Water and Soil Management and Modeling

Online ISSN: 2783 - 2546

University of Mohaghegh Ardabili

Estimating soil loss rates and land capability classification based on erosion severity in the Womba Watershed, Southern Ethiopia

Desalegne Chanie, Halie [1], Mulugeta Debele Bedhane[2], Wakshum Shiferaw[3], Gebremedhin Chameno Chalite[4], Daniel Azazie Birra[5], Zeleke Dosa Morgamo[6], Zerihun Ayalew Gebre[7], Solomon Tesfamariam[8]

[1] Assistant Professor, Department of Geography and Environmental Studies, College of Social Science and Humanities, Arba Minch University, Arba Minch, Ethiopia
[2] Associate Professor, Department of Geography and Environmental Studies, College of Social Science and Humanities, Arba Minch University, Arba Minch, Ethiopia
[3] Associate Professor, Department of Natural Resource Management of Agricultural Science, College of Agriculture, Arba Minch University, Arba Minch, Ethiopia
[4] MSc, Department of Natural Resource Management of Agricultural Science, College of Agriculture, Arba Minch University, Arba Minch, Ethiopia
[5] MSc, Department of Geography and Environmental Studies, College of Social Science and Humanities, Arba Minch University, Arba Minch, Ethiopia
[6] MA, Department of Marketing Management, College of Commerce, Arba Minch University, Arba Minch, Ethiopia
[7] PhD Candidate, Department of Psychology, College of Education and Behavioral Science, Arba Minch University, Arba Minch, Ethiopia
[8] Assistant Professor, Department of Geography and Environmental Studies, College of Social Science and Humanities, Arba Minch University, Arba Minch, Ethiopia

Abstract

Land degradation, mainly through soil erosion and nutrient depletion, threatens agricultural sustainability in Sub-Saharan Africa, particularly in Ethiopia. This study focuses on estimating annual soil loss rates and evaluating land capability in the Womba watershed to inform conservation strategies. Key factors considered include rainfall erosivity, soil erodibility, slope, land use, and management practices. The study uses ArcGIS 10.8 tools and RUSLE equation methods soil loss within the study area. Soil loss in the watershed, utilizing Digital Elevation Models (DEM) for slope calculations. Annual soil loss ranged from 2.18 t ha^{-1} yr^{-1} (slightly severe) to 163.58 t ha^{-1} yr^{-1} (highly severe), with an average rate of 10.84 t ha^{-1} yr^{-1}, totaling 28,552.96 tons annually. While soil loss in less severe classes was within tolerable limits, highly severe categories exceeded acceptable thresholds. The watershed is classified into four erosion classes, with 1,697.33 ha (64.3%) in Class I and 675.13 ha (25.6%) in Class II, suitable for agriculture and annual crops. About 208.02 ha (7.8%) of the watershed is classified as Class IV, suitable for perennial crops, urban development, and grazing, while 55.52 ha (2.3%) is Class VI, suitable for forest development and wildlife conservation. Despite their small area, both classes face significant soil erosion, highlighting the need for strategies from the government and local stakeholders to prevent further soil loss.

Keywords: Rainfall erosivity, Erodibility, Management, Land use, Land suitability, RUSLE

Article Type: Research Article

*Corresponding Author, E-mail: dessalegnechanie@gmail.com

Citation: Haile, D. C., Bedhane, M. D, Shiferaw, W., Chalite, G. C., Birra, D. A., Morgamo, Z. D., Gebre, Z. A. & Solomon, T. (2025). Estimating soil loss rates and land capability classification based on erosion severity in the Womba Watershed, Southern Ethiopia. Water and Soil Management and Modeling, 5(4), 41-64.
doi: 10.22098/mmws.2025.18258.1667

Received: 05 September 2025, Received in revised form: 07 October 2025, Accepted: 21 October 2025, Published online: 07 November 2025

Water and Soil Management and Modeling, Year 2025, Vol. 5, No. 4, pp. 41-64.
Publisher: University of Mohaghegh Ardabili

