3
v_CH_COV2.rte	0.69	1.88	0.06	4
v_CH_COV1.rte	0.42	1.76	0.08	5
v _USLE_C{EUCA}. plant.dat	0.22	-1.24	0.22	6
v _SPCON. Bsn	0.001	0.81	0.42	7
v _SPEXP. Bsn	1.33	-0.63	0.53	8
v _USLE_C{RNGB}. plant.dat	0.28	-0.10	0.92	9
v _USLE_C{PAST}. plant.dat	0.47	0.05	0.96	10

where - v_ is the existing parameter value to be replaced by a given value and r_ is the existing parameter value multiplied by (1+ given value).

4.2.4. Calibration and Validation of Sediment Yield

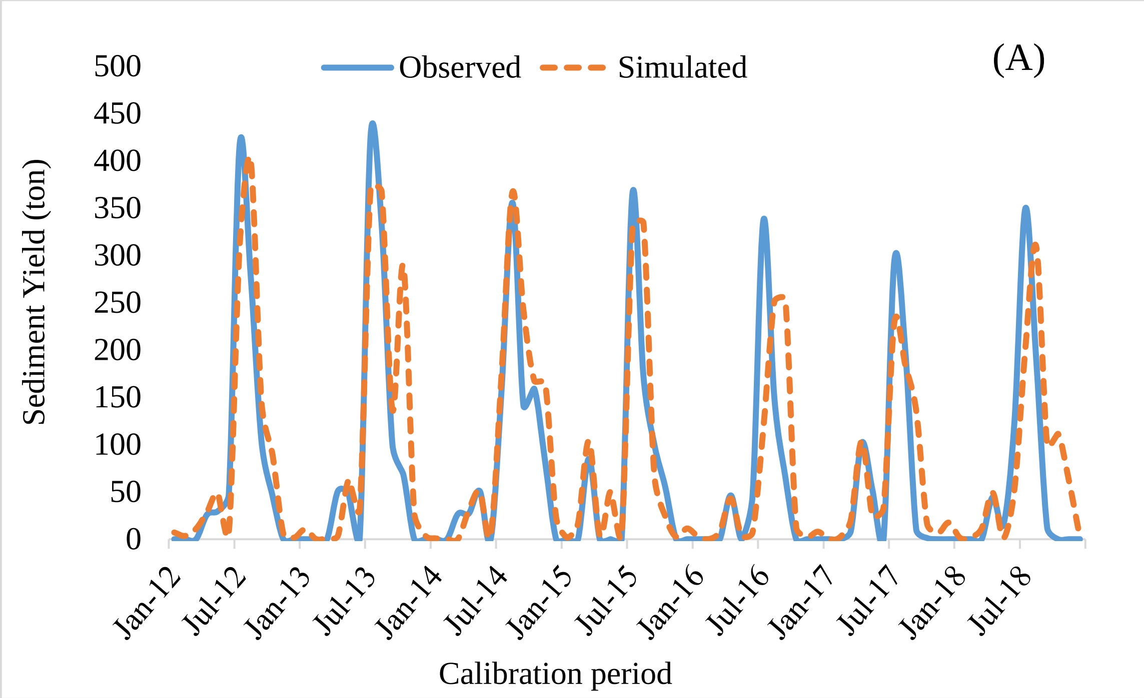
Sediment calibration and validation were also conducted after identifying the sediment-sensitive parameters (Table 17). The results indicate that the model accurately captured both the lowest and peak times of sediment load in the watershed, although there was a slight variation similar to that of the streamflow simulation. However, sediment calibration demonstrated slightly lower statistical performance, with an R^2 of 0.72, an NSE of 0.68, a PBIAS of -19.4, and an RSR of 0.56, albeit still falling within the "good" category (Table 18).

The validation findings also indicate that, akin to the calibration phase, there is an underestimation of sediment simulation compared to the observed values. Nevertheless, during validation, satisfactory agreement is observed between the simulated and measured sediment, as indicated by the following statistical measures: R^2 of 0.69, NSE of 0.67, PBIAS of -4.3, and RSR of 0.58, surpassing those obtained during calibration (Table 18).

Table 18. Statistical calibration and validation results for sediment yield

Sediment yield simulation	Model performance			
	R^2	NSE	PBIAS	RSR
Sediment calibration period (2012-2018)	0.72	0.68	-19.4	0.56
sediment Validation period (2019-2022)	0.69	0.67	-4.3	0.58

Interestingly, while the model overestimates the predicted streamflow dynamics, it tends to consistently underestimate sediment levels in both the calibration and validation seasons even though it follows the same trend as the crest and trough models (Figure 15). Several factors might contribute to this discrepancy. One potential explanation lies in the inherent challenges associated with accurately collecting suspended sediment data, which could lead to an overestimation of the observed values. Additionally, the model itself may face limitations in accurately capturing the complicated processes involved in sediment transport and deposition. The complex balance between data collection methods and modeling emphasizes the challenge of precisely representing sediment dynamics within hydrological models. Notably, equivalent differences have been noted in previous research across various geographic areas throughout the country (Betela, 2015; Gashaw, et al., 2021).



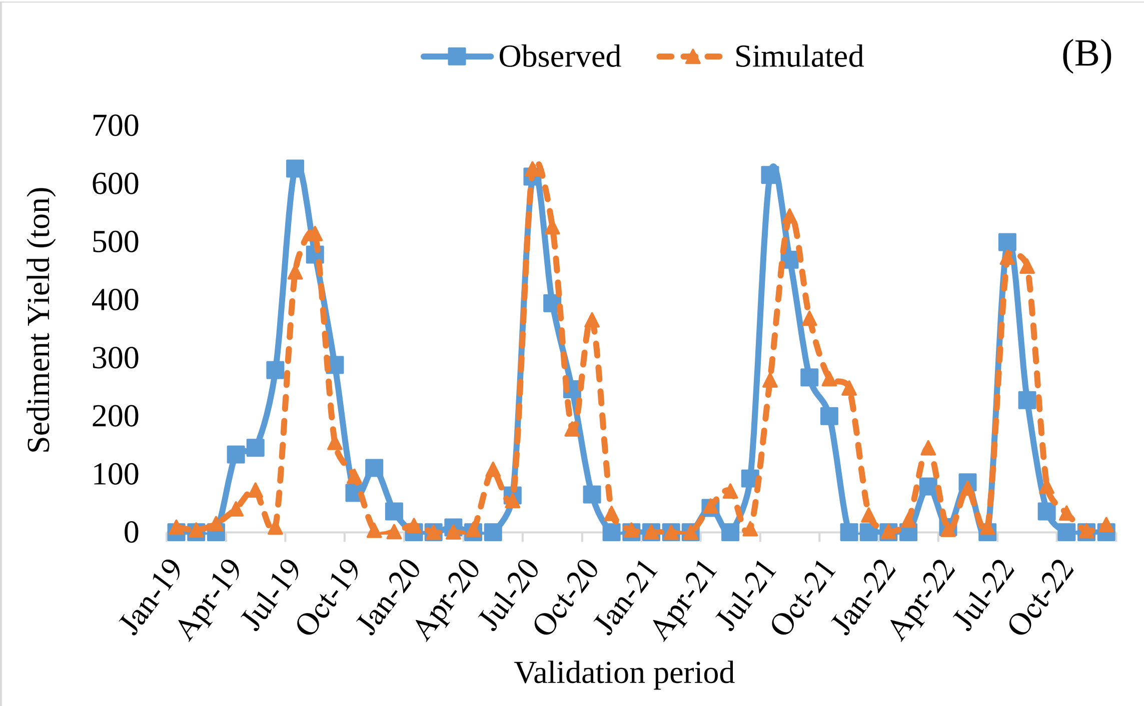


Figure 15. Sediment yield hydrographs during the calibration (A) and validation (B) periods

4.3. Erosion Hotspot Area of the Watershed

4.3.1. Sediment Delivery Ratio (SDR) of the Watershed

The sediment delivery ratio of the Andit Tid watershed was 0.47, indicating that approximately 47% of the eroded soil displaced its original place due to erosion agents and reached and passed through the watershed outlet. This finding closely aligns with the value of 0.48 reported by Abebe & Woldemariam, (2024) for the Ayigebre watershed within the same agroecological zone. Conversely, it notably surpasses the reported ratio of 0.36 from a study by Serbessa, (2021) at the Geffersa storage dam. Similarly, the sediment delivery ratio of the sub watersheds (SW) was greater than that of the main watershed, ranging from a minimum of 0.38 at SW 14, 15, and 11 to a maximum of 0.65 at SW 2 (Figure 16). This is due to the reality that SW2 have small area coverage than the other catchment. This makes the sub watershed to experience more efficient transport of sediment downstream, contributing to higher SDRs than larger catchment. Because larger catchments often have more depositional features that can act as sediment traps that is transported downstream. Smaller catchments may have less of these features, leading to less sediment storage. On the other hand, smaller catchments typically have smaller stream channels, which may have less capacity to retain sediment compared to larger channels in larger catchments (Mukhlisin & Sukoco, 2011).

