Addis Ababa University

College of Social Sciences, Arts and Humanities

Centre for Rural, Local and Regional Development Studies

Watershed Prioritization for Land Management Decisions Using Morphometric Characteristics and Soil Erosion Risk in Ribb Sub-basin, Amhara Region, Ethiopia.

By Yiftusira Yitayew

Advisor: Ermias Teferi (Ph.D)

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A Thesis Submitted To the College Of Development Studies In Partial Fulfilment Of The Requirements For The Degree Of Master Of Arts In Environment And Sustainable Development.

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Declaration

I, Yiftusira Yitayew do hereby certify that this thesis is my original work and it has not been submitted partially, or fully by any other person for award of degree in Addis Ababa University or any other university/Institution.

Submitted by:

Full Name: Yiftusira Yitayew Adane **Signature:** ______________ Date**:** ______________

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Name of Advisor: ______________ **Signature:** ______________ Date**:** ______________

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Acronyms and Abbreviations

AHP	Analytical Hierarchy Process
DEM	Digital Elevation Model
DS-SLM	Decision Support for Sustainable Land Management
FAO	Food and Agriculture Organization
GERD	Grand Ethiopian Renaissance Dam
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
InVEST-SD	Integrated valuation of Ecosystem Services and Trade-offs- Sediment Delivery Ratio
LDCI	Land Degradation Composite Index
LULC	Land Use/Land Cover
MCDA	Multi-Criteria Decision Analysis
NDVI	Normalized Difference Vegetation Index
NMI	National Meteorological Institute
OM	Organic Matter
RUSLE	Revised Universal Soil Loss Equation
SDR	Sediment Delivery Ratio
SMCE	Spatial Multi-Criteria Evaluation
SWAT	Soil and Water Assessment Tool
SWPT	Sub-Watershed Prioritization Tool
UNCCD	United Nations Convention to Combat Desertification
UNCED	United Nations Conference on Environment & Development
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
WARSSS	Watershed Assessment of River Stability and Sediment Supply
A	Basin Area
Cc	Compactness Coefficient
C	Constant of Channel Maintenance
C	Cover Management Factor
Dd	Drainage Density
Dt	Drainage Texture Ratio
Ff	Form Factor
Fs	Stream Frequency
K	Soil Erodibility Factor
LS	Slope Length and Steepness Factor
P	Basin Perimeter
P	Support Practice Factor
Rb	Bifurcation Ratio
Rc	Circulatory Ratio
Re	Elongation Ratio
Rh	Relief Ratio
Rl	Stream Length Ratio
R	Rainfall Erosivity Factor

ABSTRACT

Land degradation, driven by human activities and climate change, presents a significant threat to Ethiopia's agricultural productivity and socio-economic stability. Despite decades of restoration efforts, the issue remains unescapable, necessitating a strategic framework to prioritize watersheds for targeted and effective interventions. Systematic approaches by using state of the art technologies in identifying key hydrological and bio-physical characteristics of landscapes helps to prioritize watersheds; planning units, based on their urgency for conservation. Such kind of studies or tools helps policy makers for appropriate decision making on resource allocation and practitioners for better intervention planning. Watershed prioritization needs to be seen as a critical approach in managing soil and water resources, particularly in data-limited regions where optimal resource allocation is vital. This study has prioritized watersheds using GIS-based methodologies by integrating morphometric parameters and soil erosion risk that could contribute to land degradation in one of the key tributaries of the Tana basin; the Ribb sub-basin, ultimately contributed to Blue Nile. Morphometric parameters considered in the study includes area, perimeter, stream frequency, bifurcation ratio, form factor, elongation ratio, and drainage density were generated from Digital Elevation Models (DEM) with 30m resolution. Parameters for soil erosion risk assessment is generated from using high-resolution satellite imagery and 30-meter resolution (DEMs). The parameters are integrated using weighted overlay analysis in Arc GIS generating final prioritazation. The delineated six watersheds have their own score values showing variabilities among themselves from 0.387(W3) highest to low value of 0.241(W5). Higher values showed high sensitivity of watersheds for degradation and the need for urgent attention to conservation. The findings of this study tells that where there is limited resources and vast degradation factors, prioritazation is an essential tool to address conservation efforts based on their urgency and conservation values at watershed scale. Therefore, this study recommends prioritazation for landscape restoration into a manageable planning unit; watershed scale is an essential decision making tool informing "where to invest first" to address restoration efforts based on its urgency.

Key Words*:* Watershed Prioritization, Soil Erosion Risk, Morphometric analysis, Ribb sub-basin.

CHAPTER ONE: INTRODUCTION

1.1. Background of the study

Land degradation as a global issue, and continuous to be a global challenge where there is always reduction in biological productivity and ecological connectivity affecting about 23% of the Earth's land surface and directly impacting 3.2 billion people worldwide (UNCCD, 2019). Land use change and unwise use of resources, such as urban expansion, deforestation, and unsustainable agricultural practices have significantly affect 75% of terrestrial ecosystems, ultimately impacted reduced biological productivity and ecological fragmentation (GEF, 2025). At global scale, approximately 100 million hectares of healthy land are lost each year eroded 24 billion tons of fertile soil (FAO, 2023). Lose of fertile land has ultimately contributed to loss of productivity which is directly attributed to global economic losses; linked to land degradation range between $18-20 trillion USD annually. These loses are recorded higher in areas where land degradation rates are higher and exceeds from the global average range (6-8%) in regions like Sub-Saharan Africa, Western Asia, Latin America, and Southern Asia, (Ahmad & Pandey, 2018).

In Ethiopia land degradation is continuous to be a critical environmental challenge, affecting approximately 50% of the country's land area primarily due to soil erosion, deforestation, and unsustainable farming practices (Belay, 2024) contributing 2-3% of Ethiopia's agricultural GDP loses (Federal Democratic Republic of Ethiopia, 2021).The rate of degradation is particularly severe in highland areas, where soil loss exceeds 42 tons per hectare per year, leading to decreasing agricultural productivity (Amare, 2014). Efforts towards solving this problem have passes through several years, from traditional practices in the 1960s, 1970s, comes through top-down land restoration approach in 1980s (Belay & Getaneh, 2016). Participatory Community-based approach; a shift towards integrated watershed management with bottom-up approach was applied in the 1990s followed by policy development in 2000s (Lakew, et al., 2005). The present day mass mobilization campaign and climate resilience initiatives has stared in 2010 plus the green legacy initiative focusing on tree planting strengthens community participation including towns and cities to be involved in restoration efforts. Even though such strategies have been instrumental, land degradation still changes the countries food security and livelihoods (Office of the Prime Minister Ethiopia, 2019).

Regardless of the complex challenges and previous efforts made in land restoration, the need to think alternative approaches for land mangement is essential. In Ethiopia, even though land mangement is effective since 1960s at watershed scale, there is a lack of scientific application of integrating watershed restoration needs, conservation values and resource allocation creating gaps in planning, implementation, and sustainability (Chimdesa, 2016). Prioritizing watersheds; manageable planning units for watershed restoration; based on specific bio-physical and hydrological conditions is fundamental for land mangement where there is vast land degradation challenges and limited resources; helps to decide where to invest first; with efficient allocation of resources and maximize conservation efforts. This approach requires understanding of key bio-physical and hydrological factors for land degradation. In previous times, this was done with expert's judgement and subjective narration for specific watersheds; not supported with scientific evidences, leads to miss allocation of resources and biased decisions (Gemeda, et, al, 2024). This days, there are a number of technologies that could help to identify watershed specific condition for management planning, helps to focus on regions most at risk or benefits most with low resource allocation (Hagos et al., 2011).

Morphological and hydrological characteristics are fundamental in determining a watershed's susceptibility to degradation (Sharma & Kumar, 2022). Integrating these characteristics into watershed prioritization frameworks enables decision-makers to identify areas most vulnerable to land degradation (Teferi et al., 2023). This approach moves beyond subjective judgments, incorporates scientific evidence to prioritize watersheds based on their unique behaviour and restoration needs (Abdeta et al., 2020).

The Ribb sub-basin, a critical catchment for Lake Tana, covers a diverse landscape but faces persistent degradation challenges, including deforestation, unsustainable agricultural practices, and land-use change, which continue to threaten land degradation. Soil erosion, the primary contributor to sediment accumulation in the Ribb reservoir and Lake Tana, ultimately affects the Grand Ethiopian Renaissance Dam (GERD), disrupting ecological health and weakening the benefits derived from these water bodies. To address these challenges, comprehensive landscape analysis is essential for effective land management decisions. Using data driven decision that identifies priority areas for restoration investments would enhance resource allocation efficiency, maximize conservation benefits, and safeguard the health of the catchment and its reservoirs, including Lake Tana.

Therefore, this study aims to prioritized watersheds for land mangement decisions by integrating morphometric and hydrological characteristics with soil erosion risk factors using GIS tools.

1.2. Statement of the problem

Current trends of landscape restoration planning in Ethiopia depends on subjective judgements not supported with scientific evidences and focused only on intervention planning without considering bio-physical characteristics of the land at watershed scale (Gebregergs et al., 2021). This kind of approach leads to wrong decisions that fail to consider the inter relationship's among topographic and hydrological characteristics of watersheds influencing land degradation. Prioritizing watersheds; as ideal planning units of land restoration is vital for identifying watersheds most at risk of land degradation to make informed decision where there is limited resources and the need for sustainable land scape management is significant (Teferi et al., 2023).

Catchments like Ribb, a key contributor to the Blue Nile but suffering with land degradation issues due to many bio-physical and anthropogenic factors needs to be examined for the best alternative framework to implement land management decisions (Admas et al., 2022). Numerous studies have been conducted by various researchers to advance watershed prioritization for effective conservation planning. Watershed prioritization studies by Sineshaw et al. (2021) and Bogale et al. (2023), in the Ribb, Megech, and Gumara river basins have primarily employed geomorphometric analysis, RUSLE modelling, and flood forecasting techniques to assess erosion risk and hydrological responses. Meerut & Gangadhara (2017) conducted in Meerut District, Uttar Pradesh, India, applied morphometric and geomorphometric analyses, integrating key hydrological parameters using Principal Component Analysis (PCA) to refine morphometric parameters improving parameter selection for watershed ranking. Sineshaw et al. (2021) employed GIS-based morphometric assessment to evaluate watershed vulnerability, whereas Bogale et al. (2023) used the Revised Universal Soil Loss Equation (RUSLE) model to estimate soil erosion risk and prioritize conservation strategies.

Despite the fact that each study contributed valuable insights into prioritazation of watersheds for land management, these studies used a single parameter like soil erosion risk, LULC, or limited parameters from Morphometric characteristics for prioritazation. They lacked systematic integration of multiple parameters and systematic weighting techniques, which is crucial for accurate prioritization. The integration of weighted overlay analysis alongside RUSLE and morphometric techniques would enhance prioritization accuracy by systematically weighting multiple parameters, filling gaps left by other studies' weighted overlay analysis enables quantitative integration of multiple factors by assigning relative importance to each parameter, ensuring that erosion risk, hydrological behaviour, and land-use dynamics are comprehensively assessed. This approach enhances prioritization accuracy and supports more effective conservation planning by addressing gaps in previous studies that relied primarily on individual parameter assessments.

Therefore, this study aims to address these gaps by integrating morphometric parameters and soil erosion risk maps to prioritize watersheds for land management decisions in the Ribb sub-basin, contributing to the knowledge of "where to invest first on the landscapes" and equipping policymakers and land managers with the necessary tools and insights to make informed decisions.

1.3. Objectives

1.3.1. General objective

To prioritize watersheds for land management decisions in the Ribb sub basin.

1.3.2. Specific objectives

1. To study morphometric parameters related to drainage network, watershed geometry, and drainage texture characteristics of the Ribb sub basin.
2. To analyse watersheds hydrological and morphological characteristics and their implications for land management decisions.
3. To integrate morphometric analysis results with soil erosion model result to identify areas of high conservation value and prioritize watersheds for land management decisions.

1.4. Research questions

1. What are the key morphometric parameters related to drainage network, watershed geometry, drainage texture, and relief characteristics of the Ribb sub basin?
2. How do the selected morphometric parameters relate to the hydrological and morphological characteristics of the Ribb sub basin?
3. What are the areas of high conservation value and priority watersheds for land management decisions in the Ribb sub basin based on the integration of morphometric analysis with soil erosion model results?

1.5. Significance of the study

This study holds significant importance for several reasons, contributing crucial knowledge and practical solutions to the pressing environmental challenges related to land degradation. The research focuses on the Ribb sub-basin, a key tributary of the Blue Nile and a vital contributor to the water resources of Lake Tana, a region of both national and international significance due to its biodiversity role in supporting downstream catchment. To mention some:

1. Informing Policy and Decision-Making: The research informs how and why to give priority for a given watershed for land management based on its morphological and bio-physical characteristics. Understanding nature of the watersheds and bio-physical conditions is crucial for ensuring the long-term health of the ecosystem and the well-being of the communities that depend on it. The study's findings provides valuable evidence-based insights for policymakers and stakeholders involved in managing the Rib sub-basin and the wider Blue Nile basin.
2. Integrative Approach: This research utilizes an integrative approach, combining morphological character and hydrological modelling with GIS analysis of key factors, which directly addresses the complex and interconnected nature of land degradation more effectively than previous, isolated approaches.
3. Advancing Methodological Rigor: This study advances methodological rigor in the field by employing cutting-edge GIS techniques, including high-resolution satellite imagery using QGIS, GRASS GIS, InVEST-SDR, and ArcGIS 10.8 enhances land management decision-making by integrating morphometric parameters and erosion risk models**,** providing higher accuracy, improved spatial representation, and multi-criteria

prioritization compared to simpler hydrological models (Kanito et al., 2023; Neteler et al., 2012; Sharp et al., 2018). Previous studies in the region have been limited by Arc GIS, often emphasize morphometric analysis and RUSLE modelling, and lacks the scripting flexibility and automation of open-source tools like QGIS and GRASS GIS. This improved understanding is essential for making effective land management decisions.

1.6. Scope of the study

This study aims to prioritize watersheds within the Rib sub-basin of Ethiopia, Amhara region for effective land management decisions. The geographic focus was exclusively on the Rib sub-basin, a key catchment area for Lake Tana and a significant contributor to the Blue Nile River. The precise boundaries of the sub-basin is clearly defined using high-resolution spatial data. Temporally, the study analyses current conditions, incorporating historical data on rainfall patterns, land degradation or land use change as relevant background information.

The core methodological scope involves morphometric analysis, deriving parameters using remote sensing data such as high-resolution satellite imagery and Digital Elevation Models (DEMs). Morphometric Parameters include stream order, drainage density, form factor, elongation ratio, relief characteristics, and other relevant metrics reflecting the hydrological and morphological characteristics of the watersheds. The study integrates existing soil erosion risk maps and geomorphology characteristics of the basin. A weighted overlay analysis within a GIS environment integrates the morphometric parameters and soil erosion data with the weighting scheme transparently defined and justified based on expert knowledge and literature review.