1. Introduction

Soil erosion is a natural occurrence where the topsoil is displaced due to various influences, including land use and land cover (LULC) changes, varying rainfall intensity, topographic features, soil characteristics, and human activities like logging and farming on steep terrains, which leads to a decline in soil fertility and the degradation of resources (Pimentel et al., 1995; Maimouni et al., 2021; Firoozi, 2024; Reta et al., 2025). Severe erosion can lower crop yields, heighten flood risks and the transfer of pollutants, and pose threats to transportation and utility structures like bridges and power infrastructures (Tundu et al., 2018; Borrelli et al., 2020; Panagos et al., 2024). Furthermore, heavy rainfall often leads to mudslides, particularly after forest fires that have cleared large areas of vegetation (Tessema et al., 2020; Amasi et al., 2021; Usman et al., 2023). Over the last forty years, one-third of the world's arable land has been degraded due to soil erosion, and this trend continues to rise (Dotterweich et al., 2013). This issue is particularly severe in developing countries across Sub-Saharan Africa, attributed to inadequate soil conservation practices, aggressive agricultural methods, farming on inclined terrains, deforestation, increased rainfall, and high soil erosion potential resulting from relatively shallow soil layers and poor structural integrity combined with significant precipitation (Usman & Onokebhagbe, 2017; Tessema et al., 2020; Usman et al., 2023).

Soil erosion has risen across the nation, despite being recognized as a global concern since the 20th century (Dotterweich et al., 2013). Studies indicated that in the deforested areas of North Korea, there was a significant risk of soil erosion, estimated at 192.1 million t ha^{-1} yr^{-1} (Lee et al., 2017). Earlier findings in developing nations highlight significant vulnerability to soil erosion. For example, in Pakistan, around 16 million hectares, approximately 20% of its total land area, are impacted by soil degradation (Ashraf et al., 2017). In India, estimates suggest that nearly 30 to 32.8 million hectares experience water-induced erosion (Lal, 2017). Another case finding showed that the financial impact of soil loss occurs in the European Union found that it leads to on-site costs that affect farmers, including reduced agricultural productivity, lower yields, damage to crops, and a decrease in available farmland (Panagos et al., 2018). . Additionally, Maqsoom et al. (2020) found that the terrain characteristics of the Chitral district in Pakistan exhibited a greater susceptibility to erosion, with annual mean soil loss peaking at 78 t ha^{-1} yr^{-1}. Similarly, a recent investigation in Iran revealed an average annual soil loss of 24 t ha^{-1} yr^{-1} (Karimzadeh et al., 2023). Studies indicated that about 80% of farms around the world are affected by soil erosion, diminishing their ability to produce crops effectively (Tesema et al., 2024). The economic losses resulting from decreased land productivity due to water erosion are estimated to be approximately €1.25 billion annually (Panagos et al., 2024). From this perspective, many studies suggest that the interaction between agricultural expansion, deforestation, urbanization, soil characteristics, topographical features, and intense rainfall following extended dry spells exacerbates soil erosion by undermining soil stability and increasing erosion rates (Duan et al., 2017; Girma & Gebre, 2020; Wassie, 2020; Maimouni et al., 2021; Reith et al., 2021; Mathewos et al., 2023).