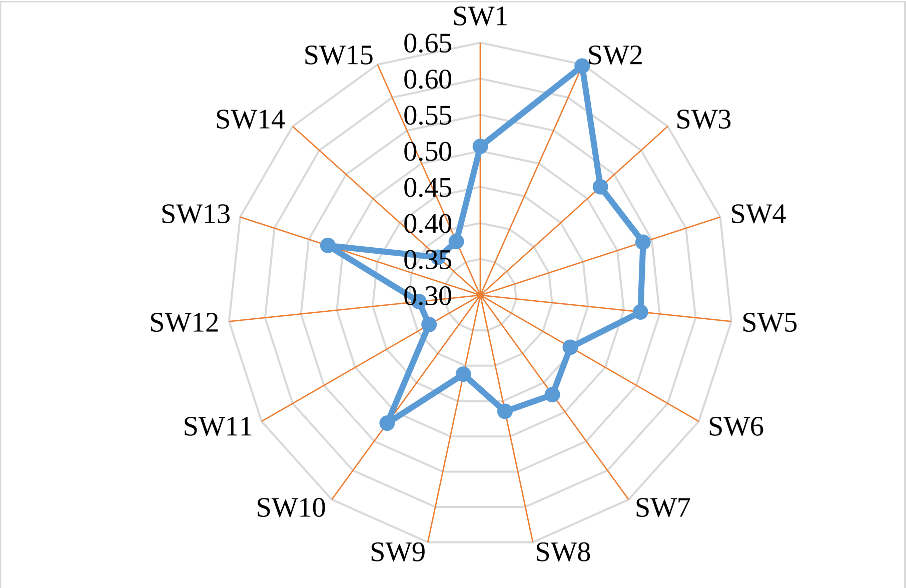


Figure 16. Sediment delivery ratio at the sub watershed level of the watershed

4.3.2. Erosion Rate of the Study Watershed

The average annual erosion rate of the Andit Tid watershed from 1998–2022 is 28.7 t ha^{-1} yr^{-1}. The findings of this study agreed with those of Woldemariam et al., (2018) 22.3 t ha^{-1} yr^{-1} and 22.6 t ha^{-1} yr^{-1} in the Aygebire watershed (Abebe & Woldemariam, 2024). The average annual soil loss rate of the watershed was summarized into five severity classes: very slight (0-10), slight (10-20), moderate (20-30), high (30-40), severe (40-50) and very severe (>50) (Figure 17), as adopted from (Olika et al., 2023).

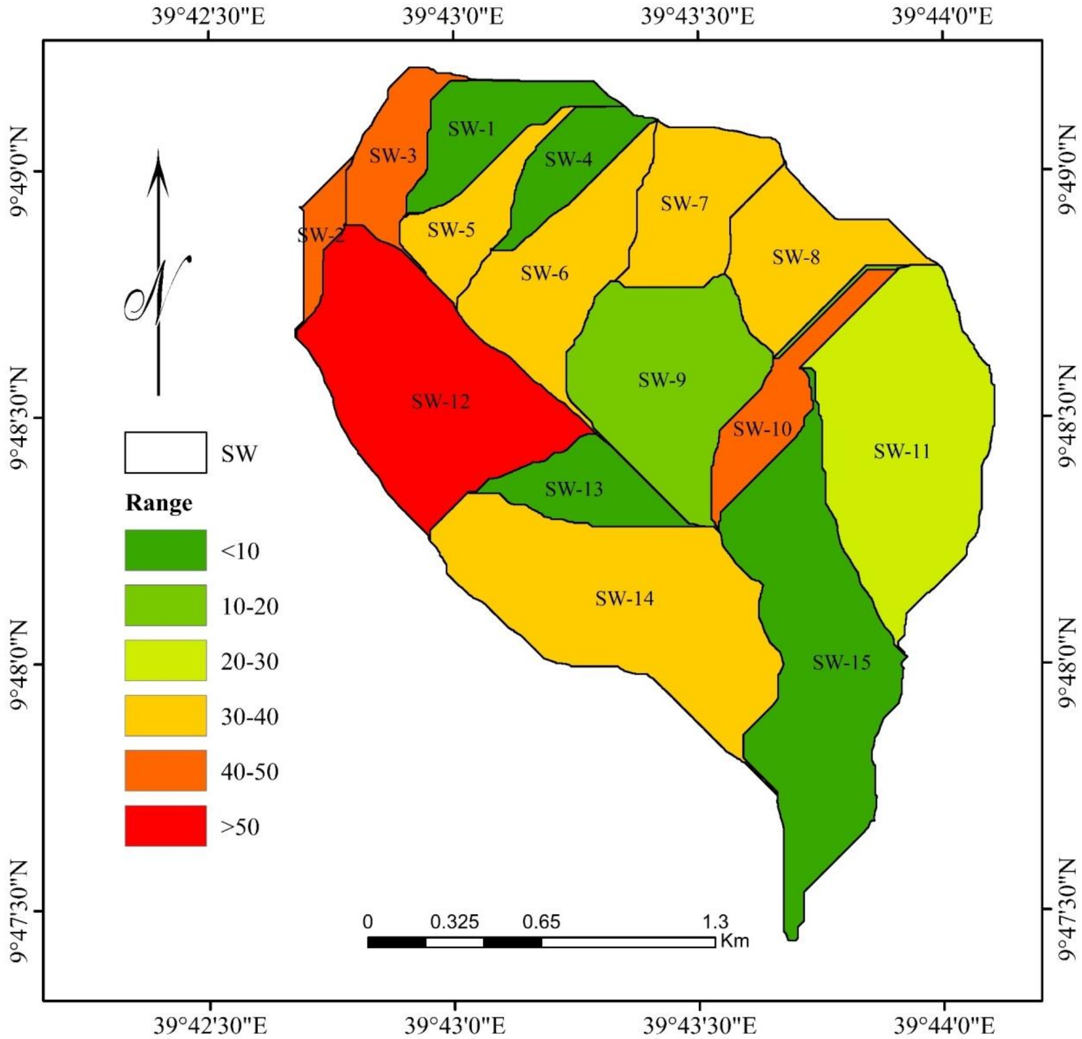


Figure 17. Spatial distribution of the erosion rate

4.3.3. Erosion Hotspot Area Identification at the Sub watershed Level

The erosion hotspot area of the watershed was identified by comparing the erosion rate to the maximum allowable soil loss rate of the watershed (Table 19). Based on the analysis of erosion rate deviations from their target soil loss tolerance limit (TSLL) in sub watersheds, the severity of soil erosion was categorized into six distinct classes: positive 0-10 t $ha^{-}1$ yr^{-1}, negative 0-10 t $ha^{-}1$ yr^{-1}, negative 10-20 t $ha^{-}1$ yr^{-1}, negative 20-30 t $ha^{-}1$ yr^{-1}, negative 30-40 t $ha^{-}1$ yr^{-1}, and negative > 40 t $ha^{-}1$ yr^{-1}, each with corresponding area coverage (Table 19). Overall, approximately 77.07% of the watershed flailed under the erosion risk class, while only 22.92% remained unaffected by erosion risk (Table 19).

Table 19. Erosion hotspot area of the watershed based on the rate deviation from the TSLL.

Deviation of erosion rate from TSLL	Severity class	Area (ha)	Area (%)	Included SWs
+(0-10)	well conserved (Free)	109.51	22.92	SW1, SW4, SW13, SW15
-(0-10)	slight sever	45.03	9.43	SW9
-(10-20)	Moderate sever	64.37	13.48	SW11
-(20-30)	Highly sever	162.59	34.04	SW5, SW6, SW7, SW8, SW14
-(30-40)	Very highly sever	34.60	7.24	SW2, SW3, SW10
- (>40)	Extremely severe	61.59	12.89	SW12

- The (-) sign indicates soil loss greater than the TSLL, and the (+) symbol indicates soil loss less than the TSLL

Furthermore, Figure 18Figure 19 shows that four sub watersheds, SW1, SW4, SW13 and SW15, exhibited soil loss rates lower than the TSLL. However, the remaining eleven SWs exhibited soil loss rates above the TSLL, ranging from 7.8 t ha^{-1} yr^{-1} to 47.5 t $ha^{-}1$ yr-1. Consequently, this finding revealed the need for strong conservation measures to intervene in SWs by prioritizing their erosion risk.