The outputs include morphometric parameter results, the spatial distribution of soil erosion risk maps finally providing a prioritized watershed maps showing the ranked prioritization of watersheds for land management decisions. This study shows the detail methodology, results, analysis, and conclusions, including recommendations.

1.7. Limitation of the study

The study acknowledge limitations inherent in the chosen methodologies and data availability, such as the accuracy of results depending on the quality of input data (DEM resolution and accuracy of soil erosion maps). It also recognize that the prioritization is based on a specific set of criteria and may not capture all relevant factors influencing land degradation. The study is not directly model and prioritized the effectiveness of specific land management interventions.

1.8. Organization of the study

The thesis is systematically divided into chapters that build upon each other to present a coherent analysis. The first chapter introduces the study, outlining the background, problem statement, objectives, research questions, significance, scope, and limitations. Chapter two presents an extensive literature review, synthesizing past studies on watershed management, morphometric analysis, and erosion risk assessment while establishing the conceptual framework. Chapter three details the methodologies employed, including description of the study area, data sources, analytical techniques, and computational models used for morphometric and soil erosion risk assessments. Chapter four focuses on results and discussions, interpreting findings from spatial analyses, prioritization scores, and comparative evaluations of sub-watersheds. Finally, chapter five concludes the study by summarizing key findings and providing recommendations.

CHAPTER TWO: LITRATURE REVIEW

2.1. Definition of terms

Watershed is sometimes used interchangeably with drainage basin or catchment, an area of land that drains all the streams and rainfall to a common outlet such as the outflow of reservoir, mouth of a bay, or any point along a stream channel having a size as small as a footprint or large enough to encompass all the land that drains water into rivers, oceans (United Nations Geological Survey-USGS).

Land Management is the sum of land-use practices that take place within broader land use categories (IPCC, 2023).

Sustainable Land Management is the use of land resources, including soils, water, animals and plants, for the production of goods to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions (UNCED, 1992).

Prioritization is a decision-making process that determines the order and focus on tasks and activities based on their relevance and urgency; allowing individuals or organizations to address the most critical items first (Dictionary Definition).

Morphometry refers to the quantitative analysis of the physical characteristics of landforms, particularly in the context of watersheds, which is crucial for understanding hydrological processes, predicting runoff patterns, and managing natural resources effectively (Shekar and Mathew, 2023).

Weighted Overlay Analysis is a GIS technique is specifically designed to prioritize areas based on multiple criteria. It combines various parameters into a single index that reflects the relative importance of each area concerning specific objectives, such as conservation or resource management.

2.2. Land management challenges in Ethiopia and the need for watershed prioritization

Historically, land management in Ethiopia relied on indigenous practices that supported subsistence agriculture. Rapid population growth rising from 33 million in 1984 to over 120 million in 2021 has led to overexploitation of resources and increased land degradation (FAO, 2021). Government policies from the late 1960s to 1980s aimed to enhance agricultural productivity but were inconsistently applied, resulting in only 30% community participation in land management programs (Taffesse et al., 2012). One of the major challenges for land degradation is poverty as reported by the World Bank; by 2020 about 23.5% of the population was living below the national poverty line (World Bank, 2020). Factors related resources limitation to invest for land mangement coupled with population pressure leads to soil degradation, unsustainable agricultural practices and land use change especially in the North-western Highlands of Ethiopia. Report by the world bank conducted in 2018 revealed that north west highlands of the country records about 42% of the land is affected by land degradation due to the bio-physical and socio- economic factors (World Bank, 2018). Resource limitation also affects sustainable practice of land management, access to financial services are also affecting the ability of rural community to invest in land management (Beyene & Hailu, 2020).

Therefore, countries like Ethiopia having diversified ecological and topographic characteristics, prioritazation of watershed according to their specific needs and level of vulnerability helps to address degradation issues in systematic manner where there is lack of resources to invest once at land scape level. Developing prioritazation frameworks is most important which enables stakeholders to concentrate on regions that are in urgent need of restoration efforts or that offer the greatest potential for restoration (Haregeweyn et al., 2017).

Ethiopia’s agricultural productivity is highly dependent watershed health, this prioritazation helps to identify key areas of intervention where restoration is implemented to mitigate soil erosion, creating ecological connectivity and enhancing biodiversity (Welde et al., 2016).

2.3. Tools and techniques for watershed prioritazation decision- making

2.3.1 GIS Techniques

Various GIS techniques and tools have been utilized by different researchers to prioritize watersheds. It plays a crucial role in watershed prioritization by integrating spatial datasets to assess erosion risk, hydrological characteristics, and land-use dynamics. GIS tools such as ArcGIS, QGIS, and GRASS GIS enable morphometric analysis, soil erosion modelling, and multi-criteria decision-making techniques for improving conservation planning. Application of GIS facilitates data integration and visualization of complex attributes (Sharma, 2023). These tools helps significantly to enhance data-driven decision making for land management. Utilization of machine learning techniques although enhances predictive capabilities of showing land use changes and their impacts on land degradation (Landgate, n.d.). As a show case, an automated tool developed by Rahmati et al. (2019); a user-friendly Sub-Watershed Prioritization Tool (SWPT) is one of GIS-based solution for ranking sub-watersheds based on morphometric and topo-hydrological factors. This kind of tools can be adopted to analyse different parameters that could help for decision making for watershed development.

2.3.2 Remote sensing

Remote sensing techniques provide large-scale data sets for watershed conditions, allows to extract watershed delineation, hydrological and morphological parameters, land use and cover classification and vegetation analysis for and hydrological and erosion risk assessments. Satellite imagery from Landsat, Sentinel, and MODIS supports morphometric analysis, erosion risk mapping and flood forecasting. A study by Singh et al. (2023) reviewed remote sensing applications in watershed prioritization, highlighting its effectiveness in identifying erosion-prone areas and aquifer recharge zones. Despite its advantages, remote sensing faces challenges such as cloud cover interference and limited resolution in certain terrains. Pre-processing of the images and identifying high resolution imageries need to ne applied for better accuracy of results.

2.3.3 Morphometric Analysis

The quantitative assessment of hydrological and morphological characteristics of watershed plays a vital role in this prioritization process, analysing to describe the physical characteristics of land forms including its size, shape, and drainage network (Strahler, 1964). These characteristics are crucial in understanding hydrological processes and identifying areas vulnerable to environmental degradation. Several studies have demonstrated the effectiveness of these parameters in prioritizing watersheds for land restoration (Pareta & Pareta, 2011; Patel et al., 2022; Rahmati et al., 2019). The values derived from morphometric parameters include drainage density, stream frequency, bifurcation ratio, and form factor serve as direct indicators of a catchment's susceptibility to runoff generation and erosion hazards (Horton, 1945; Strahler, 1957).

2.3.4 Soil erosion risk assessment

The process by which the top layer of soil is removed and transported from one location to another, primarily by natural forces such as water and wind is defined as soil erosion (Grant & Kline, 2000). Soil erosion types are different; which can be further categorized into sheet, rill, and gully erosion, depending on the scale and mechanism of water flow (Britannica, n.d.). Major factors of soil erosion includes natural elements such as rainfall intensity, slope steepness, and vegetation cover, as well as anthropogenic influences like deforestation and agricultural practices (Bonta et al., 1997; Britannica, n.d.). Proper identification of such factors using scientific approaches is crucial for prioritization of watersheds for effective soil conservation strategies and mitigating the adverse effects of erosion on land productivity and environmental health.

Revised Universal Soil Loss Equation (RUSLE); a mathematical tools designed to estimate soil erosion rates from various landscapes, identifying areas at risk of degradation is one of mostly used model (Renard et al., 1997). RUSLE is particularly effective for the identification of critical erosion hotspots for watershed prioritization, as it helps to know soil loss and enhance watershed health (Ferguson et al., 2003). Assessing factors like rainfall, soil type, slope, management practices and land use equations is to inform land management practices and prioritize conservation efforts (Wischmeier & Smith, 1978). It also helps optimize resource allocation and implement practices that promote sustainability and soil conservation (Kumar et al., 2016) by informing factors directly and indirectly contributing for erosion.

2.3.5. Multi-Criteria Decision-Making (MCDM) technique

Multi-Criteria Decision-Making (MCDM) in GIS is an approach in a spatial analysis which integrates multiple factors to inform complex decision-making used to evaluate and rank alternatives based on multiple criteria. Some of MCDM techniques includes Weighted Overlay Analysis, Analytical Hierarchy Process (AHP), and Principal Component Analysis (PCA), allow decision-makers to assign relative importance to different parameters, informing a systematic and objective prioritization of spatial units. Each of these techniques has its own advantages and limitation; Weighted Overlay Analysis is particularly effective as it allows to integrate multiple spatial data sets which enables a comprehensive assessment of watershed conditions (Jabbar et al., 2019). Weighted average overlay analysis allows to assigns weights to each factor contributed to prioritazation based on their significance, supporting for identification of priority areas for intervention (Wang et al., 2016).

A study conducted in Northern Ethiopia; Tekeze dam watershed has utilized weighted average overlay analysis to prioritize sub-watersheds for land and water management, demonstrating its effectiveness in identifying critical areas for intervention (Welde et al., 2016). Similarly study was conducted in the Ribb sub-basin by applying this method in visualizing and analysing land use/cover change impact on soil erosion, ultimately aiding in more informed land management decisions by Integration of geospatial technologies with RUSLE for analysis (Meseret & Gangadhara, 2017).

The SWPT tool offers a cost-effective approach to identifying and prioritize vulnerable areas, especially in data-scarce regions where traditional methods may be limited (Rahmati et al., 2019). There is an increasing need for automated and reliable methods in decision making for watershed management. These tools reduce uncertainties associated with manual analysis and expert opinions, leading to more objective and accurate prioritization (Rahmati et al., 2019). The successful implementation of SWPT in the Golestan Province of Northern Iran, validated by historical flood and landslide data, demonstrates the practical applicability and replicability of such tools in other regions facing similar environmental challenges (Rahmati et al., 2019). Therefore, the importance of investing and utilizing such tools to support decision making in sustainable land management is crucial.

2.4. Review of empirical evidences

Ethiopia's North-western highlands including the Abbay Basin where land degradation challenges are noticeable, but vital catchment for water resources, 60% of the land is at risk of severe erosion, necessitating urgent intervention (Ethiopian National Water Resources Management Policy, 2021). In such cases, prioritazation is vital for such regions where land resources are mitigated, restored and managed according to its urgency and impacts.

A number of studies were applying morphometric analysis to prioritize watersheds for effective land management decisions. Banti's research on the Guder and Dabus sub-basins in Ethiopia utilized GIS and RUSLE techniques to estimate annual soil loss and prioritize watersheds (Banti, 2020). It's also applied by Abdeta et al. to prioritize erosion-prone sub-watersheds to the Gidabo Basin in Southern Rift Valley, Ethiopia. The studies outputs emphasize the importance of using quantitative watershed aspects such as linear, relief, and areal parameters for ranking and prioritizing sub-watersheds.

It's found that there is similarities in utilizing morphometric parameters for watershed prioritization, the studies showed differences in parameter selection, methodologies and findings. For example, Banti's study focuses on soil loss estimation using RUSLE, whereas Abdeta et al.'s research incorporates land use/land cover analysis. It can be concluded that these differences highlight the diversity of approaches in applying prioritazation techniques based on specific regional characteristics (Banti, 2020; Abdeta et al., 2021). In these studies the arguments presented are acceptable, particularly utilization of advanced technologies like GIS and remote sensing in management decisions. The methodologies employed based on a well-established formulas and techniques made them reliable and valid.

Morphometric parameters in watershed management are also evaluated by Muluneh and Mamo (Muluneh & Mamo, 2014) on the Didessa River catchment, part of the Blue Nile Basin. This research, emphasizing the relationship between morphometric parameters and hydrological behaviour. Study by Gela et. al., conducted in the Gilgel Abay watershed also conducted; aimed to estimate mean annual soil loss and identify priority areas for conservation. Its finding showed that with25% of the watershed-experiencing moderate to severe erosion with an average soil loss rate of 39.8 t ha-1 yr-1, significantly exceeding tolerance levels. Models like RUSLE and morphometric analysis was utilized by Gela et.al, 2023 emphasized that the urgent need for soil and water conservation measures to protect Lake Tana and its resources (Gela et.al, 2023).

The Rib sub-basin, located in north-western Ethiopia, holds significant ecological and agricultural importance. This region faces various environmental challenges and land use changes, primarily driven by population growth and agricultural expansion. Over the past few decades, the Rib River watershed has undergone substantial transformations. From 1973 to 2011, approximately 57.4% of forest cover, 52.3% of bushlands, and 63.5% of water bodies were converted into cultivated and settlement lands. This shift resulted in notable increases in cultivated lands (36.2%), grazing lands (50.9%), and wetlands (66.3%) (Garede, 2014). According to Garede, 2014 the loss of vegetation cover has increased vulnerability to erosion and other environmental hazards, threatening both agricultural productivity and local livelihoods.

Therefore, these studies collectively summarizes and contributes to a deeper understanding of the hydrological dynamics and morphometric characteristics are relevant to decision making for catchment management. They provide a robust foundation for future research and practical applications in watershed prioritization and land management decisions. These studies underscores the necessity for more robust decision-making tool that incorporate key factors for land management. Policymakers are encouraged to utilize these findings to effectively prioritize sub-watersheds for conservation interventions.

Thus, the literature indicates a growing recognition of the value of morphometric parameters and weighted overlay analysis in watershed prioritization efforts in Ethiopia. By combining scientific methodology with practical applications, these studies contribute significantly to the body of knowledge necessary for sustainable watershed management.

Future research may focus on suitability analysis and intervention planning for the effectiveness implementation. This paper aims to find out approaches to develop a comprehensive decision support framework for land managers and policy makers in the Rib sub-basin. This scientific analysis techniques add values on consideration of key parameters to enrich what is already studied by other researchers in different areas other than Rib sub-catchment.

2.5. Conceptual framework

Key components influencing land degradation are Bio-physical and hydrological characteristics of watersheds. Identifying these characteristics helps to evaluate watersheds sensitivity for degradation and give priority management decisions accordingly (Sangle & Yannawar 2020; Banti, 2020). Soil erosion risk assessment utilizes the Revised Universal Soil Loss Equation (RUSLE) assess potentials for erosion within the watersheds (Aja, 2020; Dida, 2023). By combining the outputs of such factors using advanced GIS tools (Srivastava, n.d.; Wubalem, 2021) a holistic understanding of the watershed dynamics is derived. Finally prioritization value score to each watershed helps in determining their relative importance for conservation efforts. The result informs land management decisions by highlighting areas that require Land management, ensuring that resources are allocated efficiently to achieve the desired outcomes (Banti, 2020; Aja, 2020; Dida, 2023).