In the agricultural watersheds of the African highlands, soil erosion represents a significant challenge to food security and the sustainability of farming practices (Reith et al., 2021; Moisa et al., 2023; Reta et al., 2025). Africa is among the regions with the most severe erosion rates worldwide, largely influenced by factors such as deforestation, the expansion of agricultural activities, and fluctuations in climate (Nurhussen & Desale, 2016; Thapa, 2020; Mengie et al., 2022; He et al., 2024). Research has shown that the arable and pasture lands in Africa's tropical highland areas are experiencing notably high rates of soil depletion (Usman et al., 2023). While the highlands of Ethiopia possess some of the continent's most productive land, they are also facing significant challenges with soil erosion on their fertile surfaces (Kebede & Fufa, 2023). The nation faces significant soil erosion, a consequence of its rugged and steep landscape combined with increasingly frequent and intense rainstorms (Getachew et al., 2021; Tesema et al., 2024). Furthermore, various human activities exacerbate this issue, including improper land management, overgrazing, ineffective farming techniques, rapid population growth, an inefficient agricultural framework, and deforestation, all of which contribute to the widespread degradation of soil quality (Adugna et al., 2015; Aga et al., 2018; Ahmad et al., 2020; Bekele, 2021). For instance, in Ethiopia's Didessa sub-basin, the average annual soil loss rose from 4.5 t ha^{-1} yr^{-1} during 1987, the value increased to 13.5 t ha^{-1} yr^{-1} by 2002, ultimately exceeding 45.35 t ha^{-1} yr^{-1} in 2021, primarily due to changes in land use and land cover (Usman et al., 2023). In the Aleltu River watershed located in Southwestern Ethiopia, the overall average soil loss rate across the watershed stands at 23.8 t ha^{-1} yr^{-1} (Tesema et al., 2024). Additionally, average soil loss rates in Finca'aa, Oromiya were estimated at 33.3 t $ha^{-1}yr^{-1}$ (Kebede & Fufa, 2023), and the Debre Berhan urban area was predicted at 38.5 t ha^{-1} yr^{-1} (Getahun et al., 2024). In the country, soil erosion primarily results from the landscape's topography, land use and land cover changes, intensive farming methods, and substantial rainfall, representing a significant form of land degradation that has led to a long-term reduction of topsoil (Degefu et al., 2017; Desalegn et al., 2020; Negese et al., 2021; Mathewos et al., 2023). The effects of soil erosion manifest in both the loss of essential nutrients on-site and the accumulation of sediment in water resources, particularly in the arid and semi-arid regions of the country (Bekele, 2021; Temesgen, 2021). Research conducted in various regions of Ethiopia has demonstrated that erosion is a primary factor contributing to significant challenges impacting soil fertility, water retention, and environmental biodiversity (Mengie et al., 2022). However, the degree and severity of these effects differ across different areas (Haregeweyn et al., 2017; Woldemariam et al., 2018; Negese et al., 2021). Recent empirical research has revealed that the highlands of Southern Ethiopia are grappling with significant soil erosion, driven by factors such as changes in land use, high rainfall intensity, challenging topography, and a long-standing reliance on traditional farming practices, all of which exacerbate the severity of soil erosion (Girma & Gebre, 2020; Masha et al., 2021; Buraka et al., 2022; Yirgu, 2022; Mathewos et al., 2023). For example, successive authors such as Yirgu (2022) estimated that mean annual soil loss in the upper Domba watershed of Gamo highlands reached up to 95 t ha^{-1} y^{-1}. Utilizing a combination of the RUSLE and ArcGIS methods, Girma and Gebre (2020) indicated that the mean annual soil loss in the Omo-Gibe river basin was approximately 69 t ha^{-1} yr^{-1}. In the Coka watershed, Buraka et al. (2022) reported soil loss rates ranging from 2.33 t ha^{-1} yr^{-1} in bare land to as high as 237.16 t ha^{-1} yr^{-1} in forested areas. Furthermore, research conducted by Yagaso et al. (2024) indicated that land use changes led to an increase in average annual soil loss rates at the Ghibe III hydroelectric dam, rising from 30.95 t ha^{-1} yr^{-1} in 1990 to 43.85 t ha^{-1} yr^{-1} in 2020. In various land uses in the Gofa highlands, Desalegn et al. (2020) utilized the RUSLE model, revealing that the average yearly soil loss was 5.43 t ha^{-1} yr^{-1} in forested areas and 36.01 t ha^{-1} yr^{-1} in agricultural fields.

While several investigations have addressed soil erosion in the southern Ethiopian highlands, many of these studies primarily concentrated on the severity of erosion, frequently employing lower resolution data and lacking comprehensive recommendations for intervention strategies and policy implications. This research aims to evaluate annual soil loss through the RUSLE model and ArcGIS 10.8, while also proposing potential intervention mechanisms and outlining policy implications within the studied watershed. Informants consulted during preliminary observations indicated that land degradation, especially soil erosion in the upper Womba watershed, has led many households to relocate and has caused flooding that impacts water quality and availability in downstream communities. Additionally, issues such as unproductive livestock, inadequate infrastructure, low crop yields (Dessalegn et al., 2020), outmigration, and food insecurity stemming from soil erosion are significant socio-economic challenges in the watershed. Our initial assessment with local communities reveals that this area is severely affected by both erosion and flooding in the Gofa highlands. Therefore, the purpose of this study is 1) to estimate the average annual soil loss rates by integrating the RUSLE model with ArcGIS tools in the Womba watershed, 2) to assess the land capability classes in relation to the erosion severities of the Womba watershed 3) to recommend potential policy implications.

This study is contributing to the achievements of some Sustainable Development Goals (SDGs), particularly those related to responsible consumption and production, climate action, and life on land. By estimating annual soil loss rates and integrating advanced tools like RUSLE and ArcGIS, we can gain critical insights into soil degradation, which directly impacts rural livelihoods by affecting agricultural productivity and food security. Identifying and proposing sustainable land management practices not only fosters environmental conservation in the area but also enhances resilience against climate change, thus improving the overall well-being of the local communities. Furthermore, recommending informed policy implications ensures that governance frameworks support sustainable development and resource management, ultimately benefiting both the environment and the rural population.