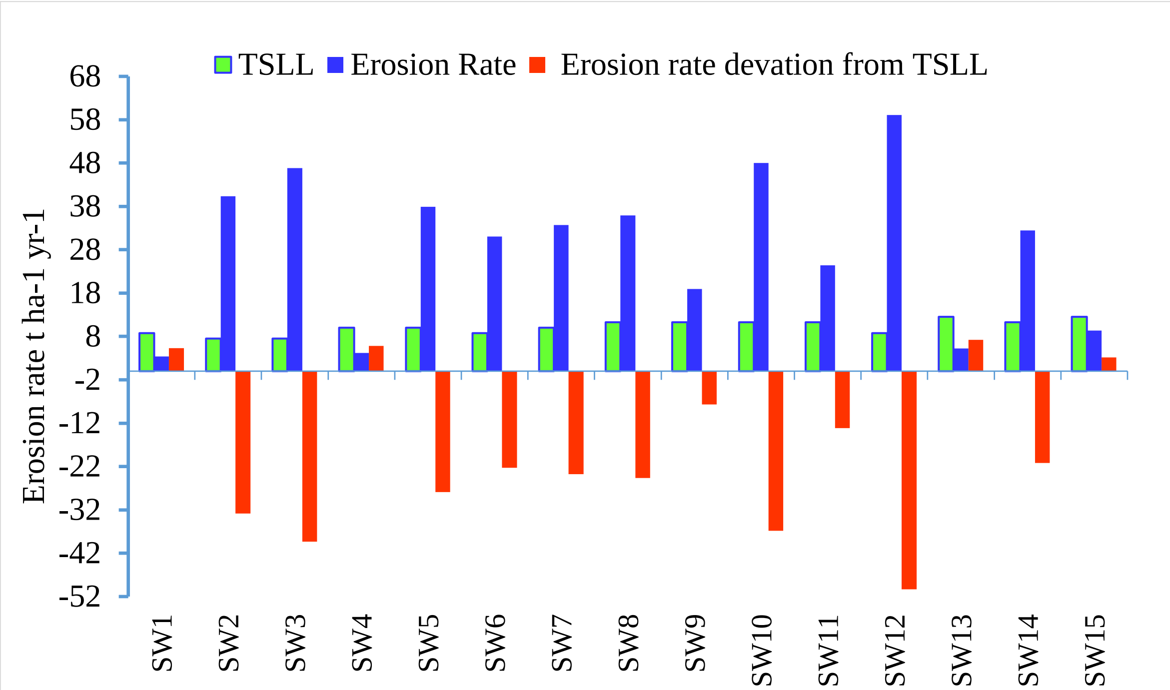


Figure 18. Erosion rate deviation against the TSSL of the sub watershed

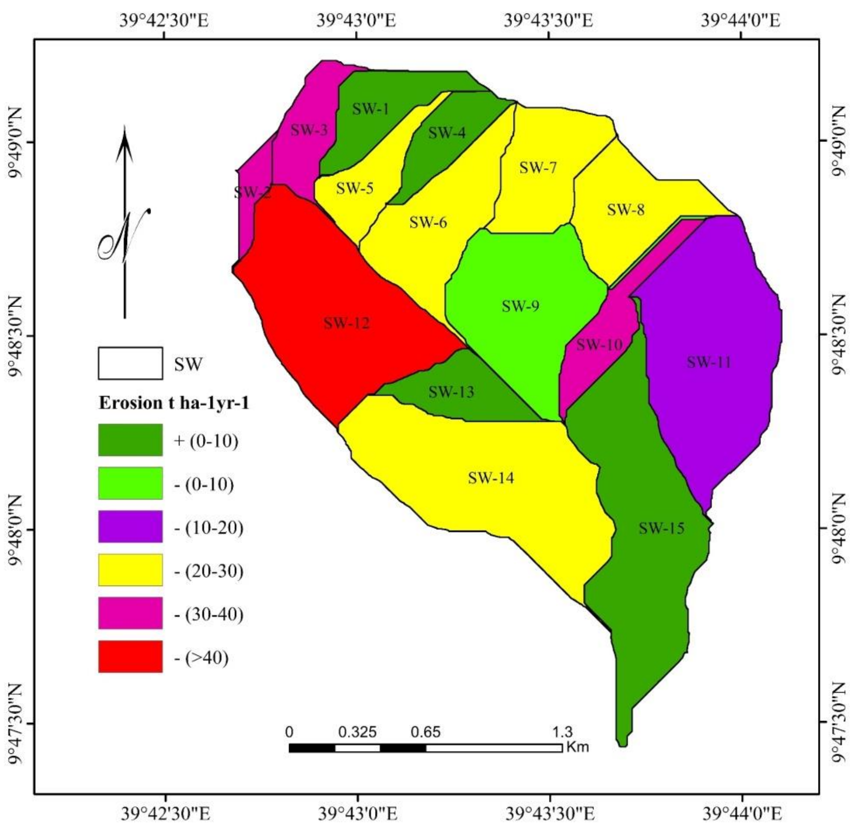


Figure 19. Spatial distribution of erosion hot spot areas with deviation from TSLL

4.4. Impact of Best Soil Conservation Practices on Soil Erosion

4.4.1. Watershed Level Impact of Best Soil Conservation Practices on Soil Erosion

The mean annual erosion rate of the watershed during the simulation period was 28.7 t $ha^{-1}yr^{-1}$. The SSB, GT, RF, SSB & GT, and SSB & RF implementation scenarios reduced the erosion rate of the watershed to 8.9, 24.6, 15.9, 8.44, and 5.5 t $ha^{-}1$ yr^{-1}, respectively (Figure 20). Among the best soil conservation practices (BSCP*s*), SSB and RF had the greatest effectiveness in reducing erosion (80.8%), followed by SSB and GT (70.6%). This demonstrates that compared with single measures, integrated soil and water conservation practices are more effective at conserving watersheds (Desta et al., 2017; Erkossa et al., 2018). The SSB scenario shows approximately 68.9% effectiveness in the Andit Tid watershed. This finding aligns with a report by Herweg & Ludi, (1999), which demonstrated 69.3% effectiveness in the same watershed through an experimental study conducted within a 28% slope limit. Additionally, this result is consistent with reports of 63.5% effectiveness in the Blue Nile Basin Amdihun et al., (2014) and 65% effectiveness in the Ethiopian highlands (Dibaba et al., 2021). Conversely, effectiveness ranged from a minimum of 6.9% in India Uniyal et al., (2020) to a maximum of 81.3% in Ethiopia according to simulation studies (Demissie et al., 2013). The implementation of SSB in the Andit Tid watershed reduced the erosion rate from 28.7 t $ha^{-}1$ yr^{-1} to 8.9 t $ha^{-}1$ yr^{-1}. However, this effectiveness causes the erosion rate of the watershed to be below its tolerable soil loss limit (TSLL) of 10 t $ha^{-1}yr^{-1}$.

The implementation of Scenario GT also showed an average effectiveness of 14.3% (Figure 20), reducing the watershed erosion rate from 28.7 t ha^{-1} yr^{-1} to 24.6 t $ha^{-1}yr^{-1}$. This finding is consistent with the 13.7% effectiveness reported by Gashaw et al., (2021) in the Gumera watershed, which shares the same agroecology as the Andit Tid watershed. A similar effectiveness of approximately 20% was reported in a simulation study by Admas et al., (2022). However, Zeberie, (2020) reported a greater erosion reduction effectiveness of 75% for GTs in the Akaki watershed in the upper Awash Basin. Similarly, a 73% effectiveness was recorded in the same watershed for the 28% slope class through an experimental study (Herweg & Ludi, 1999). The underestimation observed in simulation studies may be attributed to biases in model simulation effectiveness. Despite achieving 14.3% effectiveness in the Andit Tid watershed, the implementation of GT cannot reduce the erosion rate to the tolerable soil loss limit (TSLL) of the watershed. Following the implementation of the GT, the erosion rate remained at 24.6 t $ha^{-1}yr^{-1}$. With this rate, the erosion rate exceeded the TSLL of the watershed by 14.6 t $ha^{-}1$ yr^{-1}. On the other hand, Scenario RF shows 44.6% effectiveness (Figure 22), reducing the erosion rate of the watershed from 28.7 t $ha^{-1}yr^{-1}$ to 15.9 t $ha^{-1}yr^{-1}$. This finding aligns with the 45% effectiveness reported by Amdihun et al., (2014) in the Blue Nile Basin and the 24.9% reported by Roba et al., (2021) in the Dawe watershed, Wabi Shebelle River Basin, which share the same agroecology. However, lower erosion reduction efficiencies of 9.1% and 11.7% were reported by Betela, (2015) and Betrie et al., (2011), respectively, while a 73% effectiveness was reported by (Demissie et al., 2013). Despite achieving significant effectiveness, the watershed still experiences an annual soil loss rate of 5.9 t $ha^{-}1$ yr^{-1} above the TSLL after reforestation of areas with slopes greater than 30%.

To identify effective measures for minimizing the erosion rate of the watershed to equal or below the tolerable soil loss limit (TSLL), two combined measures were also evaluated. The combined SSB and GT scenario demonstrated 70.6% erosion reduction effectiveness. This result is almost comparable to the effectiveness of the SSB scenario, with a reduction of 0.5 t $ha^{-}1$ yr^{-1} (1.7%) more compared to SSB alone, reducing the erosion rate to 8.44 t $ha^{-}1$ yr^{-1}, which is below the TSLL of the watershed at 10 t $ha^{-}1$ yr^{-1}. However, the erosion rate of the watershed below its TSLL decreased. In contrast, SSB & RF emerged as a standout performer, boasting a high effectiveness rate of 80.8%. This combined strategy not only reduces the erosion rate of the entire watershed but also extends its success to the sub watershed level, achieving erosion rates that comfortably lie below the TSLL thresholds.