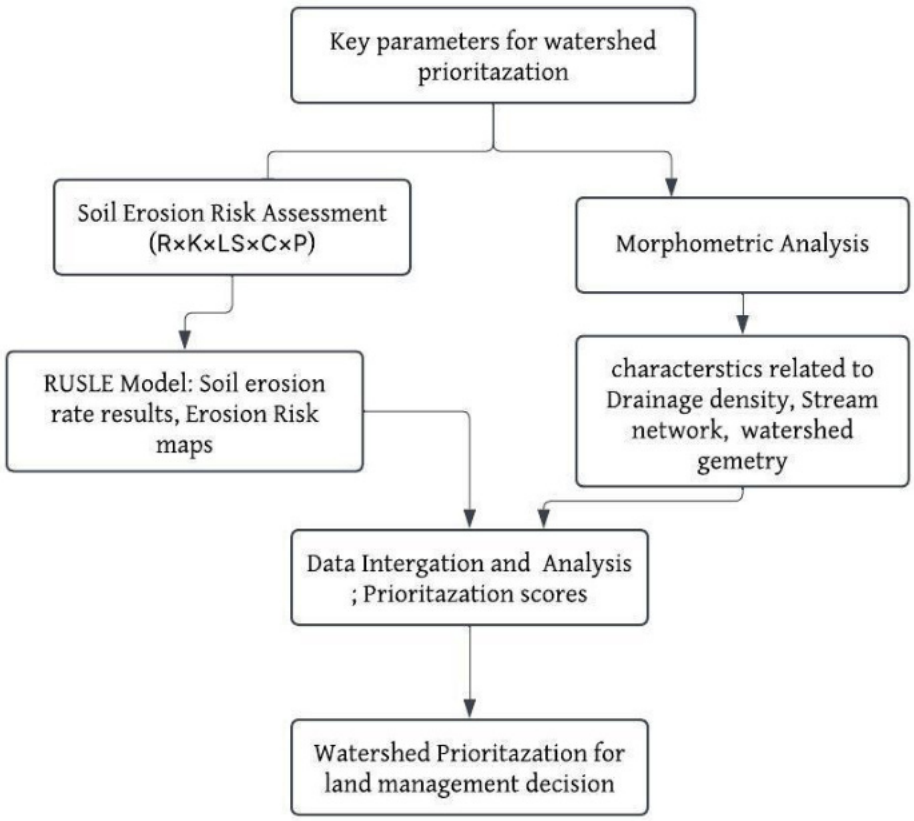

Figure 1. Conceptual framework of the study

CHAPTER THREE: MATERIALS AND METHODS

3.1. Description of the study area

The Rib sub basin, contributing a source region of the Blue Nile, located in the northwest highlands of Ethiopia, primarily within South Gonder zone of the Amhara Region. It encompasses the Rib River, which flows through areas characterized by a mix of highlands (Guna Mountain) and plain (forgera plain). The catchment area is situated near key towns and cities such as Bahir Dar, Gondar, Debre Tabor and Addis Zemen, and it includes several woredas, notably Libo Kemkem, Fogera and Ebenat. The diverse topography, from lowland plains to mountainous terrains, contributes to a variety of microclimates, supporting different land use practices. This sub-basin covers an area of approximately 1,923.75km², with coordinates ranging from 11°70′ N to 12°20′ N latitude and 37°30′ E to 38°20′ E. Its elevation varies between 1,785 to 4,104 meters above sea level (masl.), significantly influencing local climate patterns. The region experiences an average annual rainfall of about 1,200 mm, with the majority of precipitation occurring during the main rainy season from June to September (Mechal et al., 2015). Temperature ranges from a minimum of 8.5 °C to a maximum of 28.5 °C throughout the year.

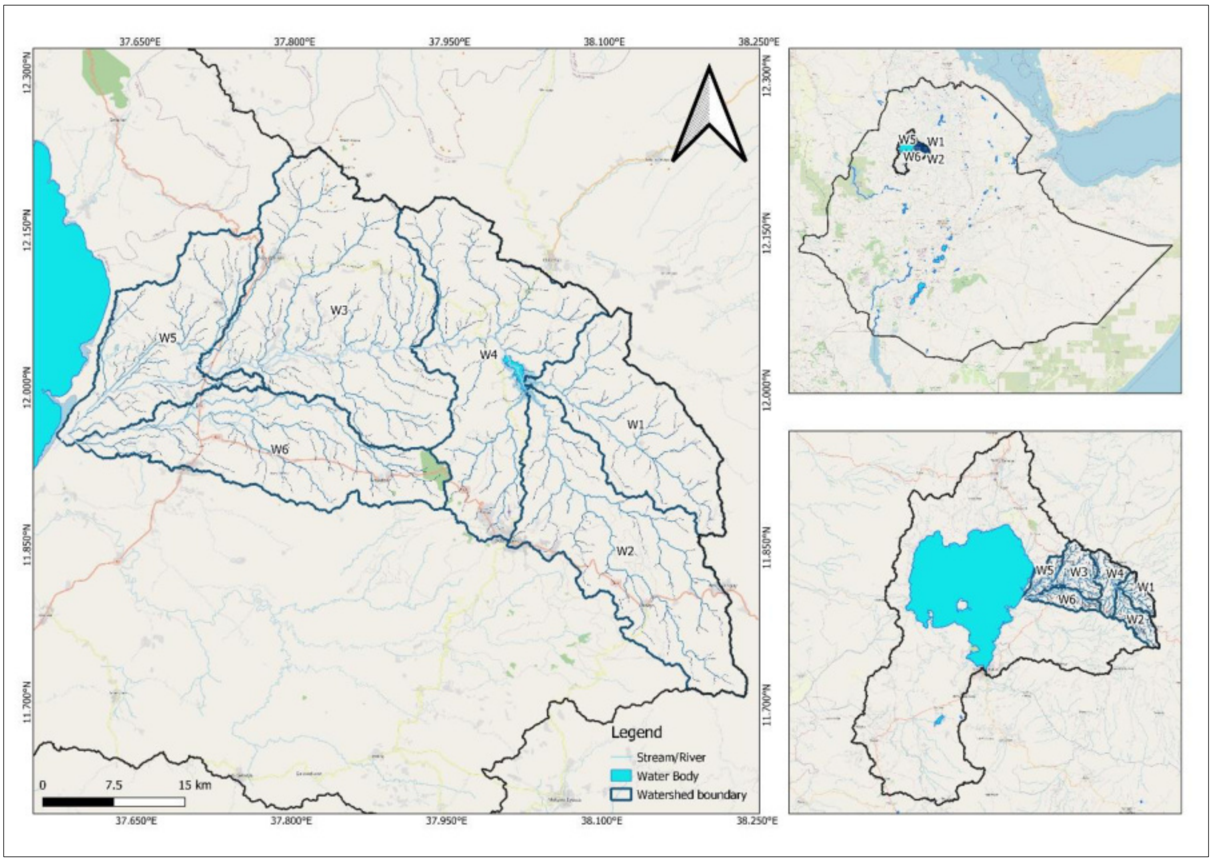

Figure 2. Location map of the study area

The sub-basin is characterized by a range of soils types primarily, Luvisols and Nitosols, which are conducive to agricultural activities but soil erosion is a serious challenge with rates reaching up to 100 tons per hectare annually in severely affected areas (Gajbhiye et al., 2013). In the Ribb catchment, approximately 70% of the land for agriculture for cultivation of crops such as teff, barley, and wheat (Mechal et al., 2015). The Ribb sub-basin also has broad biodiversity with most of the indigenous species are included; diverse flora and fauna. The highland grasslands and forested areas, essential for maintaining ecological balance and supporting local livelihoods in many aspects (Mechal et al., 2015).

The Ribb sub-basin hosts estimated 1.5 million resulting with a population density of approximately 150 people per square kilometre (CSA, 2013). According to the study by Gajbhiye et al., 2013, the primary economic activity of the is agriculture contributing over 50% to the regional GDP, principal crops types produced including teff and barley vital for both subsistence and market sales (Gajbhiye et al., 2013). Livestock farming is also prevalent, with cattle, sheep, and goats being the main livestock raised in the area (Mechal et al., 2015).

The Ribb Reservoir completed in 2009 plays a crucial role in enhancing the livelihoods of surrounding communities by providing irrigation water for a gross command area of 14,500 hectares and benefited about 28,000 households. The storage capacity of approximately 1.2 billion cubic meters and a surface area of about 3,400 hectares when full benefited communities are from the Libo Kemkem and Fogera woredas (Aschalew, 2021). Dry-season irrigation has greatly contributed to agricultural development by increasing cropping intensity and yields through the provision of water, improved drainage, and better access to agricultural inputs (Ribb Reservoir Resettlement Action Plan, 2018). According to Sebestain et al., 1995 and Gajbhiye et al., 2013, in contrast, the Ribb sub-basin faces significant challenges, including soil erosion, deforestation, and water scarcity, all of which threaten food security and economic stability.

3.2. Materials / Data sources and tools

This study utilized Primary and secondary data sources. The primary data source was Geospatial datasets; a 30 m resolution SRTM DEM for topographic processing, and 10 m resolution Sentinel-2 multispectral imagery for land cover classification (Drusch et al., 2012). Secondary data sources include rainfall data for erosivity (R-factor) analysis, soil data for erodibility (K) analysis is used. Revised Universal Soil Loss Equation (RUSLE) integrated in InVEST-SDR model were applied to estimate soil erosion risk, guiding conservation efforts in vulnerable areas (USDA, 2020). RUSLE is an empirical model that estimates soil erosion rate caused by rainfall and overland flow, by utilizing five critical factors: Rainfall Erosivity (R factor), Soil Erodibility (K factor), Cover Factor (C factor), Topographic Factor (LS factor), and Conservation Practice Factor (P factor). Rainfall erosivity (R-factor) were estimated from long-term precipitation records provided by the National Meteorological Institute (NMI) of Ethiopia since 1994. The soil erodibility factor (K) was derived from the Ethio Soil Grids 1.0, a machine-learning based soil classification system developed using Ethiopian legacy data (Ali et al., 2021).

QGIS 3.28, ArcGIS 10.8 for spatial analysis, Integrated Valuation of Ecosystem Services and Trade-offs (InVEST 3.13) for soil erosion modelling are tools utilized for the study. The concrete advantage of using the InVEST SDR tool provides a more holistic and policy-relevant assessment of land management decisions (Sharp et al., 2020). Its advantage for soil loss analysis, compared to solely relying on ArcGIS or QGIS, lies in its integrated ecosystem service-modelling framework, which extends beyond simple erosion estimation to explicitly model sediment delivery ratios and downstream impacts on water quality and other ecosystem services, used to check key parameters the study.

3.3. Methods

A comprehensive methodology were applied to assess and analyse soil erosion risk and morphometric characteristics and integrate to find reliable results. Satellite imagery from Sentinel-2 multispectral imagery, and SRTM Digital Elevation Models (DEMs) with 30-meter resolution provide vital elevation data which are crucial for important for watershed delineation and hydrological modelling such as morphometric parameters analysis.

Secondary data used as input data to estimate of soil erosion in Revised Universal Soil Loss Equation (RUSLE), factors such as rainfall erosivity (R factor), soil erodibility (K factor), cover factor (C factor), topographic factor (LS factor), and practice factor (P factor) are utilized. As direct impacting erosion potential and hydrological characteristics of watersheds, land use data, providing information on current land use and land cover types within the watershed, is analysed. Thus, both primary and secondary data play a crucial role in the effective assessment and prioritization of watersheds. These datasets were processed using various Geographic Information System (GIS) techniques, including ArcGIS 10.8, QGIS 3.16, SAGA and GRASS GIS.

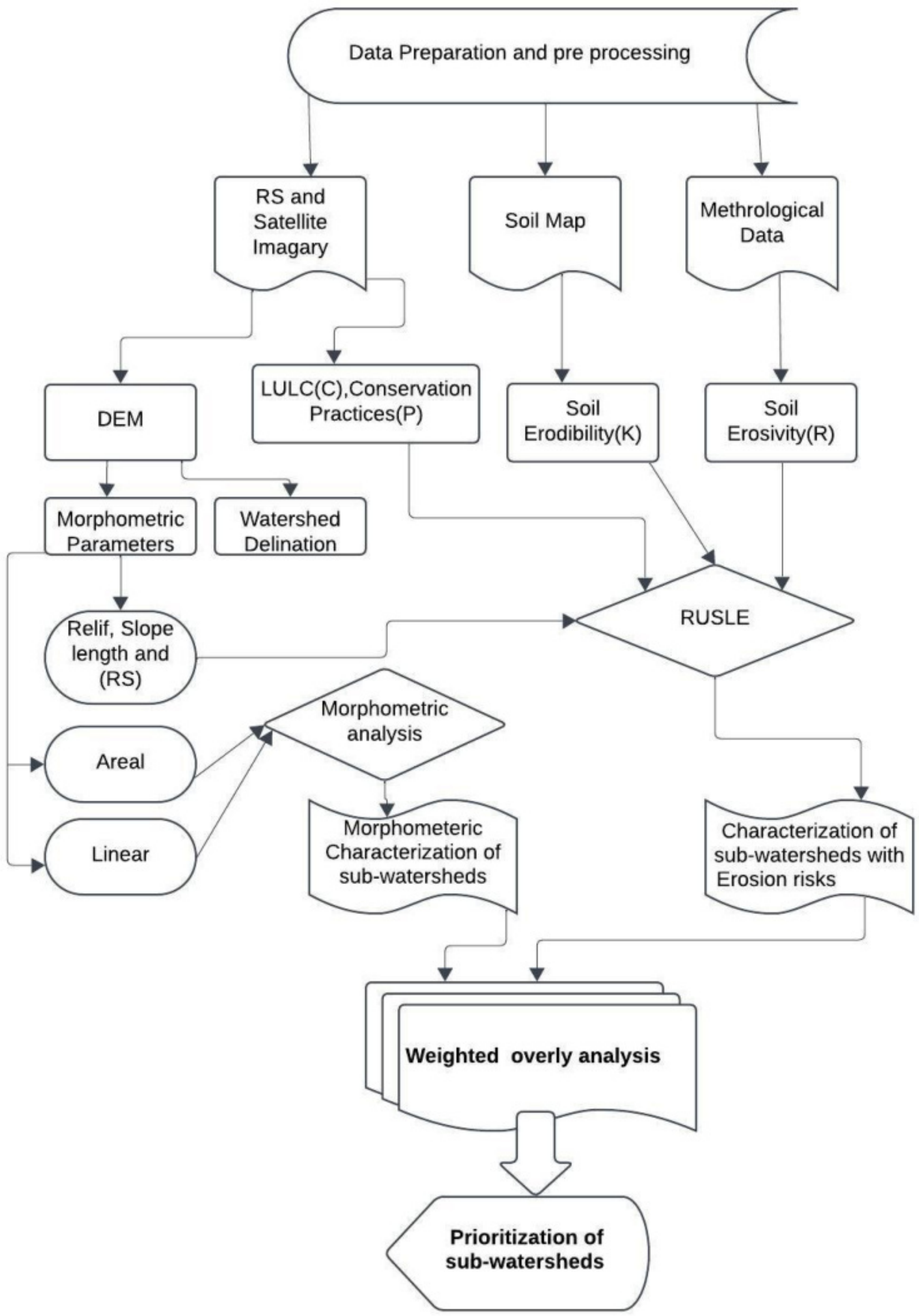

Figure 3, Methodological flow chart/Analytical framework

3.3.1. Data preparation and pre-processing

The pre-processing phase involves several critical steps. First, Geospatial datasets used included a 30 m resolution SRTM DEM for topographic processing, and 10 m resolution Sentinel-2 multispectral imagery for land cover classification. Concurrently, the SRTM DEM were processed in QGIS 3.16 to create a seamless digital elevation model (DEM) for the study area. This integrated DEM facilitated subsequent watershed delineation, key morphometric analysis and RUSLE parameters.