2. Materials and Methods

2.1. Descriptions of the study watershed

The study was conducted at the Womba watershed in the administrative unit of Demba Gofa district in southern Ethiopia (Figure 1). The watershed, which is fed by the Woba River, is a semi-perennial river that originates in the hills of the Geze Gofa district and drains into the Zenti River, a tributary of the upper Omo River (Desalegn et al., 2020). It is situated between the Geze Gofa and Demba Gofa districts, approximately 155 km northwest of Arba Minch city. Astronomically, it is located between latitudes 6°17'20" N and 6°30'00" N, and longitudes 36°49'20" E and 36°53'20" E, covering an area of 2,633.74 hectares (1,750.5 hectares from Dakisho-Subo and 883.24 hectares from Karcho-Mela *kebeles* (Figure 1). The project site lies within two *kebeles* (administrative units), with the majority located in Dakisho-subo *Kebele*[1] within the watershed (Figure 1). The watershed is marked by various landforms, including mountains, undulating terrains, plains, and rugged surfaces. The geological setup of the Womba watershed originates from the Trapp series lava flows associated with Tertiary volcanic eruptions (Desalegn et al., 2020). This area is among the most affected parts of the Ethiopian mountain system regarding soil erosion, forest degradation, farmland exhaustion, and associated disruptions to livelihoods (Saguye, 2017). Dakisho Mountain, the highest peak in the area, separates the *Jawula* highlands from the *Karcho-Mella* hills. The elevation of the watershed ranges from 2,649.5 meters to 1,407.5 meters above mean sea level (Figure 1).

The climatic conditions of the watershed fall under the categories of dega (temperate climate), weyna-dega (moderate climate), and kola (hot) agro-ecological zones (Desalegn et al., 2020). Rainfall and temperature data from the Ethiopian Meteorology Institute at the Sawla station indicate that the mean annual temperature ranges from 25 to 35.1 degrees Celsius (°C). The average daily maximum and minimum temperatures are 30.3 °C and 14.8 °C, respectively (Tadele et al., 2022). The distribution of rainfall throughout the year is categorized into two rainy seasons known as *Belg* (March–May) and the main rainy season or summer (June–September) (Saguye, 2017). In the project site, the dominant vegetation includes Agam (*Carissa edulis*), Girar (*Acacia bussei*), Bahirzaf (*Eucalyptus camaldulensis*), Sesbania (*Sesbania sesban*), Wanza (*Cordia africana*), and Kitkita (*Dodonaea viscosa*) (Desalegn et al., 2020). The diverse geology, relief, climate, and LULC of the study area have fostered the development of dystric cambisols, orthic acrisols, and dystric nitosols (Desalegn et al., 2020).