Remarkably, these findings resonate strongly with a prior report by Dibaba & Ebsa, (2022), which also documented a similarly high effectiveness rate of 77%. This consistency underscores the robustness and reliability of the proposed combined approach in effectively combating erosion within the watershed.

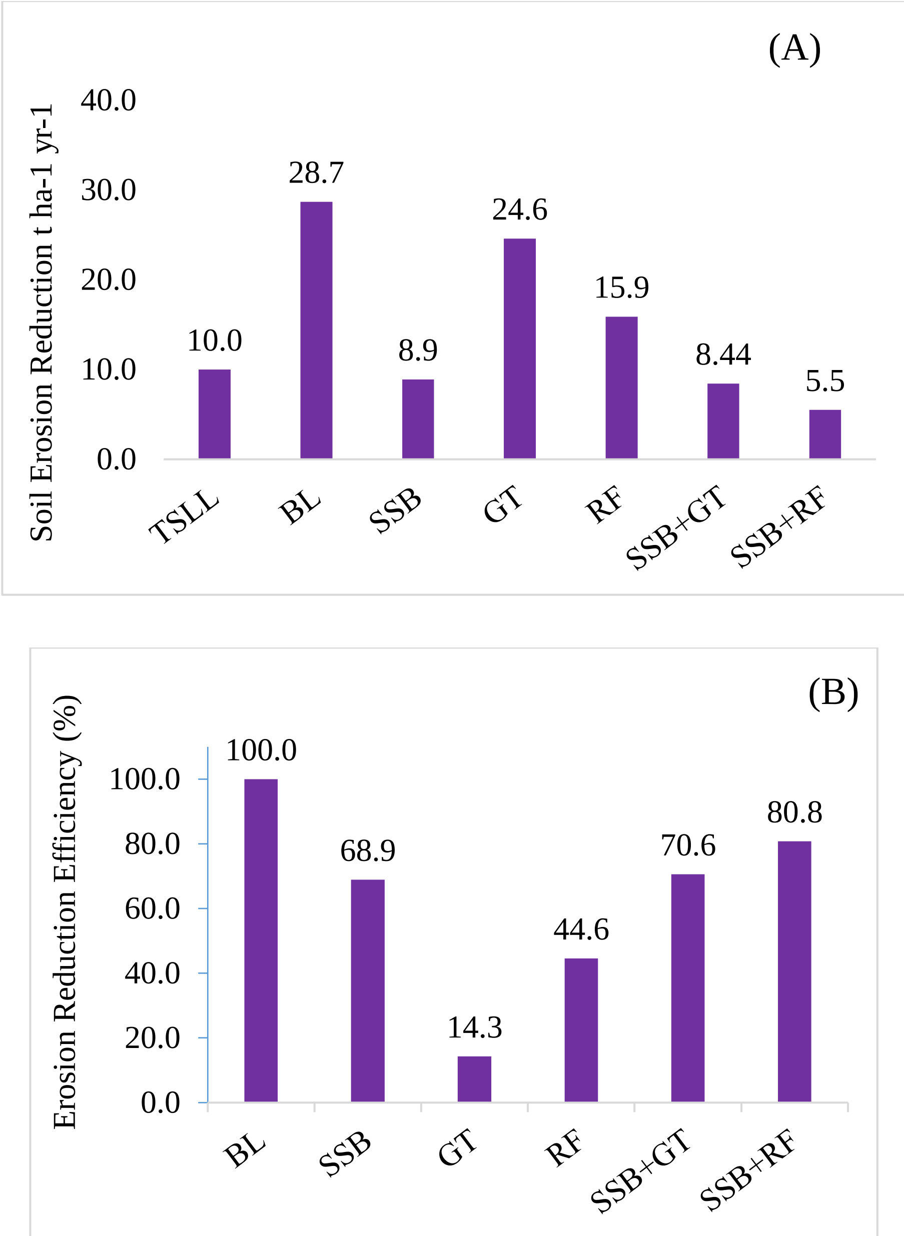


Figure 20. Mean annual erosion reduction efficiency of BSCPs t ha^{-1} yr^{-1} (A) and in % (B)

The implementation of the RF scenario removed areas with erosion rates greater than -30 t $ha^{-}1$ yr^{-1}, covering 20% of the watershed area. This action reduces the highly severe erosion area from 34% to 3%. The RF effectively improved highly severe, highly severe, and extremely severe erosion areas to slightly severe levels, and slight improvements were observed toward becoming risk-free (erosion below the TSLL). The implementation of scenario SSB increased the risk-free area from 22.9% at BL, 22.9% at GT, and 32.4% at RF to 54.6%. On the other hand, the implementation of SSB and GT increased the risk-free area to 64.2% and slightly improved the erosion severity area to 35.8%, compared to 45.4% in SSB, 47% in RF, 9.4% in GT, and 12.1% in BL (Table 20).

Severity of the erosion potential area under a given scenario

Soil loss rate t ha^{-1} yr^{-1}	Erosion severity class	Scenario (Area %					
		BL	GT	RF	SSB	SSB &GT	SSB & RF
+ (0-10)	Risk free	22.92	22.90	32.40	54.60	64.20	100.0
- (0-10)	slight sever	9.43	9.40	47.00	45.40	35.80	
- (10-20)	Moderate	27.55	44.50	17.60			
- (20-30)	highly sever	19.96	6.20	3.00			
- (30-40)	Very highly	7.24	4.10				
- (>40)	Extreme sever	12.89	12.89				

NB. A negative (-) indicates a rate/loss above the TSLL, and a positive (+) indicates a rate below the TSLL.

4.4.2. Sub watershed Level Impacts of Best Soil Conservation Practices on Erosion

The effectiveness of Scenario SSB ranges from a minimum of 28% at SW4 to a maximum of 79.6% at SW10 (Figure 21). Within this effectiveness range, the extreme severity class of SW12 is reduced to a slightly severe erosion severity class. Similarly, SW2 and SW3 changed to slightly severe erosion classes, with rates of 0-10 t ha^{-}1 yr^{-1} above the TSLL, and SW10 was classified as a well-established erosion severity class, shifting from the very high severity class. This scenario categorizes the sub watersheds into well-established and slightly severe erosion severity classes. On the other hand, the implementation of the GT scenario leaves SW2 and SW3 in the very highly severe class and minimizes the very highly severe erosion severity class of SW10 to a highly severe one. The severity of three sub watersheds, SW5, SW7, and SW8, decreased from the highly severe to moderately severe erosion severity classes (Figure 22). However, the GT scenario did not significantly reduce erosion in SW2, SW3, SW5, SW12, SW9 or SW11 (Figure 21). The RF scenario demonstrated an effectiveness ranging from 17.5% to 65% at SW8 and SW12, respectively. The implementation of the RF scenario reduced the extremely severe erosion risk in sub watershed SW12 to a slightly severe risk, largely due to the probability of large areas affected by RF. Similarly, SW2 and SW10 changed from highly severe to moderately severe erosion classes, while sub watersheds SW5, SW7, and SW8 also experienced a reduction from highly severe to moderately severe erosion classes (Figure 22).

Furthermore, the two integrated measures show better performance against erosion (Figure 21). The implementation of the SSB & GT scenario demonstrated erosion reduction efficiencies ranging from 28.6% to 75.6%. With this efficiency, sub watersheds SW2, SW3, SW8, SW11, and SW12 are converted to the slightly severe erosion class, while the other sub watersheds are categorized as well-established or erosion-free classes. This finding contrasts with Dibaba & Ebsa, (2022), who achieved better erosion reduction results through the implementation of SSB and GT in the Toba watershed. This difference may be attributed to variations in topography and other erosion control factors between the two watersheds. On the other hand, the implementation of the SSB & RF scenario demonstrated erosion reduction efficiencies ranging from a minimum of 51.6% in SW1 to a maximum of 91.3% in SW2. This scenario proves to be a more effective erosion reduction measure for areas with slopes greater than 30%. Sub watersheds with more extensive coverage of slopes greater than 30% exhibit better erosion reduction potential. Implementing SSB and RF reduces the erosion rate of sub watersheds to a level below the TSLL. These findings regarding the implementation of the SSB & RF scenario align with those of (Dibaba & Ebsa, 2022).