3.3.2. Identifying and defining the parameters

3.3.2.1. Morphometric analysis

Morphometric analysis were done with the extraction of the drainage network and watershed geometry from the processed DEM using ArcGIS 10.8. Following this, the Ribb sub-basin was delineated based on the drainage network and DEM. Key morphometric parameters, including basin area, stream frequency, drainage density, drainage texture and shape factor, was calculated using ArcGIS 10.8 and QGIS, providing essential insights into the watershed's characteristics.

Data processing were done to standardize these morphometric parameters to ensure comparability across watersheds, followed by the creation of spatial maps to illustrate the distribution of these parameters. Prioritization criteria was focused on key parameters considering these factors indicate increased erosion risks.

Basic Parameters: These fundamental measurements provide a general understanding of the watershed's size and scale used inputs to determine key parameters they typically include:

- **Area (A)**: The area of a watershed refers to the total surface area it encompasses, typically measured in square units (e.g., square kilometres or square miles).
- **Perimeter (P)**: is the total length of its boundary, measured along the outer edge of the watershed, providing information of its shape and configuration.
- **Stream Order (U):** a hierarchical classification system that categorizes streams based on the branching pattern of their tributaries. A first-order stream is defined as a stream with no upstream tributaries, two streams of the same order intersect, the resulting stream assigned as second stream order, continuing with increasing order.

- **Total Stream Length (Lu):** cumulative length of all stream segments within a specific stream order in a watershed, measuring the length of each stream segment of a given order and summing these lengths to obtain a total for that order.
- **Basin Length (Lb):** longest dimension of a watershed, typically measured along the primary flow path from the watershed outlet to the most distant point on the basin divide. The maximum length of the watershed and is a fundamental parameter used in calculating shape indices

Key parameters described the characteristics of the stream network as the following:

Table 1. Morphometric parameters for watershed characterization

Parameter	Formula	Implications for Land Degradation	References
Fs - Stream Frequency	Fs = Number of streams(N) / Basin area(A)	A higher stream frequency indicates a more dissected landscape, which can lead to increased soil erosion and runoff, contributing to land degradation.	Schumm (1956); Dzwairo, et.al.,2024
Rb - Bifurcation Ratio	Rb = Nu / N(u+1); where Nu=Total Number of stream segment of order u. Nu+1=Number of segments of the next higher order.	A high bifurcation ratio suggests greater structural complexity in the stream network, which can enhance runoff potential and exacerbate erosion during heavy rainfall.	Schumm, (1956); Hema, et.al.,2021
Rf (Ff) - Form Factor	$Ff = A / L^2$ A=Basin area (km2), L^2=Basin length(km)	More circular watershed shape shows higher form factor, which can lead to rapid runoff and increased erosion, particularly in areas with intense rainfall.	Horton, (1945); Singh, et.al.,2003 ; Gajbhiye et al. (2015)
Re (Er) - Elongation Ratio	$Er = 2\sqrt{(A/\pi)} / L$ Where , Lb=Length of basin(km), A=Area of basin(km2)	An elongated watershed can lead to prolonged runoff times, potentially reducing erosion risk but increasing flood risk during heavy rainfall events.	Gajbhiye et al. (2015)

Parameter	Formula	Implications for Land Degradation	References
Rc (Cr) - Circular Ratio	Cr = (4πA) / P^2 Where, A=Area of basin , π=3.14, Rc=Circulatory ratio, P=Perimeter of basin(km)	A higher circular ratio indicates a more compact watershed, which can enhance runoff efficiency and increase the risk of soil erosion.	Miller, 1953; Hema, et.al., 2021; Gajbhiye et al. (2015)
D (Dd) - Drainage Density	Dd = Total length of streams(Lu) / Basin area (A) ; where Where, Dd=Drainage density Lu=Total stream length of all order, A=Area basin(KM^2)	Increased drainage density can lead to higher runoff and erosion rates, as more water is channeled quickly through the landscape.	Mohammed, et.al.,2018; Gajbhiye et al. (2015)
Rt (T) - Drainage Texture Ratio	T = Nu / P Where, Nu=Total no streams of all order, P=Basin Perimeter (km)	A higher draining texture ratio indicates a more complex drainage network, which can enhance runoff and increase soil erosion risk.	Horton, 1945; Gajbhiye et al. (2015)
Cc - Compactness Constant	Cc=P^2/4πA where A=Area of basin(km2), P=Perimeter of the basin(km), π=3.14	A lower compactness constant suggests a more elongated shape, which can affect runoff patterns and increase erosion potential.	Gajbhiye et al. (2015)
C - Constant of Channel Maintenance	Cc = L / (A^0.5) Where, L= Stream Length(km), A= Area of the basin(km^2)	This constant helps assess the maintenance needs of channels; higher values may indicate a need for more frequent maintenance to prevent erosion and degradation.	Gajbhiye et al. (2015)

3.3.2.2. Soil erosion risk analysis

Revised Universal Soil Loss Equation (RUSLE) model integrated in the InVEST SDR tool computed A factor (estimate soil erosion risk) across the watersheds. The study utilized the pre-processed DEM, land use/land cover data, and soil data to generate erosion risk maps. The InVEST SDR model utilizes essential raster inputs like a Digital Elevation Model (DEM) for calculating the Length-Slope Factor (LS-factor) and flow accumulation, Rainfall Erosivity (R-factor), Soil Erodibility (K-factor), and Land Cover, along with a Land Cover Table linking land cover types to C-factor values, inputs include a Support Practice Factor (P-factor) raster and user-defined SDR parameters for calibration. The model generates raster outputs of Potential Soil Loss as well as tabular outputs summarizing watershed results.

The Revised Universal Soil Loss Equation (RUSLE) estimates soil erosion by water and incorporated several key factors as listed below, each representing different aspects of the erosion process.

Rainfall Erosivity (R): measures the impact of rainfall on soil erosion, accounting for the intensity and duration of rain events, typically determined by analysing historical rainfall data to calculate the potential for erosion based on storm characteristics.

Soil Erodibility (K): the susceptibility of soil to erosion, influenced by soil texture, structure, organic matter content, and permeability.

Slope Length and Steepness (LS): The LS factor combines the length of the slope and its steepness helps to know increase water runoff velocity, which enhances erosion potential. This factor is calculated using the slope gradient and the length of the slope contributing to runoff.

Cover Management (C): This factor accounts for the effects of vegetation cover, crop management, and land use practices that protect the soil. Different types of land cover (e.g., forest, grass, crops, and bare soil) have varying abilities to reduce erosion by intercepting rainfall and promoting infiltration.

Support Practice (P): This factor represents conservation practices that help reduce soil erosion, such as contour farming, terracing, and strip cropping. These practices can alter the flow of water and improve soil retention, effectively lowering the overall erosion rate.

The RUSLE equation is expressed as: $A=R\times K\times LS\times C\times P$

Where:

- **A** = estimated average annual soil loss (tons per hectare per year)- output
- **R-factor** was derived using interpolated precipitation data from NMI Ethiopia.

- **K-factor** was extracted from the Ethio Soil Grids 1.0, which classifies Ethiopian soil properties using a combination of field legacy data and machine learning algorithms (Ali et al., 2021).
- **LS-factor** was generated from the DEM using flow length and slope layers in InVEST.
- **C-factor** was assigned using a land use classification based on Sentinel-2 imagery, with cover management coefficients based on tropical land use types (Morgan, 2005).
- **P-factor** was assigned based on general land management practices for each land cover class.

Rainfall erosivity (R-factor) was estimated from long-term precipitation records provided by the National Meteorological Institute (NMI) of Ethiopia; open-source platforms that contain over 30 years (from 1984 to 2024) of precipitation data from 10 meteorological station namely Yifag, Addis Zemen, Ebinat, Kimir Dingay, Amed Ber, Debere Tabor, Wanzay, Gassary, Leway, Woreta. The soil erodibility factor (K) was derived from the EthioSoil Grids1.0, a machine-learning based soil classification system developed using Ethiopian legacy data.

Topographic data was acquired through DEMs to determine slope length and steepness, which contribute to the LS factor. Furthermore, the Cover Management (C) factor and Conservation Practice (P) factor are critical components in the Revised Universal Soil Loss Equation (RUSLE) model, as they reflect the influence of vegetation cover and conservation interventions on soil erosion processes. In this study, both C and P values were assigned based on land use/land cover (LULC) classification derived from high-resolution Sentinel-2 imagery (10 m) as of 2024, using supervised classification techniques within the Google Earth Engine (GEE) platform. Once the data was collected, the RUSLE components was calculated using InVEST SDR model. Following this, spatial analysis was conducted used to create maps that illustrate annual soil erosion rates across the watersheds.

3.3.3. Integration and prioritization

Each of the 10 defined parameters (soil erosion risk and morphometric characteristics) of each watershed is collected and analysed, standardized to a common scale, such as from 0 to 1, min-max normalization technique was employed. Normalization of the input parameters is done to standardize to a common scale to ensure comparability all the parameters should come to a common scale:

$$X' = X - X_{min} / X_{max} - X_{min}$$

Where;

- *X' = normalized value*
- *X= original value*
- *Xmin= minimum value of the feature*
- *Xmax= maximum value of the feature*

Once the parameters are normalized, weights were assigned to each parameter based on their significance; specific weighting scheme was developed based on the significance of each parameter in influencing hydrology, erosion potential, and flood risk. The weights were assigned based on literature review and expert input on with adjustments based on local conditions.

Table 2. Assigning weights for each parameter

	Parameter	Weight	Rationale	References
1	**Stream Frequency (Fs)**	0.15	Higher value indicates a more dissected landscape, leading to increased runoff and flood risk(Horton, 1945; Strahler, 1957; Kourgialas & Karatzas, 2017).	Horton, R. E. (1945); Strahler, A. N. (1957); Kourgialas, N. N., & Karatzas, G. P. (2017).
2	**Bifurcation Ratio (Rb)**	0.1	High ratio indicates a complex structure that significantly influences hydrological responses, leading to increased potential for rapid runoff during precipitation events; essential for predicting hydrological dynamics (Schumm, 1956).	Schumm, S. A. (1956).
3	**Form Factor (Rf)**	0.15	Higher values indicate more circular shapes, leading to quicker peak flows and increased flood risk. (Miller, 1953).	Miller, V. C. (1953).
4	**Elongation Ratio (Re)**	0.1	Lower values indicate elongated basins, which exhibit slower runoff responses (Schumm, 1956).	Schumm, S. A. (1956).

	Parameter	Weight	Rationale	References
5	**Circular Ratio (Rc)**	0.05	Higher circular ratio suggests a more efficient drainage system, which can lead to quicker runoff and increased erosion potential (Miller, 1953).	Miller, V. C. (1953).
6	**Drainage Density (D)**	0.15	Higher drainage density often correlates with impermeable surfaces and steep slopes, increasing the potential for erosion (Horton, 1945).	Horton, R. E. (1945).
7	**Drainage Texture Ratio (Rt)**	0.1	Higher ratio indicates a more dissected terrain, enhancing runoff potential and erosion (Smith, 1950).	Smith, K. G. (1950).
8	**Compactness Constant (Cc)**	0.1	A lower compactness coefficient suggests a more elongated basin, which may exhibit reduced peak flow and erosion potential (Gravelius, 1914).	Gravelius, J. (1914).
9	**Constant of Channel Maintenance (C)**	0.05	Indicative of channel stability; lower values suggest higher stream density and potentially more unstable channels (Horton, 1945).	Horton, R. E. (1945).
10	**Soil Erosion Rate (A)**	0.15	Higher soil erosion rates correlate directly with land degradation, highlighting the urgent need for conservation measures (Renard et al., 1997).	Renard, K. G., et al. (1997).

The value score for each of the parameter were determined by summing the products of the weights assigned to each parameter and their corresponding standardized values as follows:

Weighted Layeri=Weighti× Layeri

Where:

- *Weighted Layer-i is the weighted layer.*
- *Layer-i is the original layer.*

Finally, the output score is done by adding all the weighted layers together to create a final output score and prioritization map was created for visualization based on the respective values of watersheds. Watersheds scored high value were identified as first priority watershed, suggesting they are more susceptible to erosion and require immediate conservation efforts (Rahmati et al. (2021). Watershed scored lower value were identified as first priority having better conservation value with limited management efforts.

$$\textbf{Output Layer} = \sum (\textbf{Weighted Layer-i})$$

Where:

- *Output Layer is the final output map.*
- *Weighted Layer-I is the individual weighted layers to be summed*

Integrated prioritization map was created to visualize these scores across the watersheds, illustrating watersheds that require immediate conservation attention.

CHAPTER FOUR: RESULT and DISCUSSION

Results

4.1. Watershed delineation

Ribb sub-basin was delineated using the hydrologically corrected DEM, flow direction and accumulation layers were generated. Stream networks were extracted using threshold-based flow accumulation values, and pour points were set to delineate six watersheds. This process was executed using SAGA GIS and QGIS's hydrology toolbox [Jenson & Domingue, 1988].