[1] the smallest administrative unit below the district level in Ethiopia

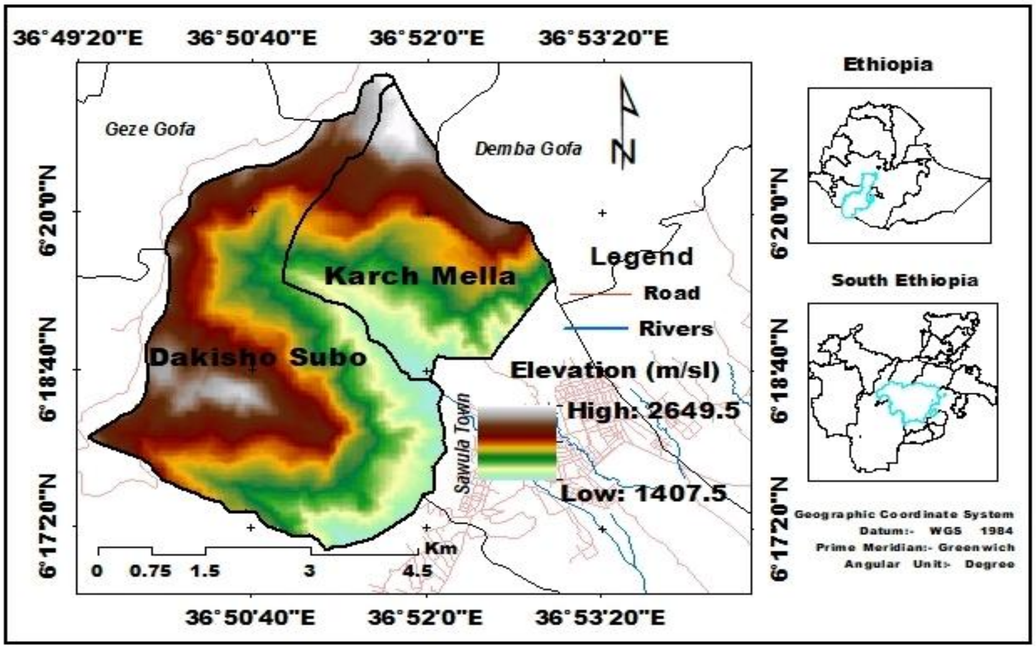


Figure 1. The location map of the Womba watershed, Source: Developed by authors

The projected total population of Demba Gofa district for July 2107 was 91,412 (males = 45,486, females = 45,926) (Haile et al., 2024). According to the Demba Gofa District Finance Office (DGDFO) annual report for June 2024, nearly 2,132 household heads (males = 2,301 and females = 169) live in the Womba watershed. Agricultural activities are characterized by a small-scale subsistence mixed farming system, with livestock production as an integral component. Crop production includes maize (*Zea mays*), sorghum (*Sorghum bicolor*), barley (*Hordeum vulgare*), wheat (*Triticum aestivum*), teff (*Eragrostis tef*), sweet potatoes (*Ipomoea batatas*), taro (*Colocasia esculenta*), and yams (*Dioscorea spp*.), cultivated across the watershed. Perennial crops such as enset (*Ensete ventricosum*), cassava (*Manihot esculenta*), and moringa (*Moringa oleifera*), as well as stimulants like coffee (*Coffea arabica*) and chat (*Catha edulis*), are also grown in significant quantities. In addition to crop production, livestock rearing is a key occupation, with communities raising cattle, sheep, goats, donkeys, and poultry. Off-farm activities, petty trade, and handicrafts serve as additional income-generating endeavors.

2.2. Data source and collection

Annual soil loss rates in the Womba watershed were estimated using a combination of both primary and secondary data sources. Rainfall data covering a period of twenty-four years (from 2000 to 2024) was obtained from the Ethiopian National Meteorology Institute Service (ENMIS). Soil data for the study watershed were collected from the Ministry of Water and Energy (MoWE) of Ethiopia. The digital soil map was prepared at a scale of 1:50,000 based on the FAO soil classification system. Land management and conservation support data were obtained from key informant interviews, field observations, and literature reviews. The Digital Elevation Model (DEM) was obtained from the USGS website, featuring a resolution of 30 meters by 30 meters. The parameters of the Revised Universal Soil Loss Equation (RUSLE) model are derived from factors, including the rainfall erosivity factor (R value), soil erodibility factor (K value), slope length and steepness factor (LS value), crop cover factor (C value), and management or conservation practice factor (P value). To acquire comprehensive data, field observations (transect walks) were conducted across the watershed to assess its topography, natural resource base, land use types, slope gradient and length, and existing land management practices.

2.3. Estimation of annual soil loss: RUSLE model

The RUSLE model has several key advantages for estimating annual soil loss, including empirical simplicity and adaptability to diverse environments (Reusing et al.,2000; Haileslassie et al., 2005; Tessema et al., 2020). Additionally, the model is well-suited for integration with geospatial technologies like GIS and remote sensing, improving spatial accuracy and the use of existing data (Maqsoom et al., 2020; Pandey et al., 2021; Barbosa et al., 2024). Additionally, its adaptability to local conditions is supported by the findings of (Millward & Mersey, 1999; Mekuriaw, 2017). The RUSLE model effectively balances reliability and lower data requirements compared to process-based models, making it ideal for resource-constrained areas (Barbosa et al., 2024). It is also actively utilized in small watershed decision-making for land management and intervention practices (Usman et al., 2023). Besides, Heyder et al.(2023) noted that it is an empirical model capable of predicting the long-term average annual soil loss in sloped fields based on precipitation trends, soil classifications, landforms, agricultural systems, and management strategies. Hence, the study utilized the RUSLE model to estimate average soil loss rates in the Womba watershed under Ethiopian conditions, as described by Hurni et al. (2008) and Adugna et al. (2015).