Generally, the implementation of all scenarios results in better performances for sub watersheds SW-1, SW-4, SW-13 and SW-15, which have erosion rates lower than their TSLL in the baseline scenario. Consequently, the application of these scenarios serves to fortify the resilience of these sub watersheds against erosion risks, ensuring that they maintain sustainable erosion rates well below the TSLL thresholds. Certain interventions were also found to be effective, particularly within specific sub watersheds. For instance, the implementation of the SSB strategy has proven beneficial for SW-7, SW-9, SW-10, and SW-14, effectively reducing the soil loss rate below the TSLL levels prescribed for these sub watersheds. Similarly, the combined approach of SSB and GT demonstrated positive outcomes for SW-5, SW-6, SW-7, SW-9, SW-10, and SW-14, contributing to a notable reduction in soil loss rates below their respective TSLL. Additionally, the implementation of RF specifically benefits SW-9, aiding in lowering the soil loss rate to levels below the TSLL thresholds established for this sub watershed (Figure 21).

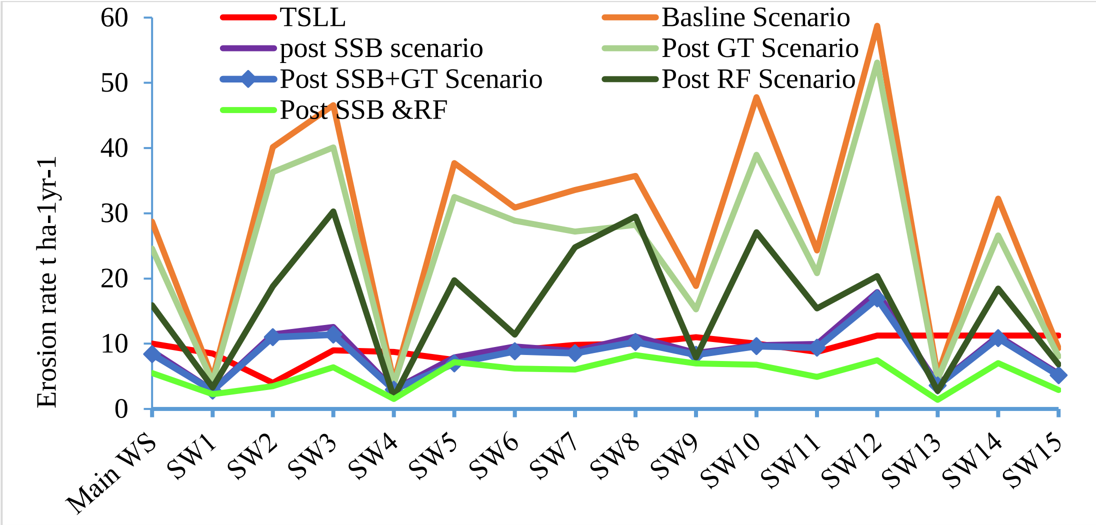


Figure 21. Sub watershed level erosion reduction effectiveness of BSCPs

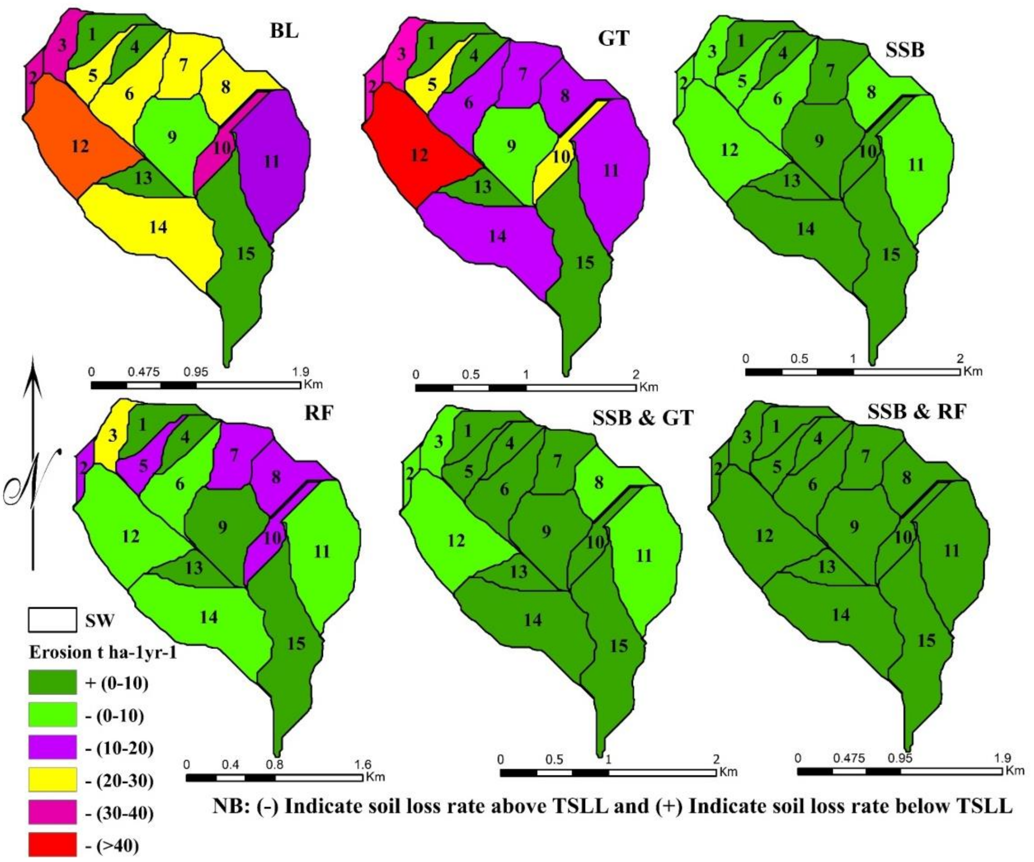


Figure 22. Spatial distribution of BSCPs impact on reduction of erosion

These findings underscore the targeted efficacy of the implemented scenarios, showcasing their ability to address erosion vulnerabilities at the sub watershed level. By tailoring interventions to the unique characteristics and needs of each sub watershed, these strategies not only mitigate erosion risks but also promote sustainability by ensuring that soil loss rates remain within acceptable limits, thus safeguarding the ecological integrity of the watershed as a whole. Because all sub watersheds have different erosion risk levels (Figure 18), prioritizing the implementation of BSCPs is imperative to respond quickly to highly degraded and degraded areas before they reach an irreversible stage (Admas et al., 2022; Gashaw et al., 2021). Accordingly, from the 1st to the 5th order, SW-12, SW-10, SW-3, SW-2 and SW-5, which need to be given priority based on their erosion rate deviation from their recommended maximum tolerable soil loss rate (TSLL), were selected. The final implementation in less risk areas ranks 15th, 14th, 13th, 12th, 11th and 10th for SW-13, SW-4, SW-1, SW-15, SW9 and SW11, respectively, which are less or risk-free areas.

In general, the sub watersheds exhibiting higher deviation rates should be prioritized over those with lower risks in terms of the deviation of the soil loss rate from the TSLL

Table 21. Erosion rate, recommended BSCPs and management priority of sub watersheds

Sub watershed	TSLL t ha^{-1} yr^{-1}	Av. soil erosion t ha-1 yr-1	Deviation (TSLL-Erosion) rate t ha^{-1}	Severity class	Recommended BSCPs	Priority for implementation
SW-1	8.75	4.7	4.1	Risk free	SSB & RF	13
SW-2	7.5	40.1	-32.6	V. high	SSB & RF	4
SW-3	7.5	46.6	-39.1	V. high	SSB & RF	2
SW-4	10	4.2	5.8	Risk free	SSB & RF	14
SW-5	10	37.7	-27.7	High	SSB & RF	5
SW-6	8.75	30.9	-22.1	High	SSB & RF	8
SW-7	10	33.5	-23.5	High	SSB & RF	7
SW-8	11.25	35.7	-24.5	High	SSB & RF	6
SW-9	11.25	18.8	-7.6	Slight	SSB & RF	11
SW-10	11.25	47.8	-36.5	V. high	SSB & RF	3
SW-11	11.25	24.3	-13.0	Moderate	SSB & RF	10
SW-12	8.75	58.7	-50.0	Extreme	SSB & RF	1
SW-13	12.5	5.2	7.3	Risk free	SSB & RF	15
SW-14	11.25	32.3	-21.0	High	SSB & RF	9
SW-15	12.5	9.3	3.2	Risk free	SSB & RF	12

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

To address the issue of soil erosion, various studies have been conducted, and this study contributes to this effort by providing information on the tolerable soil loss limit (TSLL), erosion hotspot areas, and best soil conservation practices that reduce soil loss to a rate equal to or less than the TSLL in the Andit Tid watershed, Ethiopia. The TSLL of the watershed is determined to be 9.63 t ha^{-}1 yr^{-1}, with a maximum of 12.5 t ha^{-}1 yr^{-1} covering 45.1% of the watershed and a minimum of 5 t ha^{-1}yr^{-1} covering 8.2% of the watershed. The average soil loss rate of the watershed was 28.7 t ha^{-1}yr^{-1}, with a sediment delivery ratio of 0.47. At the sub watershed level, the soil loss rates ranged from 4.16 to 58.75 t ha^{-1}yr^{-1}, with sediment delivery ratios ranging from 0.54 to 0.39. Among the evaluated best soil conservation practices in the Andit Tid watershed that affect the erosion rate under the TSLL, both SSB and RF individually, as well as their combination (SSB + RF), demonstrate effective reduction efficiencies. Notably, the combination of SSB + RF exhibited the greatest effectiveness at all sub watershed levels. Consequently, this study concluded that the Andit Tid watershed is prone to high erosion rates with a low tolerable soil loss limit. To mitigate soil erosion and decrease the erosion rate below the TSLL, SSB should be implemented with reforestation of cultivated land that exhibits greater than 30% slope.