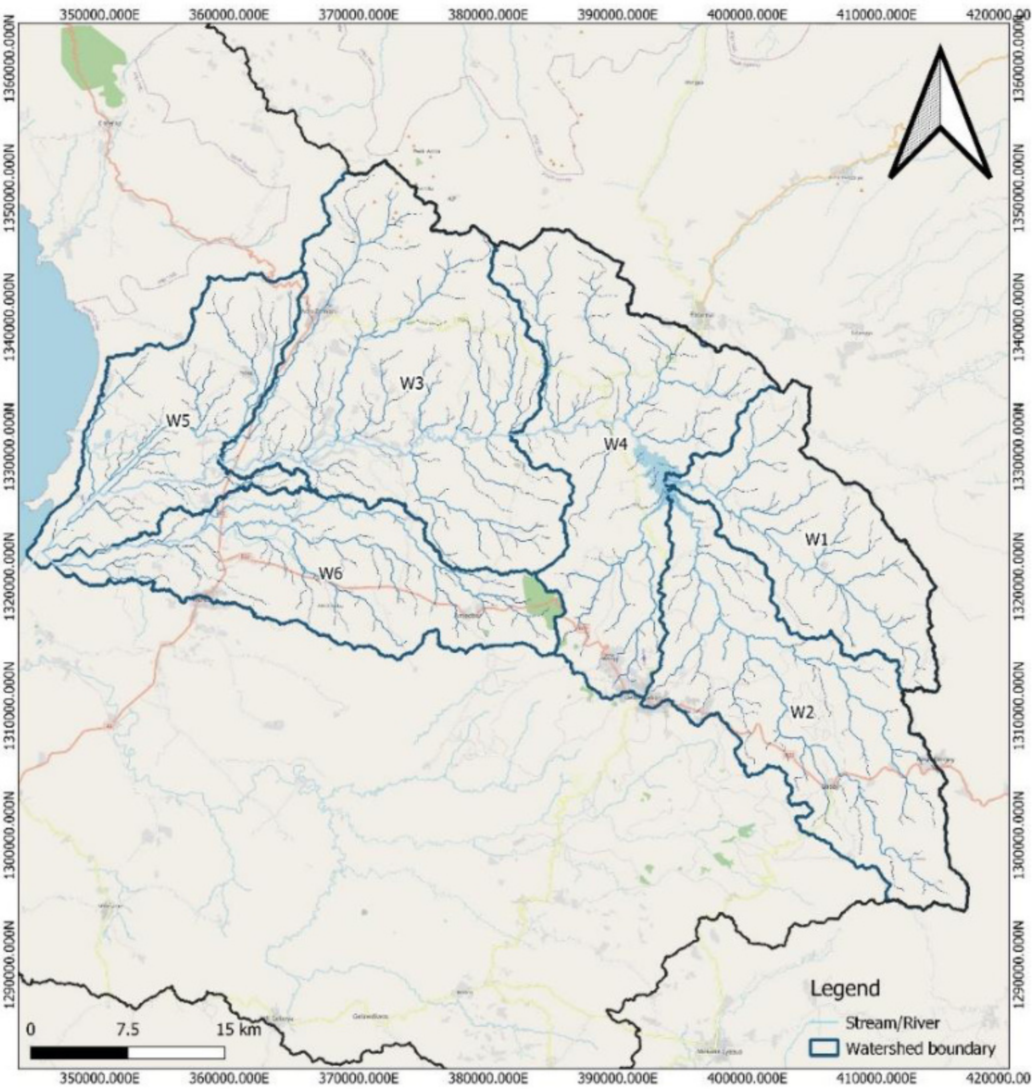

Figure 4. Delineated sub watersheds

4.2. Basic parameters

Linear and shape input parameters used to calculate key parameters of this study were calculated for the 6 watersheds: area (A) and perimeter (P) the area (A), perimeter (P), and stream number (Nu), stream order (u), basin length (Lb), and stream length (L).

4.2.1. Area and perimeter

Area and perimeter are that offer key insights into watershed characteristics and behaviour. Analysis of fundamental morphometric parameters such as area and perimeter across six watersheds helps to show capacity of capturing rainfall and related runoff. The largest area shows at W3; 486.4246 km², possesses a substantial capacity for capturing rainfall and runoff, while W1, the smallest at 218.6693 km², may have lower water availability. W4 164.09 km suggests a complex shape influencing hydrological processes and erosion risks, in relation to perimeter whereas W1 113.434 km, with perimeter shorter indicates a more compact form potentially reducing edge effects and erosion.

Table 3. Perimeter of each watershed of the Ribb sub-basin

Watershed	Area in square kilometre	Perimeter in kilometres
W6	278.9658	145.868
W5	231.4068	136.883
W4	369.9989	164.09
W3	486.4246	161.398
W2	338.2831	155.221
W1	218.6693	113.434
Total	**1923.7485**	**876.894**

4.3. Linear parameter

4.3.1. Stream frequency (Fs)

The finding in table 4 revealed that watershed W5 has the highest stream frequency at 0.000000648, indicating a dense network of streams that enhances water connectivity and runoff potential, which can be beneficial for water supply but may also increase the risk of flooding and erosion if not managed properly.. In contrast, Watershed W2 exhibits the lowest stream frequency at 0.000000186, suggesting a sparse stream network that may lead to reduced water connectivity and slower runoff, potentially aiding groundwater recharge but limiting water availability during dry periods.

4.3.2. Drainage density (D)

Higher values score shown in W5 suggests increased erosion potential, indicating a greater potential for erosion due to increased runoff while W2, with the lowest density, may require less urgent for intervention.

4.3.3. Drainage texture ratio (Rt)

According to the score value of this specific parameter, W5 has the highest drainage texture ratio at 0.001096, indicating a denser and more interconnected network of streams, which enhances water conveyance and runoff potential, thereby improving water availability but also increasing the risk of flooding and erosion if not managed effectively. W2 shows the lowest drainage texture ratio at 0.000405, suggesting a sparser drainage network resulted in reduced runoff and slower water movement which can be beneficial for groundwater recharge but potentially limiting surface water availability during dry periods.

4.3.4. Bifurcation ratio (Rb)

W6 has the highest bifurcation ratio at 2.5, indicating a complex drainage network characterized by a high degree of branching, lead to increased runoff and erosion risks, as the intricate structure may facilitate faster water flow. W6 may require more intensive management strategies to mitigate these risks and ensure sustainable water resources whereas Watershed W5 has the lowest bifurcation ratio at 1.88, suggesting a relatively simpler drainage network. This simplicity may result in slower runoff and reduced erosion risks, as the straightforward structure allows for more gradual water flow.

4.3.5. Constant of channel maintenance (C)

W2 exhibits the highest value at 1624.93, indicating a greater need for channel maintenance to ensure stability and prevent erosion, suggesting that the channel may be more susceptible to changes in flow or sediment transport. W3 has a lower value of 1467.34, implying a somewhat less demanding maintenance requirement, yet still significant. Watersheds W4 and W1 follow with values of 1291.25 and 1394.60, respectively, indicating moderate maintenance needs. Watershed, W6 with a value of 1142.86 suggests a relatively efficient channel system that requires less maintenance, making it potentially more resilient to disturbances.

4.4. Shape parameters

4.4.1. Form factor (Rf)

W3 and W4 exhibit the highest form factors, 0.79 and 0.71 respectively, indicating more compact, less elongated shapes, which typically result in quicker runoff responses and potentially higher peak flows. Watersheds W2, W6, and W1 have lower form factors (0.22, 0.32, and 0.31, respectively), suggesting more elongated shapes that tend to have slower runoff responses and a greater potential for water retention. Watershed W5, with a form factor of 0.40, falls in between, exhibiting a moderate shape influence on its hydrological behaviour.

4.4.2. Elongation ratio (Re)

Variations in watershed shape that impact runoff characteristics ranges from 0 to 1. Watersheds W3 and W4, with elongation ratios of 1.00 and 0.95 respectively, tend toward circular shapes, suggesting a more uniform response to rainfall and potentially lower peak flows due to shorter flow paths. W2, W6, and W1, with elongation ratios of 0.53, 0.64, and 0.63 respectively, exhibit more elongated shapes, which can lead to longer flow paths, increased infiltration opportunities, and potentially delayed or dampened peak flows. W5, with an elongation ratio of 0.72, falls in the middle, indicating a moderate influence of shape on its hydrological response. These findings suggest that W3 and W4 may be less prone to flash floods compared to W2, W6, and W1, due to their more circular and compact forms.

4.4.3. Circular ratio (Rc)

W6 and W5 have the lowest circular ratios, indicating potentially inefficient drainage. This may lead to waterlogging and increased erosion, necessitating improved drainage management strategies in these areas.

4.4.4. Compactness constant (Cc)

W3 lower compactness constant suggests an elongated watershed shape, which may contribute to slower runoff and improved infiltration. Management strategies should aim to enhance water retention in these elongated areas.

Table 4: Morphometric parameter results

Watershed	Morphometric Parameters								
	Stream Frequency (Fs)	Drainage Density (D)	Drainage Texture Ratio (Rt)	Bifurcation Ratio (Rb)	Constant of Channel Maintenance (C)	Form Factor (Rf)	Elongation Ratio (Re)	Circular Ratio (Rc)	Compactness Constant (Cc)
W6	0.000000452	0.000875	0.000864	2.5	1142.86	0.32	0.64	0.16	2.46
W5	0.000000648	0.000996	0.001096	1.88	1004.24	0.4	0.72	0.16	2.54
W4	0.000000351	0.000774	0.00079	1.89	1291.25	0.71	0.95	0.17	2.41
W3	0.000000201	0.000682	0.000606	2.24	1467.34	0.79	1	0.23	2.07
W2	0.000000186	0.000615	0.000405	2.03	1624.93	0.22	0.53	0.18	2.39
W1	0.000000348	0.000717	0.00067	1.98	1394.6	0.31	0.63	0.21	2.16

4.5. RUSLE model parameters for soil erosion risk (A) analysis

To estimate and analyse the annual long-term average soil loss due to sheet and rill erosion, Revised Universal Soil Loss Equation (RUSLE) integrated in the Integrated Valuation of Ecosystem Services and Trade-offs - Sediment Delivery Modelling (InVEST SDR) tool is used. The following sections detail the creation and characteristics of raster maps representing each RUSLE factor. These maps, essential for soil loss estimation, were generated using a variety of data sources.

4.5.1. R-factor (rainfall erosivity)

The map generated from long term recorded mean annual rainfall data shows a spatial distribution of rainfall erosivity across the watershed, with values ranging from a low of 780.309MJmm ha-1 hr-1 yr-1 (green areas) to a high of 901.087 MJmm ha-1 hr-1 yr-1 (red areas). The eastern part of the watershed (particularly within W1 and W4) experiences the highest rainfall erosivity, while the western part (W5) has the lowest. The meteorological stations located in high rainfall areas like Ebinat, Debere Tabor, and Gassary are critical for accurately monitoring and predicting erosive events, while stations in lower rainfall areas such as Yifag and Addis Zemen provide essential data for understanding the spatial variability of rainfall and informing broader watershed management strategies.

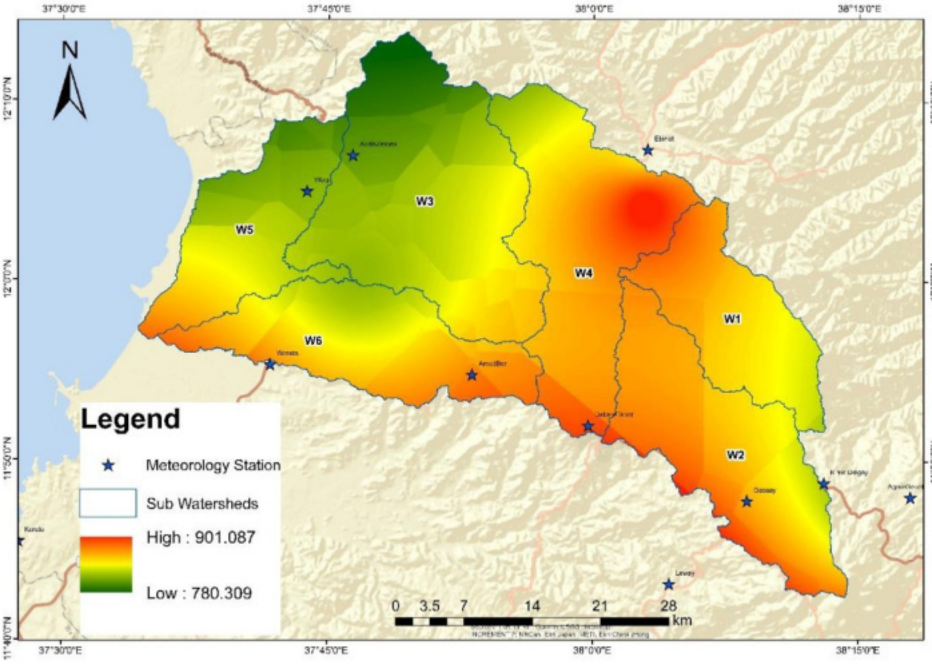

Figure 5. Map of rainfall erosivity (R) factor

4.5.2. Soil Erodibility (K) Factor

In reference to table 13, The K-values for various soil types were determined through a combination of literature reviews and empirical studies, based on their erosion susceptibility and physical characteristics. The result showed that Alisols, with a K-value of 0.30, are noted for their low permeability and acidity, making them prone to erosion, as reported by FAO (1980) and Panagos et al. (2014). According to Ashenafi et al. (2023) and Wischmeier & Smith (1978) Cambisols and Fluvisols have a K-value of 0.23, indicating moderate organic matter and weak development, stratified sediments and low structure, have a K-value of 0.25, respectively. Other soil types, such as Gleysols (K-value of 0.20) and Leptosols (0.10), exhibit specific traits like waterlogging and shallow stoniness, respectively. Luvisols and Nitisols, with K-values of 0.28 and 0.20, respectively, reflect moderate structure and stability, while Phaeozems, known for their high organic matter, have a K-value of 0.18. Regosols, easily eroded due to their sandy nature, have the highest K-value of 0.32, while Vertisols, which are resistant to erosion due to their clay content, and have a K-value of 0.15, as outlined by Ashenafi et al. (2023).

Table 5. K value of the soil types

Soil Type	K-value	Remarks / Source
Alisols	0.30	Low permeability, acidic; prone to erosion – FAO, 1980; Panagos et al., 2014
Cambisols	0.23	Weakly developed, moderate OM – Ashenafi et al., 2023; Wischmeier & Smith, 1978
Fluvisols	0.25	Stratified sediments, low structure – Ashenafi et al., 2023; FAO, 1980
Gleysols	0.20	Waterlogged, fine texture – Panagos et al., 2014
Leptosols	0.10	Shallow and stony, low erodibility – Ashenafi et al., 2023
Luvisols	0.28	Clay-rich subsurface; moderate structure – FAO, 1980; Ashenafi et al., 2023
Nitisols	0.20	Deep, stable clay; moderate OM – Ashenafi et al., 2023; Wischmeier & Smith, 1978
Phaeozems	0.18	High OM, stable aggregates – Panagos et al., 2014
Regosols	0.32	Poorly developed, sandy; easily eroded – FAO, 1980; Ashenafi et al., 2023
Vertisols	0.15	High clay, shrink-swell; resistant to splash – Ashenafi et al., 2023

The findings showed significant variability in soil erosion susceptibility across the identified watersheds. Regosols, with the highest K-value of 0.32, are prominently found in W1, suggesting a 25% proportion of this watershed is at high risk of erosion due to their poorly developed, sandy characteristics. Alisols and Luvisols, in contrast having K-values of 0.30 and 0.28 respectively, cover approximately 20% and 15% of Watershed W3, indicating moderate erosion susceptibility. W4 exhibits a diverse composition, with Cambisols (K-value of 0.23) and Fluvisols (K-value of 0.25) accounting for about 30% of its area. These soils, characterized by weak development and stratified sediments, suggest a moderate risk profile, necessitating targeted management strategies. Conversely, W2, primarily composed of Gleysols (K-value of 0.20) and Nitisols (K-value of 0.20), constitutes roughly 35% of the watershed area, offering a relatively stable soil environment that may mitigate erosion risks.