5.2. Recommendations

It is well established that different watersheds have varying tolerable soil loss limits (TSLLs), erosion rates, hotspot area distributions, and conservation measures. This research confirms these differences, and based on the results, the following recommendations are proposed:

- For watersheds with slopes greater than 30%, special emphasis should be given to selecting and prioritizing tree species with high ecological value through the implementation of physical SWC measures.

- *Eucalyptus* litter decomposes more slowly than litter from other forest plantation species. Therefore, special attention should be given to *Eucalyptus* forestland by supporting it with physical soil and water conservation structures and adopting shrubs under the open canopy of *Eucalyptus* Forest.

- To ensure that the watershed is conserved from erosion, integrated soil and water conservation measures should be implemented rather than individual measures alone.

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7. APPENDICES

Appendix 1. Saturated hydraulic conductivity and soil erodibility factor of Andit Tid watershed

Sample No.	% Sand	% Silt	% Clay	OC(%)	BD(g/cm3)	f_{csand}	f_{ci-si}	f_{orgac}	f_{hisand}	K_{USLE}	Ks(cm/hr)
1	28	46	26	0.49	1.57	0.21	0.87	0.99	1.00	0.18	0.63
2	18	36	46	0.71	1.63	0.22	0.78	0.97	1.00	0.16	0.44
3	26	32	42	0.68	1.64	0.20	0.78	0.97	1.00	0.15	0.57
4	54	30	16	0.37	1.61	0.20	0.88	0.99	1.00	0.17	1.38
5	30	40	30	3.58	1.25	0.20	0.85	0.75	1.00	0.13	0.75
6	44	36	20	1.67	1.46	0.20	0.88	0.79	1.00	0.14	1.07
7	30	38	32	4.28	1.19	0.20	0.83	0.75	1.00	0.13	0.77
8	50	24	26	4.78	1.16	0.20	0.80	0.75	1.00	0.12	1.43
9	62	8	30	4.90	1.21	0.20	0.63	0.75	0.99	0.09	2.00
10	56	30	14	4.30	1.16	0.20	0.89	0.75	1.00	0.13	1.73
11	34	38	28	4.25	1.18	0.20	0.85	0.75	1.00	0.13	0.87
12	46	32	22	4.38	1.17	0.20	0.85	0.75	1.00	0.13	1.27
13	48	30	22	4.14	1.20	0.20	0.85	0.75	1.00	0.13	1.33
14	36	24	40	0.37	1.69	0.20	0.75	0.99	1.00	0.15	0.75
15	42	28	30	1.39	1.54	0.20	0.80	0.83	1.00	0.13	0.97
16	28	34	38	2.04	1.47	0.20	0.80	0.76	1.00	0.12	0.65
17	40	34	26	1.53	1.49	0.20	0.84	0.81	1.00	0.14	0.93
18	36	32	32	1.76	1.49	0.20	0.81	0.78	1.00	0.13	0.82
19	28	38	34	3.68	1.26	0.20	0.83	0.75	1.00	0.13	0.70
20	42	30	28	1.53	1.51	0.20	0.82	0.81	1.00	0.13	0.98
21	58	26	16	0.91	1.56	0.20	0.87	0.94	1.00	0.16	1.58
22	30	36	34	1.72	1.49	0.20	0.82	0.78	1.00	0.13	0.68
23	30	36	34	1.87	1.47	0.20	0.82	0.77	1.00	0.13	0.69
24	60	26	14	1.72	1.47	0.20	0.88	0.78	0.99	0.14	1.75
25	56	22	22	4.46	1.19	0.20	0.81	0.75	1.00	0.12	1.70
26	50	32	18	4.28	1.17	0.20	0.87	0.75	1.00	0.13	1.44
27	38	30	32	4.36	1.20	0.20	0.80	0.75	1.00	0.12	0.97
28	66	6	28	4.74	1.23	0.20	0.59	0.75	0.98	0.09	2.24
29	52	26	22	4.66	1.16	0.20	0.83	0.75	1.00	0.12	1.52
30	44	36	20	4.28	1.16	0.20	0.88	0.75	1.00	0.13	1.20
31	40	34	26	4.30	1.18	0.20	0.84	0.75	1.00	0.13	1.05
32	54	26	20	0.77	1.59	0.20	0.84	0.96	1.00	0.16	1.38
33	22	40	38	3.48	1.29	0.21	0.82	0.75	1.00	0.13	0.58
34	56	28	16	2.80	1.34	0.20	0.87	0.75	1.00	0.13	1.62
35	44	28	28	4.76	1.15	0.20	0.81	0.75	1.00	0.12	1.19
36	34	46	20	4.16	1.14	0.20	0.90	0.75	1.00	0.14	0.89
37	46	40	14	4.23	1.14	0.20	0.91	0.75	1.00	0.14	1.29
38	46	36	18	3.99	1.19	0.20	0.89	0.75	1.00	0.13	1.26
39	22	32	46	3.46	1.34	0.21	0.77	0.75	1.00	0.12	0.56
40	28	38	34	2.87	1.35	0.20	0.83	0.75	1.00	0.13	0.68

Appendix 2. Each soil parameter value, unitless score, aggregate score, aggregate group, soil depth and TSLL of Andit Tid watershed.

Sample No.	Ks(cm/hr)	Ks Score	BD (g/cm3)	BD Score	K_{USLE}	Kusle _ Score	OC %	OC_ Score	PH	PH_ Score	Agg. Score	Agg. Group	Soil depth	TSLL
1	0.63	0.20	1.57	0.30	0.18	0.80	0.49	0.20	5.35	0.30	0.38	2	25	5
2	0.44	0.20	1.63	0.20	0.16	0.80	0.71	0.30	4.85	0.20	0.37	2	30	5
3	0.57	0.20	1.64	0.20	0.15	0.80	0.68	0.30	4.85	0.20	0.37	2	65	7.5
4	1.38	0.30	1.61	0.80	0.17	0.20	0.37	4.82	4.82	0.30	1.00	3	10	7.5
5	0.75	1.00	1.25	0.80	0.13	1.00	3.58	4.78	4.78	0.20	1.43	3	150	12.5
6	1.07	0.30	1.46	0.80	0.14	0.80	1.67	1.00	5.25	0.30	0.58	2	200	12.5
7	0.77	1.00	1.19	0.80	0.13	1.00	4.28	4.85	4.85	0.20	1.44	3	140	12.5
8	1.43	0.80	1.16	1.00	0.12	5.15	4.78	1.43	5.15	1.00	2.03	3	125	12.5
9	2.00	1.00	1.21	1.00	0.09	4.86	4.90	2.00	4.86	1.00	2.11	3	100	12.5
10	1.73	1.00	1.16	0.80	0.13	1.00	4.30	5.10	5.10	0.30	1.49	3	80	10
11	0.87	1.00	1.18	0.80	0.13	1.00	4.25	5.15	5.15	0.20	1.48	3	60	10
12	1.27	0.30	1.17	1.00	0.13	0.80	4.38	1.00	4.82	0.20	0.59	2	150	10
13	1.33	0.30	1.20	1.00	0.13	0.80	4.14	1.00	5.27	0.30	0.60	2	105	10
14	0.75	0.20	1.69	0.20	0.15	0.80	0.37	0.20	5.00	0.30	0.37	2	30	5
15	0.97	0.50	1.54	0.80	0.13	0.80	1.39	5.19	5.19	0.20	1.26	3	95	10
16	0.65	0.80	1.47	0.80	0.12	1.00	2.04	5.82	5.82	0.20	1.51	3	100	12.5
17	0.93	0.20	1.49	0.50	0.14	0.80	1.53	1.00	5.60	0.50	0.55	2	100	10
18	0.82	0.50	1.49	0.80	0.13	1.00	1.76	5.65	5.65	0.20	1.38	3	105	12.5
19	0.70	1.00	1.26	0.80	0.13	1.00	3.68	5.46	5.46	0.20	1.53	3	100	12.5
20	0.98	0.50	1.51	0.80	0.13	1.00	1.53	5.44	5.44	0.20	1.35	3	150	12.5
21	1.58	0.30	1.56	0.80	0.16	0.50	0.91	5.33	5.33	0.30	1.15	3	100	12.5
22	0.68	0.50	1.49	0.80	0.13	1.00	1.72	4.88	4.88	0.20	1.27	3	100	12.5
23	0.69	0.80	1.47	0.80	0.13	1.00	1.87	5.77	5.77	0.20	1.51	3	70	10
24	1.75	0.80	1.47	0.80	0.14	1.00	1.72	5.00	5.00	0.30	1.41	3	80	10
25	1.70	0.80	1.19	1.00	0.12	5.20	4.46	1.70	5.20	1.00	2.08	3	85	10
26	1.44	0.30	1.17	1.00	0.13	0.80	4.28	1.00	5.40	0.30	0.60	2	85	7.5
27	0.97	1.00	1.20	0.80	0.12	1.00	4.36	5.20	5.20	0.20	1.49	3	80	10
28	2.24	1.00	1.23	1.00	0.09	4.82	4.74	2.24	4.82	1.00	2.14	3	120	12.5
29	1.52	0.80	1.16	1.00	0.12	4.95	4.66	1.52	4.95	1.00	2.00	3	150	12.5
30	1.20	0.30	1.16	1.00	0.13	0.80	4.28	1.00	4.95	0.20	0.59	2	150	10
31	1.05	0.30	1.18	1.00	0.13	0.80	4.30	1.00	4.80	0.20	0.59	2	175	12.5
32	1.38	0.80	1.59	0.50	0.16	5.10	0.77	1.38	5.10	0.30	1.86	3	100	12.5
33	0.58	1.00	1.29	0.80	0.13	1.00	3.48	5.45	5.45	0.20	1.53	3	200	12.5
34	1.62	1.00	1.34	0.78	0.13	1.00	2.80	5.03	5.03	0.30	1.48	3	150	12.5
35	1.19	1.00	1.15	0.80	0.12	1.00	4.76	5.23	5.23	0.30	1.51	3	150	12.5
36	0.89	0.20	1.14	1.00	0.14	0.80	4.16	1.00	5.25	0.30	0.57	2	160	12.5
37	1.29	0.30	1.14	1.00	0.14	0.80	4.23	1.00	5.02	0.30	0.60	2	100	10
38	1.26	0.30	1.19	1.00	0.13	0.80	3.99	1.00	5.07	0.30	0.60	2	30	5
39	0.56	0.20	1.34	1.00	0.12	0.80	3.46	1.00	5.26	0.30	0.57	2	30	5
40	0.68	1.00	1.35	0.80	0.13	1.00	2.87	5.22	5.22	0.20	1.49	3	30	7.5