In W5, the soil composition is characterized by a lower susceptibility to erosion, predominantly featuring **Leptosols** (K-value of **0.10**) and **Vertisols** (K-value of **0.15**). Approximately **40%** of this watershed, indicating a relatively stable environment with low erodibility, which is beneficial for maintaining soil health and agricultural productivity. W6, is marked by a mix of **Phaeozems** (K-value of **0.18**) and **Gleysols** (K-value of **0.20**), about **30%** of its area. Showing presence of these soils suggests moderate stability and organic matter content, which can help mitigate erosion risks, although careful management practices are still necessary to preserve these favourable conditions. The two W5 and W6 showed lower erosion potential compared to other watersheds.

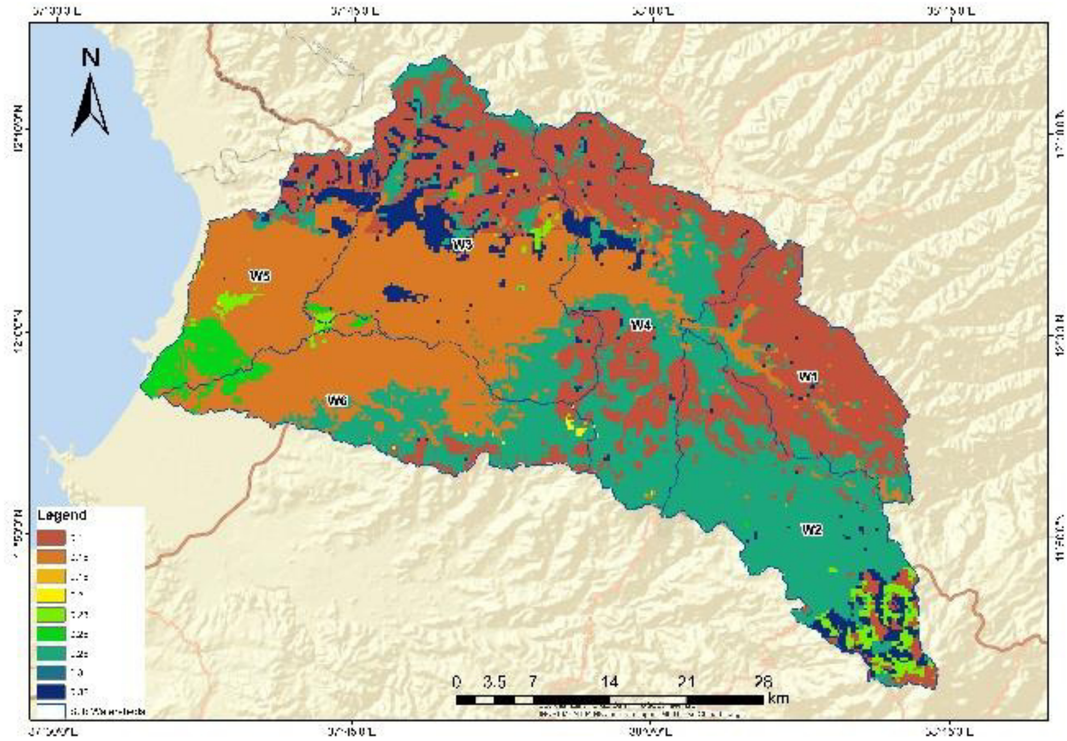

Figure 6. Erodibility (K) factor map

4.5.3. Slope steepness and slope length (LS) factor

The InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) model requires input data, including a Digital Elevation Model (DEM) to employ the LS factor. Equation proposed by Moore and Burch to evaluate soil erosion potential utilized internally for each watershed which is essential for deriving slope and flow accumulation maps((Moore & Burch, 1986)).

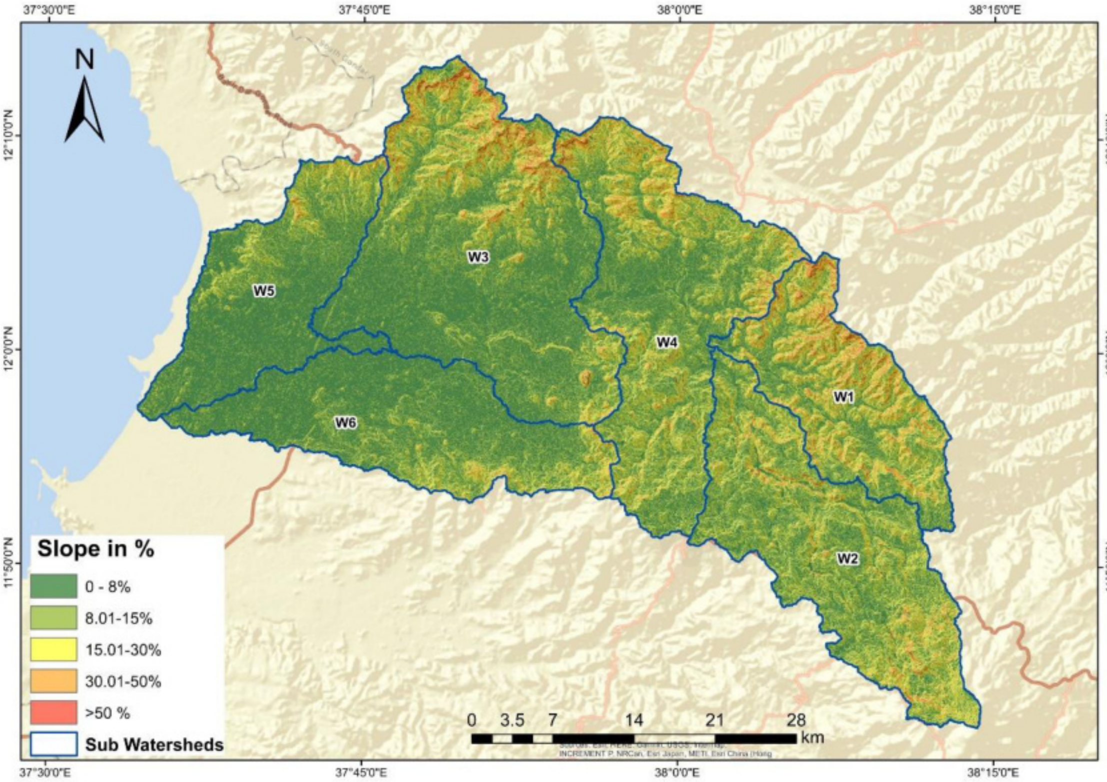

Figure 7. Slope map of the study area

The LS factor map indicates varying erosion potential across the watershed, with areas of high LS factors (up to 27.82) highest value; showing a greater risk of soil erosion, typically found in steep or elongated slopes.

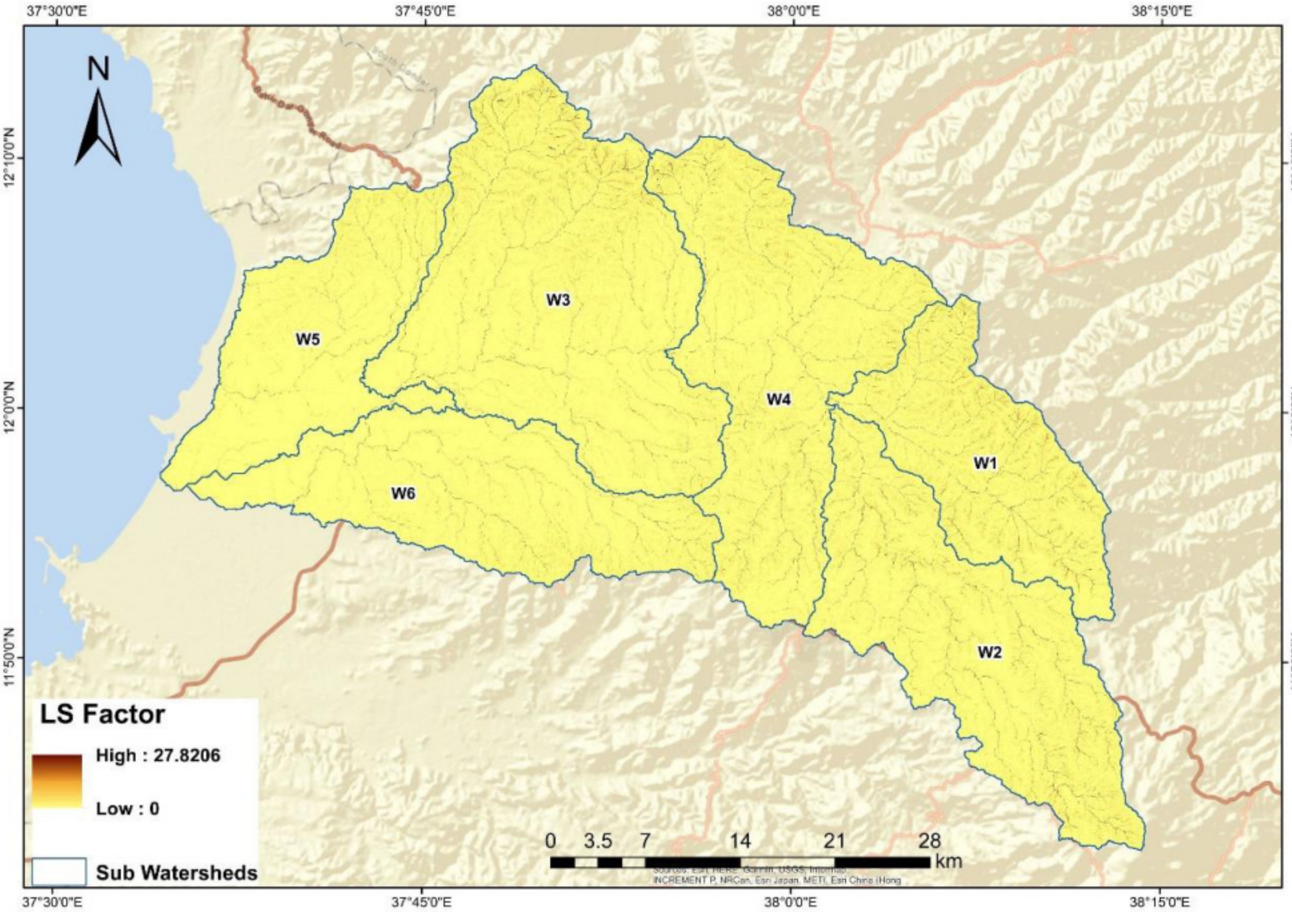

Figure 8: Map of LS factor

4.5.4. Land use and land cover (C) factor

Dense and moderate forests were assigned the lowest C-value of 0.001, indicating maximum protection against erosion. Croplands, open shrub lands, and bare land received higher values (e.g., 0.34 and 0.5) reflecting minimal vegetative cover and greater susceptibility to erosion. This approach aligns with methods used in similar studies by Panagos et al. (2015) and Alewell et al. (2019), which emphasize the sensitivity of erosion rates to vegetation density.

Table 6. C- factor value by land cover

Value	Class Name	C
1	Moderate forest	0.001
2	Annual cropland	0.34
3	Open grassland	0.1
4	Closed grassland	0.07
5	Dense forest	0.001
6	Sparse forest	0.01
7	Wetland	0.079
8	Built up	0.15
9	Open shrub land	0.12
10	Closed shrub land	0.11
11	Water body	0
12	Bare land	0.5

As mentioned in section 3.3.2.2, C factor were generated by linking literature-supported values with each LULC. The below land cover map was used to assign C-factor values in the InVEST model; lower C-factor values to areas with dense forest and higher C-factor values to areas with annual crops or bare land. The analysis showed that the relative C-factor values assigned to each land cover type like W3 and W6 face the highest risk of soil loss due to the dominance of annual crops, which cover approximately 30% of W3 and 25% of W6, leaving large areas with limited protective vegetation. Meanwhile, W1, W2, and W4 also exhibit significant erosion potential, with agricultural land accounting for about 20% of W1, 15% of W2, and 18% of W4, making them vulnerable to soil degradation and runoff. The presence of wetlands in W5; covering roughly 10% of the watershed, could help reduce sediment delivery downstream, provided they have sufficient capacity to trap sediment efficiently. Additionally, W4 is particularly susceptible to reservoir sedimentation due to its high erosion potential from surrounding agricultural land.

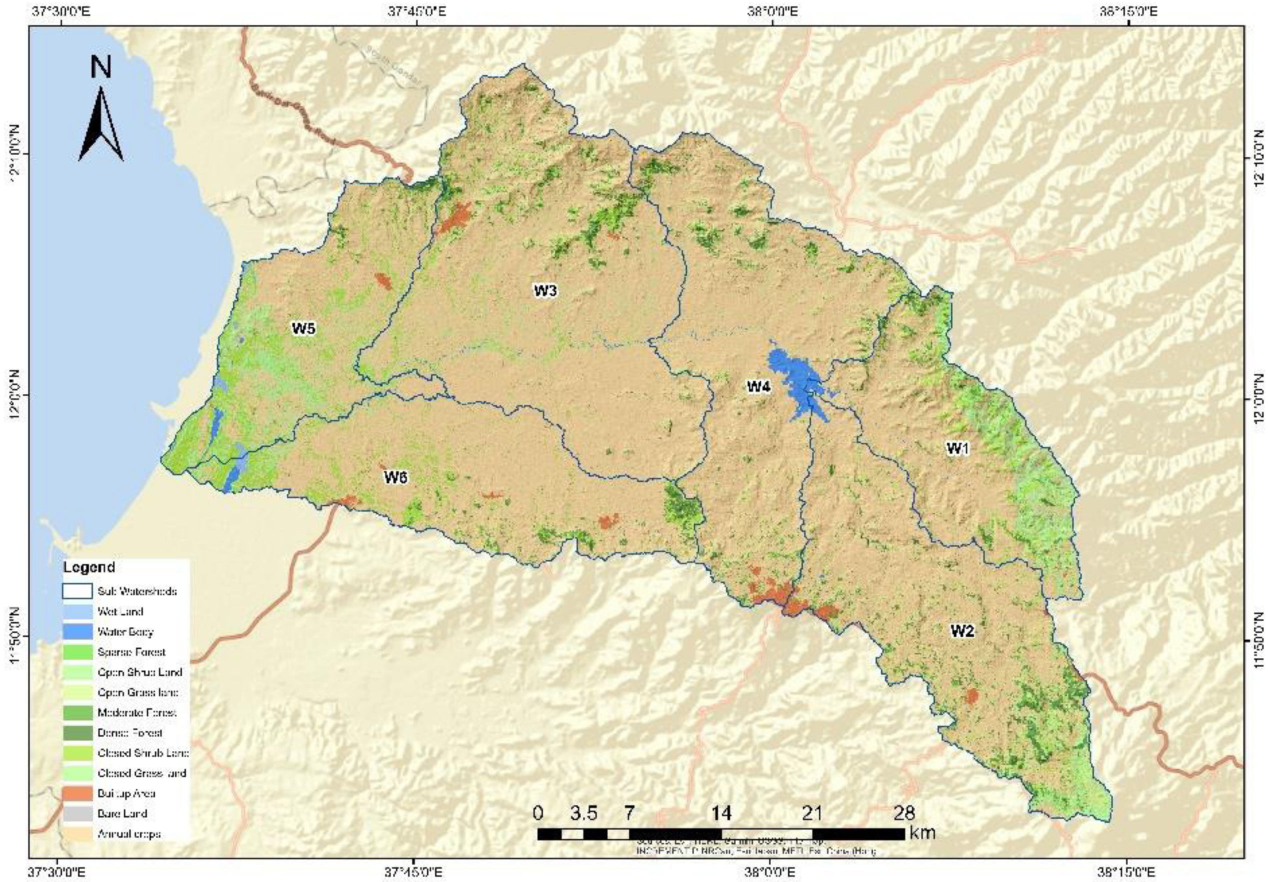

Figure 9. LULC Map for generated C- factor

4.5.5. Conservation practice (P) factor

The P-factor values were also assigned based on LULC as mentioned in section 3.3.2.2 and derived using geospatial conservation practice datasets specific to the Ethiopian context, in accordance with guidelines from Hurni (1985) and Ganasri & Ramesh (2016). Forest and wetland classes received very low P-values (e.g., 0.001–0.079), reflecting minimal need for artificial conservation efforts. In contrast, annual cropland, bare lands, and urban areas, which often lack physical SWC interventions, were assigned higher values (e.g., 0.34 and 0.9), indicating reduced protection and increased erosion risk.

Table 7. P- Factor value by Land Cover

Value	Class Name	P
1	Moderate forest	0.001
2	Annual cropland	0.34
3	Open grassland	0.1
4	Closed grassland	0.07
5	Dense forest	0.001
6	Sparse forest	0.01
7	Wetland	0.079
8	Built up	0.9
9	Open shrub land	0.12
10	Closed shrub land	0.11
11	Water body	0
12	Bare land	0.9

4.5.6. Annual soil loss estimated (A)

The variation in soil loss across the sub-watersheds (W1-W6) within the Ribb sub-catchment is attributed to a combination of spatially variable factors. Land cover differences significantly influence erosion rates; for instance, sub-watersheds like W3 and W6, with higher annual crop coverage, tend to experience increased soil loss, while W5, containing more wetlands, potentially benefits from reduced net soil loss due to sediment trapping. Topographic variations also contribute, with steeper slopes in areas like W3 accelerating runoff and increasing erosive power. Furthermore, the proximity to water bodies, as seen in W4's unique erosion dynamics related to reservoir sedimentation, localized land management practices and soil type variations influence the spatial distribution of soil loss across the sub-catchment indicating higher values indicating greater risk.

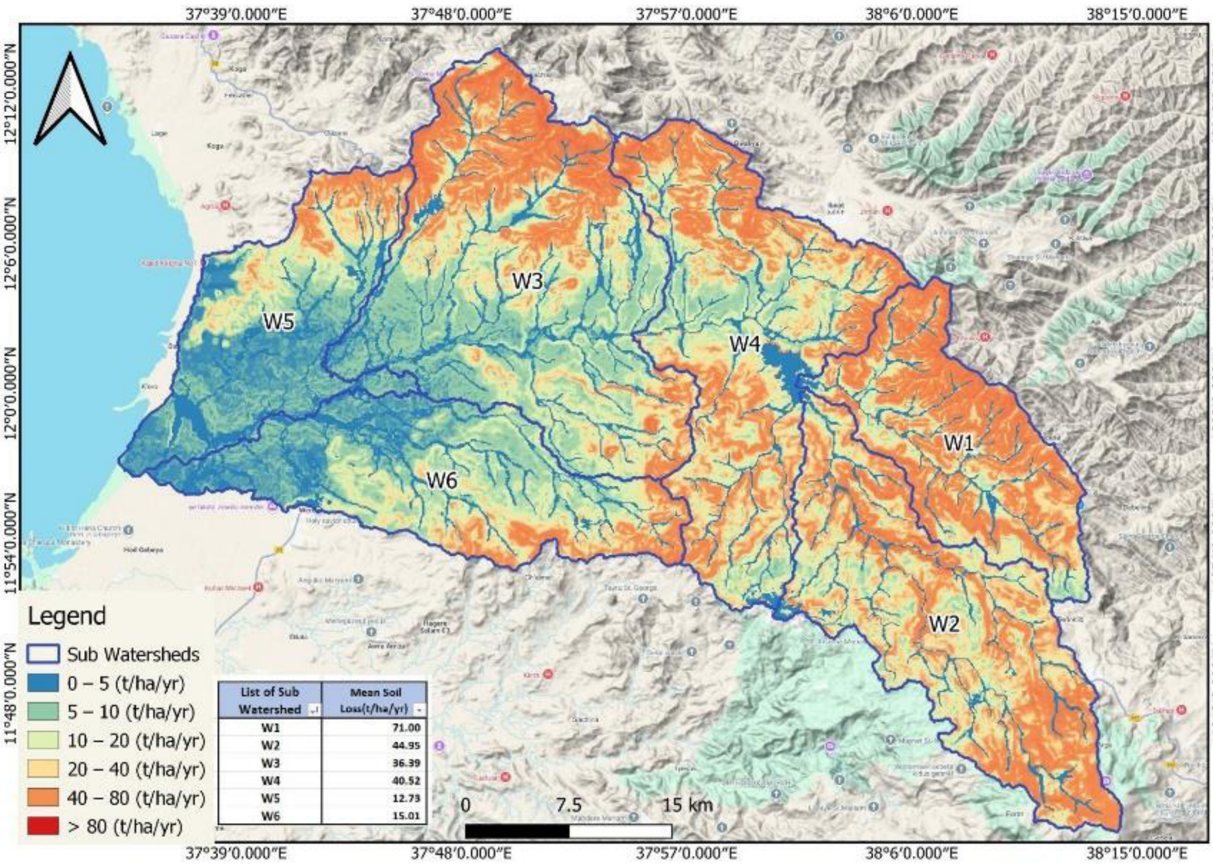

Figure 10. Soil erosion risk map (A)

As visualized in the map, the Ribb sub-catchment exhibits considerable spatial variability in annual soil loss, ranging from 12.73 t/ha/yr in W5 to 71.00 t/ha/yr in W1. These findings align with the broader range of soil loss rates reported for the Ethiopian Highlands, where erosion rates can vary significantly based on land use, topography, and management practices (Hurni, 1988). While some studies have documented soil loss exceeding 300 t/ha/year in cultivated lands with inadequate conservation (Hurni, 1988), the values observed in W1, W2, W3, and W4 are generally lower, suggesting localized variations in erosion severity. Moges and Bhat (2017) estimated an average soil loss of 25 t/ha/yr in the Ribb Dam catchment, with a range of 0-50 t/ha/yr, indicating that the current study's findings for some sub-watersheds (W1, W2, W3, and W4) exceed this average. However, another study focusing on the Rib watershed found an increasing trend in annual soil loss from 40 t ha^{-1} $year^{-1}$ in 1986 to 68 t ha^{-1} $year^{-1}$ in 2016, with a range of 0–807 t ha^{-1} $year^{-1}$ in 2016, suggesting a potential escalation of erosion over time (Moges & Bhat, 2017). Factors such as land cover (dominance of annual crops), slope steepness, and land management practices likely contribute to this spatial variability.

4.6. Standardization and developing prioritization rank

First, each parameter under consideration is standardized using min-max normalization, scaling the values to a common range between 0 and 1. The normalization is to ensure all parameters are on a comparable scale regardless of their original units. A weighted overlay technique was applied for each normalized parameters and multiplied by its assigned weight. The final weighting reflects the relative importance of each parameter in determining the overall prioritization score. Finally, the weighted parameters are summed for each watershed, resulting in a final prioritization score that reflects the cumulative influence of all parameters. This score were ranged from 0 to; higher values is determined as the first priority and other sub-watersheds will be ranked accordingly. These values serves as the basis for categorizing watersheds into high, medium, or low priority levels, guiding conservation efforts and resource allocation.

Table 8. Prioritization score and final ranking of watersheds

Watershed codes	Parameters										Prioritization Score
	Fs	Rb	Rf	Re	Rc	D	Rt	Cc	C	A	
W6	0.000000452	1	0.324383	0.642674	0.164796	0.000875	0.000864	0.838027	0.223323	0.039139202	0.322
W5	0.000000648	0.0000463747	0.404773	0.717905	0.155053	0.000996	0.001096	1	0	0	0.241
W4	0.000000351	0.008741624	0.710394	0.951067	0.171775	0.000774	0.00079	0.730578	0.462398	0.476840308	0.379
W3	0.000000201	0.573932803	0.792929	1.004798	0.233596	0.000682	0.000606	0	0.746108	0.406020096	0.387
W2	0.000000186	0.235264006	0.217266	0.525966	0.175603	0.000615	0.000405	0.674384	1	0.552952987	0.318
W1	0.000000348	0.154628578	0.311105	0.629383	0.213562	0.000717	0.00067	0.201631	0.628921	1	0.338

The analysis of the six watersheds reveals critical insights into their hydrological characteristics for management decision. Analysing the prioritization scores and key contributing parameters for each watershed provides insights into the specific factors driving erosion risk and informs intensity of intervention planning as follows:

Watershed W6 (Prioritization Score: 0.322): The high Bifurcation Ratio (Rb=1), indicating a complex stream network, and a relatively high Compactness Constant (Cc=0.838), suggesting a less elongated basin, are key contributors. The Stream Frequency (Fs=0.000000452) and Drainage Density (D=0.000875) are low, which might partially offset the risk. The Soil Erosion

Rate (A=0.039) is also relatively low compared to other watersheds. Conservation efforts should focus on managing the complex stream network to reduce runoff and erosion potential, particularly given the basin's shape.

Watershed W5 (Prioritization Score: 0.241): The extremely low Bifurcation Ratio (Rb=0.0000463747) suggests a simple stream network with limited branching, and the high Compactness Constant (Cc=1) indicates a circular basin shape. While the Stream Frequency (Fs=0.000000648) and Drainage Density (D=0.000996) are moderate, the Soil Erosion Rate (A=0) is the lowest among all watersheds. These factors collectively contribute to the low erosion risk, suggesting minimal intervention is required.

Watershed W4 (Prioritization Score: 0.379): The high Form Factor (Rf=0.710) and Elongation Ratio (Re=0.951) indicate a more circular and less elongated basin, leading to quicker peak flows. The Soil Erosion Rate (A=0.477) is also relatively high, contributing significantly to the overall score. The Stream Frequency (Fs=0.000000351) and Drainage Density (D=0.000774) are relatively low, but the basin shape and erosion rate necessitate conservation efforts to manage runoff and reduce soil loss.

Watershed W3 (Prioritization Score: 0.387): Similar to W4, the high Form Factor (Rf=0.793) and Elongation Ratio (Re=1.005) suggest a circular basin shape, promoting rapid runoff. The Soil Erosion Rate (A=0.406) is also a significant factor. The Drainage Texture Ratio (Rt=0.000606) is the lowest among all watersheds, potentially reducing the overall erosion risk. However, the basin shape and erosion rate warrant conservation measures to mitigate runoff and soil loss.

Watershed W2 (Prioritization Score: 0.318): The Soil Erosion Rate (A=0.553) is the second highest among all watersheds, making it a primary concern. The Compactness Constant (Cc=0.674) is moderate, suggesting a slightly elongated basin. The Stream Frequency (Fs=0.000000186) and Drainage Density (D=0.000615) are the lowest, which might partially offset the risk. However, the high erosion rate necessitates immediate conservation efforts to reduce soil loss.

Watershed W1 (Prioritization Score: 0.338): The Soil Erosion Rate (A=1) is the highest among all watersheds, indicating a severe erosion risk. The Stream Frequency (Fs=0.000000348) and Drainage Density (D=0.000717) are moderate, but the high erosion rate dominates the overall score. The Compactness Constant (Cc=0.202) is the lowest, suggesting a highly elongated basin, which might slow down runoff. However, the extreme erosion rate requires urgent and comprehensive conservation measures to prevent further soil loss.