Appendix 3.Monthly rainfall(mm) distribution of Andit Tid watershed

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1995	0.0	0.0	0.0	0.0	0.0	0.0	305.7	429.4	232.0	33.7	0.0	68.3	1069.0
1996	78.7	1.1	206.5	178.3	291.8	144.4	589.6	414.6	162.3	61.4	89.4	1.0	2219.2
1997	46.7	0.0	144.0	65.2	87.7	206.5	375.6	479.0	155.3	423.4	159.2	0.0	2142.5
1998	46.5	34.3	67.7	121.5	110.5	42.9	486.1	536.0	265.3	152.9	0.0	0.0	1863.5
1999	49.3	0.0	27.1	32.0	181.7	122.9	591.6	540.4	206.4	385.3	47.3	0.0	2183.6
2000	0.0	0.0	5.1	147.2	112.4	40.3	370.5	503.0	333.6	223.5	186.5	57.7	1979.7
2001	1.4	49.5	225.3	34.2	112.8	43.9	499.7	445.5	137.9	54.6	7.7	37.8	1650.2
2002	29.4	7.0	85.1	126.2	30.3	67.7	270.7	390.7	315.1	17.6	3.2	60.1	1403.1
2003	5.2	34.5	70.7	211.5	49.6	119.1	387.9	311.3	253.2	17.5	21.6	57.0	1538.9
2004	24.6	23.8	64.4	147.9	19.8	134.8	369.1	442.6	187.8	177.8	94.6	12.1	1699.0
2005	21.4	0.0	106.8	85.4	155.4	97.6	431.9	335.6	248.7	40.6	51.6	0.0	1574.9
2006	90.6	13.1	51.8	75.0	76.8	82.4	442.3	422.9	219.5	148.4	2.9	143.2	1768.8
2007	8.1	54.0	55.8	132.2	44.4	81.5	400.6	684.5	168.1	85.3	85.0	0.0	1799.3
2008	39.2	0.0	0.0	137.2	161.9	27.0	336.8	287.5	149.8	164.2	88.0	0.0	1391.5
2009	32.3	4.2	51.4	60.3	37.3	44.4	360.1	387.3	63.3	164.3	55.2	80.6	1340.6
2010	0.0	37.7	128.4	161.0	218.8	36.8	345.7	468.7	192.5	31.1	21.4	13.2	1655.3
2011	0.0	0.0	122.6	94.0	127.3	52.1	326.0	445.5	240.1	10.8	0.0	0.0	1418.5
2012	0.0	0.0	17.6	146.2	83.3	162.5	359.8	406.1	154.3	3.3	0.0	20.1	1353.1
2013	12.1	22.1	21.6	76.6	62.6	49.3	467.6	396.6	116.7	154.7	73.2	0.0	1453.1
2014	0.0	1.7	144.5	191.3	222.1	30.3	281.8	426.1	202.9	284.8	14.3	5.5	1805.2
2015	15.6	0.0	24.5	0.0	180.3	111.4	57.6	376.2	220.0	15.7	145.0	47.6	1193.9
2016	24.9	1.3	33.7	187.5	137.1	103.4	513.9	358.8	173.5	22.9	9.4	3.7	1570.0
2017	0.0	67.7	57.7	71.8	257.4	21.8	306.4	471.2	180.6	24.7	9.9	0.0	1469.0
2018	0.0	24.2	15.5	171.2	105.5	203.9	299.1	409.5	190.3	0.0	104.2	112.2	1635.5
2019	0.0	0.0	54.4	236.5	101.8	115.5	379.2	277.1	354.7	139.8	134.9	133.1	1927.0
2020	0.9	6.6	59.5	109.7	160.4	52.0	502.9	501.6	136.9	26.6	7.4	12.0	1576.5
2021	4.6	15.3	2.3	68.7	162.1	50.7	496.0	278.3	170.6	99.1	16.0	0.0	1363.6
2022	41.7	0.0	106.5	57.0	13.9	183.0	453.9	424.4	203.9	73.6	67.8	8.2	1633.9

Appendix 4. Mean monthly minimum temperature(oC) of Andit Tid watershed

Year	Jua	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1995	5.5	8.2	8.8	9.4	9.7	9.7	8.3	8.6	8.7	6.9	6.2	6.1	8.0
1996	6.5	7.5	7.8	8.8	9.0	8.6	8.1	8.5	8.2	7.1	5.8	6.3	7.7
1997	7.0	6.6	8.3	8.9	9.6	9.6	9.2	8.8	9.3	7.9	7.9	6.9	8.4
1998	8.0	8.7	9.5	10.2	10.4	9.6	9.1	9.0	8.8	8.6	5.8	4.3	8.5
1999	5.4	6.5	8.1	9.1	9.4	9.2	7.8	8.0	8.1	7.4	5.1	5.1	7.4
2000	5.5	6.6	8.2	8.7	9.2	9.0	8.5	6.6	3.8	3.4	1.5	1.9	6.1
2001	2.2	6.9	8.1	9.0	9.4	9.0	8.4	8.5	9.0	8.4	5.6	6.1	7.5
2002	6.2	7.1	8.8	8.7	10.4	9.1	9.1	8.7	8.8	7.8	6.5	7.8	8.3
2003	6.8	8.0	8.3	9.2	9.9	9.2	8.7	8.9	8.7	7.5	6.4	5.4	8.1
2004	7.5	7.0	7.5	9.0	9.8	8.7	7.8	7.4	8.5	6.9	6.4	6.5	7.7
2005	6.4	8.0	8.3	9.5	9.5	9.1	8.3	8.5	8.3	7.4	5.5	4.5	7.8
2006	6.5	7.7	8.0	8.6	9.4	8.7	8.1	8.3	7.8	7.2	4.3	3.5	7.4
2007	3.9	6.5	5.3	5.6	6.3	8.5	7.1	7.1	8.0	6.3	5.9	3.9	6.2
2008	6.5	6.6	7.6	8.5	8.5	8.3	7.2	7.0	7.7	6.6	2.8	5.3	6.9
2009	6.3	7.0	8.4	8.8	9.0	9.6	7.5	7.6	8.6	7.2	5.8	7.0	7.7
2010	6.1	8.0	7.7	9.0	9.3	9.0	7.9	6.5	7.7	7.2	6.1	6.0	7.5
2011	5.9	6.4	7.1	8.8	9.5	9.0	8.1	7.5	7.5	7.5	7.4	5.9	7.5
2012	6.5	6.1	8.0	7.9	9.0	8.8	6.6	6.0	7.9	6.3	6.9	5.8	7.1
2013	6.7	7.7	8.9	8.5	9.6	9.4	7.2	6.6	8.5	6.8	7.0	4.7	7.6
2014	6.8	7.7	8.5	8.9	8.2	9.2	8.5	6.4	8.2	6.4	6.5	5.3	7.5
2015	4.7	7.3	8.2	9.0	8.7	8.9	8.9	6.3	8.0	8.3	6.6	7.0	7.7
2016	7.6	7.4	9.0	8.6	8.3	8.0	6.6	6.2	7.8	7.3	5.6	4.5	7.2
2017	4.4	7.7	8.2	9.0	8.9	9.2	7.0	5.2	7.2	7.6	5.8	4.0	7.0
2018	5.9	6.6	7.3	7.7	8.8	6.4	6.0	4.7	6.3	7.1	6.2	6.0	6.6
2019	5.6	7.0	7.6	7.5	8.1	8.2	6.8	6.7	6.9	6.3	6.9	6.2	7.0
2020	6.1	7.7	7.6	9.0	8.2	7.9	6.8	6.7	7.1	6.6	5.3	4.9	7.0
2021	4.8	6.1	4.5	6.6	7.5	5.9	6.2	6.1	6.5	6.5	4.6	4.3	5.8
2022	6.1	7.0	7.4	9.0	9.7	8.4	9.0	8.2	8.4	7.6	5.9	5.5	7.7

Appendix 5. Mean monthly maximum temperature(oC) of Andit Tid watershed

Year	Jua	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1995	15.0	16.3	17.0	15.8	17.4	18.6	15.8	16.4	16.0	15.8	15.0	15.0	16.2
1996	14.6	16.6	16.5	16.8	16.7	17.3	16.3	16.6	16.7	15.6	14.2	14.2	16.0
1997	15.4	15.8	17.3	16.3	18.5	17.6	16.6	17.0	17.0	14.8	14.8	15.0	16.3
1998	16.2	17.4	17.4	18.6	18.9	20.5	16.6	16.3	16.4	15.3	14.6	15.1	16.9
1999	15.8	18.3	17.4	19.0	19.8	20.4	15.7	16.5	16.4	14.6	14.3	15.6	17.0
2000	16.0	16.6	18.0	17.7	18.9	20.1	17.2	16.2	15.8	14.6	13.9	14.7	16.6
2001	16.6	17.3	15.7	18.1	19.2	19.6	16.6	16.0	16.5	16.3	15.4	15.7	16.9
2002	15.5	17.7	17.8	17.8	20.6	20.3	18.7	16.6	16.3	16.7	16.1	15.5	17.5
2003	17.5	17.9	18.0	18.1	19.6	19.6	16.8	16.4	16.6	16.7	15.8	15.2	17.3
2004	18.1	16.5	17.8	18.1	20.5	19.9	18.3	18.2	17.4	16.1	16.5	16.8	17.9
2005	17.3	19.5	19.4	19.4	19.1	19.6	18.4	18.5	18.4	17.8	17.7	17.8	18.6
2006	19.0	19.7	19.6	19.6	20.8	21.8	18.8	18.3	18.3	18.4	17.5	16.7	19.0
2007	18.4	19.0	20.1	19.4	21.3	19.7	17.6	18.6	19.1	17.8	16.5	17.5	18.7
2008	18.7	18.5	21.3	20.1	19.6	20.2	18.8	18.5	18.9	18.1	16.5	17.5	18.9
2009	18.3	19.1	20.6	20.4	21.3	22.6	17.8	18.6	19.6	18.4	18.3	16.0	19.2
2010	17.5	18.8	18.0	19.6	19.8	21.3	18.0	17.6	17.9	18.4	17.6	16.6	18.4
2011	16.1	18.9	16.6	18.9	18.4	20.2	17.9	17.1	16.9	16.5	16.0	14.8	17.3
2012	16.3	17.1	17.7	17.7	18.1	19.3	17.2	17.4	16.8	15.7	16.5	16.5	17.2
2013	17.7	17.8	18.7	18.9	19.0	20.1	16.9	16.5	17.1	15.8	15.0	15.8	17.4
2014	16.8	18.0	17.6	17.4	17.1	19.1	18.3	16.9	16.7	15.6	15.4	15.7	17.0
2015	17.3	18.4	18.9	20.4	18.4	19.7	19.9	18.0	17.8	17.9	16.3	15.9	18.2
2016	17.5	18.2	20.6	18.8	18.9	19.7	17.8	17.2	18.1	17.9	16.8	15.6	18.1
2017	17.8	17.6	19.3	19.7	19.2	20.6	19.2	19.3	18.2	17.5	16.5	16.2	18.4
2018	16.8	19.1	18.1	17.5	19.3	19.0	17.2	17.6	17.1	16.9	15.9	16.4	17.6
2019	18.2	18.3	19.6	18.3	19.2	19.7	17.8	18.1	17.7	15.9	15.2	16.0	17.8
2020	19.2	18.2	19.4	18.6	18.5	20.1	16.9	17.1	17.6	17.2	16.2	15.3	17.8
2021	17.4	17.4	18.6	19.3	18.8	20.1	16.4	17.0	17.6	15.9	16.2	16.6	17.6
2022	16.2	17.7	19.1	20.2	21.5	20.2	15.9	15.9	17.0	15.9	15.2	14.6	17.4

Appendix 6. Mean monthly observed stream flow of Andit Tid watershed (m^3/s)

Month	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Jan	0.010	0.032	0.005	0.010	0.010	0.015	0.010	0.001	0.002	0.014	0.002
Feb	0.010	0.020	0.005	0.051	0.010	0.010	0.005	0.001	0.001	0.009	0.005
Mar	0.010	0.011	0.040	0.054	0.025	0.010	0.010	0.002	0.011	0.009	0.046
Apr	0.015	0.031	0.031	0.025	0.066	0.054	0.015	0.002	0.012	0.042	0.023
May	0.016	0.077	0.024	0.032	0.022	0.021	0.010	0.026	0.005	0.042	0.042
Jun	0.070	0.001	0.002	0.022	0.025	0.001	0.038	0.003	0.001	0.001	0.041
Jul	0.181	0.331	0.183	0.146	0.059	0.109	0.128	0.090	0.181	0.183	0.195
Aug	0.154	0.253	0.238	0.201	0.233	0.148	0.277	0.244	0.265	0.234	0.236
Sep	0.092	0.134	0.192	0.179	0.184	0.086	0.043	0.117	0.180	0.151	0.037
Oct	0.083	0.128	0.080	0.016	0.030	0.020	0.030	0.053	0.149	0.116	0.014
Nov	0.026	0.011	0.056	0.016	0.020	0.015	0.048	0.010	0.028	0.103	0.026
Dec	0.022	0.025	0.051	0.018	0.020	0.015	0.002	0.001	0.023	0.050	0.001

Appendix 7. Monthly observed sediment yield of Andit Tid Watershed (ton)

Month	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Jan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Feb	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mar	0.0	0.0	26.7	85.0	0.0	8.5	0.0	0.0	8.4	0.0	78.8
Apr	25.9	50.9	27.2	0.0	46.3	102.0	44.5	133.9	0.0	41.9	8.9
May	29.7	46.9	50.9	0.0	0.0	51.1	16.0	145.7	0.0	0.0	86.0
Jun	47.1	1.8	0.0	0.0	46.1	0.0	124.1	279.4	63.6	92.5	0.0
Jul	417.6	426.9	158.3	366.2	337.7	294.9	349.7	626.2	612.4	615.0	499.3
Aug	279.7	333.8	355.7	172.4	148.9	198.9	188.9	478.2	394.5	469.5	227.6
Sep	103.3	99.9	141.5	100.0	66.0	10.2	12.2	288.3	246.0	266.6	36.0
Oct	46.2	68.2	159.0	55.1	0.0	1.2	0.0	67.7	65.0	199.9	0.0
Nov	0.0	0.0	81.1	0.0	0.0	0.0	0.0	110.7	0.0	0.0	0.0
Dec	0.0	0.0	0.0	0.0	0.0	0.0	0.0	36.0	0.0	0.0	0.0

BIOGRAPHY

The author Tilahun Getachew Abebe was born on January 20, 1989, in Gishe district, North Shoa zone, Amhara region, Ethiopia, from his father Prist Getachew Abebe and mother W/ro Enani Alemayehu. He attended Yesha and Dell elementary schools, and later Gishe Rabel and Worailu town for his secondary and preparatory education, respectively. Upon completing his preparatory studies, he enrolled at Dilla University, graduating in July 2012 with a BSc Degree in Natural Resource Management.

Following graduation, Tilahun began his professional career at Menz Gera Mider woreda agricultural office, as a soil and water conservation expert. After five years, he also joined the Debre Birhan Agricultural Research Center in February 2018 as a Junior Researcher.
Subsequently, he enrolled in the regular Master of Science program in Soil and Water Conservation at Debre Berhan University, College of Agriculture and Natural Resource Sciences, supported by the Amhara Agricultural Research Institute. He successfully completed his studies in 2024.