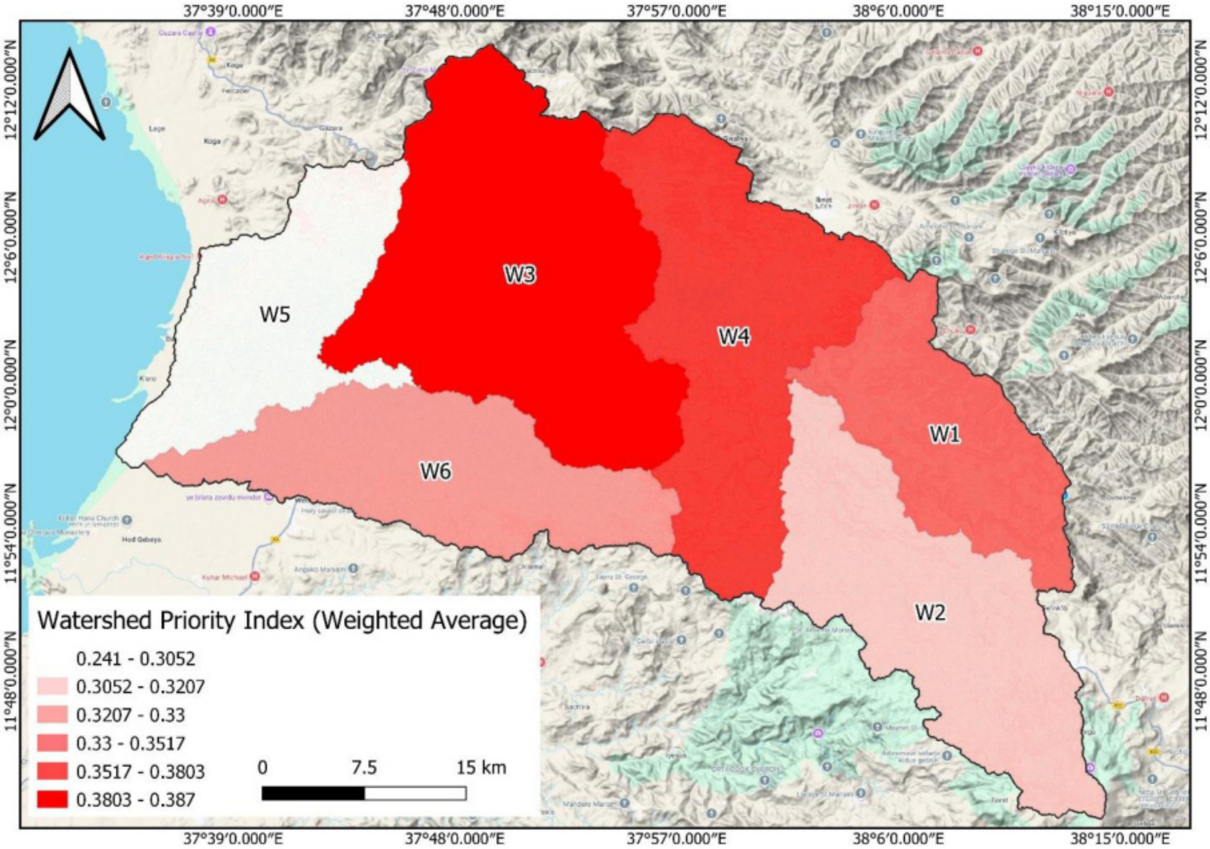

Figure 11. Integrated watershed priority map based on weighted morphometric and erosion rate parameters.

Therefore, the analysis highlights the importance of Soil Erosion Rate (A) as a primary driver of prioritization scores, particularly in W1 and W2. Basin shape, as indicated by Form Factor (Rf) and Elongation Ratio (Re), also plays a significant role in determining runoff potential and erosion risk in W3 and W4. Stream network characteristics, represented by Bifurcation Ratio (Rb), influence the overall hydrological response and erosion potential in W6. These findings underscore the need for targeted conservation strategies tailored to the specific characteristics of each watershed to effectively manage erosion risk, efficient resource allocation and promote sustainable land management practices.

Discussion

Morphometric parameters and RUSLE-derived erosion indicators were integrated across the six delineated watersheds of the Ribb sub-basin to understand spatial variability in watershed behaviour and its erosion potential. The variation in physical attributes of the watersheds, which are area, stream frequency, drainage density, and shape manifests a clear need for site-specific management intervention.

Watersheds W3 and W4, with higher form factors and elongation ratios, show much compact shapes. Thus, they are more sensitive to rainfall events which leads to runoff being generated very quickly. W2 and W1 showed elongated forms with lower form factors indicating longer flow paths and delayed peak discharges typical favourable conditions for infiltration but may be negative for available water during dry spells. Notably, W6 having the highest bifurcation ratio indicates a very complicated stream system network; therefore, it is very hydrologically responsive and needs closer monitoring as well as robust soil conservation strategies. W5 had the highest value for stream frequency; however, this sub-watershed also gave the lowest value for RUSLE-predicted annual soil loss. This illustrates that other factors, land use practices in particular, can significantly decrease or increase the total amount of soil loss expected based on stream density alone. The sub-watershed W1 recorded the highest soil loss of about 71.00 t/ha/yr, hence an erosion control priority area; this must be considered in view of its significant coverage of Regosols and croplands.

The R-factor distribution identified W1 and W4 as zones of high rainfall erosivity, which corresponds to the pattern of observed soil loss. The K-values further differentiated the susceptibility of the watersheds. Regosols (K=0.32) and Alisols (K=0.30) add to elevated risk profiles. C- and P-factors very effectively brought out human-induced influences showing that high cropland coverage in W3, W6 is directly related to increased soil degradation; in return, wetlands and stable forest cover in W5 provide critical buffer

The weighted overlay analysis indicated that the importance of the soil erosion rate (A) as a governing criterion for prioritization is supported by compound contributions from compactness, bifurcation ratio, and drainage density. Watersheds W1 and W2, ranking at the top in prioritization score, should be considered focal areas for immediate conservation investments particularly through slope stabilization, agroforestry, and erosion-resistant cropping systems. W5 on the other hand shoed minimal erosion and simple drainage network structure, may serve as a reference site for studying successful land cover configurations.

Therefore, spatial trends such as land use land cover intensity, slope gradient and soil type and structure plays principal role indicating the morphometric-erosion risk integration is vital approach for watershed prioritazation in larger landscapes. Findings of the studies by by Moges and Bhat (2017) and Hurni (1988), also matches with findings of this study; both of which assured that erosion rates and watershed behaviour in similar settings within the Ethiopian highlands could inform land management decisions.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

5.1. Conclusion

This study is typically based morphometric and soil erosion risk analysis of Ribb Sub-catchment using GIS techniques with the aim to prioritize watersheds for land management decisions. Watershed delineation, hydrology and morphology analysis used DEM as input data. For soil loss estimation InVEST SDR is model was applied.

The analysis of ten key parameters in this study; Stream Frequency, Bifurcation Ratio, Form Factor, Elongation Ratio, Circular Ratio, Drainage Density, Drainage Texture Ratio, Compactness Constant, Constant of Channel Maintenance, and Soil Erosion Risk; provides a comprehensive understanding of the hydrological behavior and erosion potential within the sub-watersheds. Normalization and standardization of all the values were applied for each of the ten parameters using assigned weights of each parameter to ensure that all parameters are on a comparable scale, regardless of their original units or magnitude.

Prioritization scores, ranging from 0.241 to 0.387, indicate varying levels of urgency for management interventions. Watersheds W3 (0.387) and W4 (0.379) are identified as higher priority, necessitating immediate conservation efforts due to their heightened susceptibility to erosion. W1 (0.338) and W2 (0.318) fall into a medium priority category, requiring targeted management practices to address moderate erosion risks. Conversely, W5 (0.241) and W6 (0.322) are categorized as lower priority, exhibiting relative stability and lower erosion susceptibility.

Therefore, the findings showed that management practices should be tailored based on prioritization scores, higher values are priority watersheds for conservation planning. Lower values showed lower priority areas; can be monitored with less immediate intervention, focusing on maintaining their current stability; the tool offers a strategic framework for decision-making, enabling efficient resource allocation for effective watershed development planning by focusing on the most vulnerable areas.

5.2. *Recommendations*

Based on the comprehensive analysis made in the Ribb sub-basin, several key recommendations can be used to guide effective land management decisions. First, prioritize watersheds for intervention planning based on the study's prioritization scores. Watersheds having higher scores (W3 and W4) should be the focus of immediate conservation efforts due to their high susceptibility to erosion. On the other hand, watersheds W1 and W2 require targeted management practices to address moderate erosion risks. Watersheds W5 and W6 can be monitored for maintaining stability. Major finds supporting these recommendations are as follows:

- Watershed W3 has the highest prioritization score (0.387), indicating urgent conservation needs.
- Watershed W5 has the lowest score (0.241), demonstrating relative stability.
- Soil erosion rates range significantly, from 12.73 t/ha/yr in W5 to 71.00 t/ha/yr in W1.

Second, utilize integrated GIS-based methodologies to evaluate watershed characteristics comprehensively. Utilization of integrated models like RUSLE and the InVEST Sediment Delivery Ratio model, for morphometric analysis and soil erosion risk assessment provides a holistic understanding of watershed dynamics, enabling evidence-based decision-making. This recommendation is based on the findings that:

- Key morphometric parameters, including stream frequency, bifurcation ratio, form factor, and drainage density, significantly influence watershed behavior.
- GIS-based methodologies allow for the integration of diverse datasets, enhancing the accuracy of erosion risk assessments.

Third, implement sustainable land management practices to enhance the long-term ecological and socio-economic resilience of the Ribb sub-basin. Encourage practices that improve soil health, reduce erosion, and enhance water infiltration. Sustainable land management practices are crucial for mitigating soil erosion, improving water quality, and enhancing biodiversity.

Fourth, inform policy and decision-making by providing policymakers and land managers with the study's findings. Equip them with the tools and knowledge necessary to make informed decisions that consider watershed-specific conditions. This recommendation is based on the understanding that:

- Current approaches to watershed management often lack systematic prioritization, relying on subjective judgments.
- The study provides valuable evidence-based insights for managing the Ribb sub-basin as a showcase.

Fifth, address data limitations and enhance monitoring to improve the accuracy of future watershed assessments. Regularly monitor the effectiveness of implemented interventions and adjust management plans as needed. This recommendation acknowledges that:

- The study's accuracy depends on the quality of input data, such as DEM resolution and soil erosion maps.
- Continuous monitoring is essential for adapting management practices to changing conditions.

Sixth, promote community participation during specific intervention planning and implementation of those prioritized watersheds to ensure their long-term sustainability and effectiveness. Consider their indigenous knowledge and involve them in decision-making processes.

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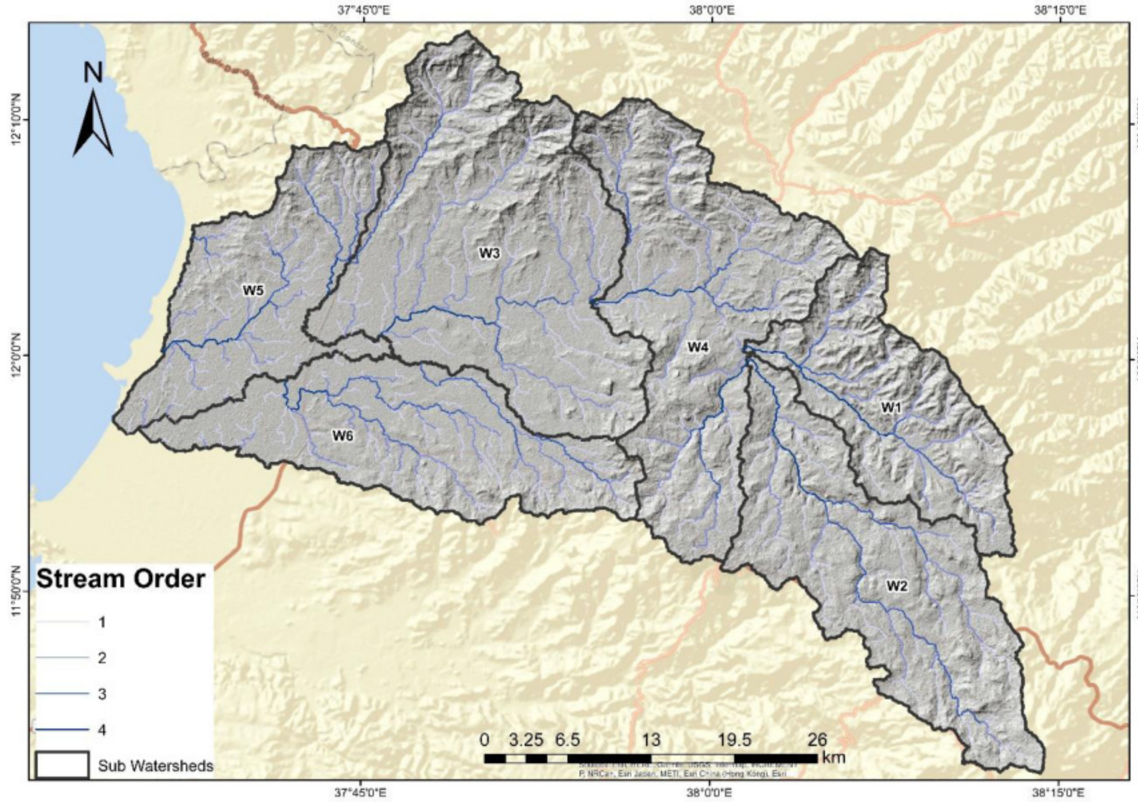
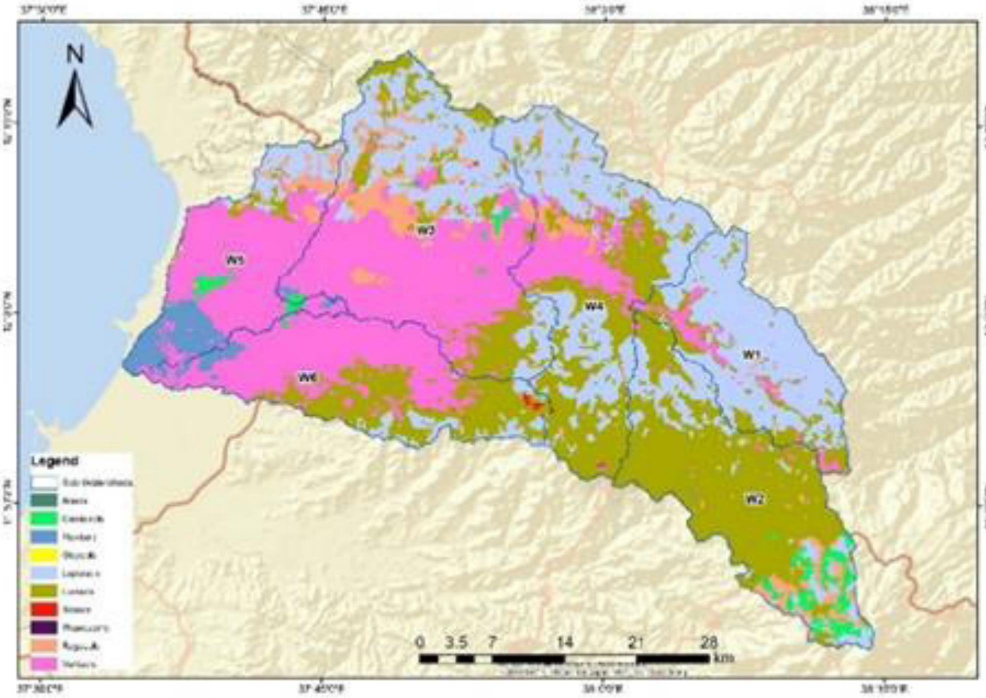
ANNEX

Stream Order	Number of Streams	Sub Watersheds
1	59	W1
2	30	
3	15	
4	13	
1	47	W2
2	25	
3	14	
4	7	
1	78	W3
2	44	
3	18	
4	8	
1	102	W4
2	60	
3	20	
4	17	
1	113	W5
2	58	
3	29	
4	11	
1	99	W6
2	47	
3	31	
4	8	



Map of stream order of the watersheds



LULC map of the watersheds