2.3.1. Analysis of RUSLE parameters

To estimate the likelihood of average soil loss rates in the study watershed, an empirical RUSLE model was used in conjunction with the ArcGIS tool. In this context, R, K, SL, C, and P parameters were considered as input parameters (Duan et al., 2017; Haseeb et al., 2024). The RUSLE model is mathematically computed employing the formula suggested by Kimberlin & Moldenhauer (1977) shown in Eq. (1).

$$A = R \times K \times LR \times C \times P \quad (1)$$

In this context, A represents the average annual soil loss (t ha^{-1} yr^{-1}), R denotes the rainfall erosivity (MJ mm ha^{-1} h^{-1} yr^{-1}), K indicates the soil erodibility (t ha h ha^{-1} MJ^{-1} mm^{-1}), LS signifies the slope length and steepness factor (dimensionless), and C stands for the cover factor (dimensionless), and P is the management practice factor (dimensionless).

- Rainfall erosivity factor (R)

The erosivity factor R measures the ability of rain to cause the erosion of soil particles on an exposed and unprotected surface (Addis & Klik, 2015; Kebede & Fufa, 2023). According to Heyder et al. (2023), the R factor is a climatic factor that contributes to soil loss by detaching and transporting soil particles through the forces of raindrops and runoff. In general, the R factor is determined by the kinetic energy combined with the peak 30-minute rainfall intensity calculated over the course of a year (Wischmeier and Smith, 1978). The erosivity factor R was quantified using the regression equation provided by (Hurni, 1985) in Eq. (2) for Ethiopian highlands and subsequently utilized by many authors (Reusing et al., 2000; Desalegn et al.,, 2020; Girma & Gebre, 2020; Mengie et al., 2022; Heyder et al., 2023) equation Eq. (2).

$$R = -8.12 + 0.562P \quad (2)$$

Where R stands for rainfall erosivity, whereas P denotes the average annual precipitation calculated from 24 years of rainfall data (2000 - 2024) acquired from the Ethiopian National Meteorology Institute Services. The analysis was conducted using the ArcGIS 10.8 spatial analysis tool, utilizing the inverse distance weighting (IDW) interpolation method (Girma & Gebre, 2020).

- Soil erodibility factor (K)

Soil erodibility values directly indicate the rate of soil loss in relation to the rainfall-runoff erosivity index (Tessema et al., 2020; Pandey et al., 2021). These values are affected by a range of soil properties, such as permeability, infiltration capacity, water retention ability, particle size distribution, stability of soil aggregates, dispersion and absorption tendencies, transportability, structure, and humus content (Haileslassie et al., 2005; Reusing et al., 2000; Mengie et al., 2022; Haseeb et al., 2024). The soil data for this study were obtained from a soil map of Ethiopia provided by the Ministry of Water and Energy (MoWE). The map is in polygon shape

format, and the feature map for the watershed is created by clipping the national soil map in a GIS environment. Consequently, erodibility values (K-factors) are assigned to each of the four soil types based on their properties as specified by the FAO (2006). The polygon soil map is changed into raster format using the spatial analysis tool in ArcGIS 10.8, then the soil layer's value field is sorted by the K-factor values, creating a raster layer of the K-factor with a size of 30 m × 30 m.
Different methods and equations have been developed over the years to indirectly estimate soil erodibility using soil properties such as soil texture and organic matter content (Darmawan et al., 2023). For this study, the K factor for each soil type was computed by utilizing Wischmeier and Smith (1978) and Luzio et al. (2002) equation Eq. (3).

$$K = F_{csand} * F_{clsilt} * F_{orgc} * F_{hisand} \quad (3)$$
$$K_{RUSLE} * 0.1317$$

Where: F_{csand} is a factor that lowers the k indicator in soils with high coarse sand content and higher for soils with little sand, F_{clsilt} gives low soil erodibility factors for soils with a high clay to silt ratio, F_{orgc} reduces K values in soils with high organic carbon content, while F_{hisand} lowers K values for soils with extremely high sand content.
Texture is the principal factor affecting the K factor, but soil profile, organic matter, and permeability also play a role. The K factor varies from 70/100 for the most fragile soils to 1/100 for the most stable soils. It is measured on bare reference plots that are 22.2 m long, situated on 9% slopes, tilled in the direction of the slope, and have not received organic matter for three years. Values ranging from 0 to 0.6 are considered reasonable, while higher values should be scrutinized. The K factor is sometimes included in standard soil data maps or can be calculated from soil properties.

Slope length and slope steepness (LS) factor

The Slope Length and Steepness (LS) factor is a critical component of the RUSLE model, which computes the influence of topography on soil erosion. It combines the slope length (L-factor) and the slope steepness (S-factor) (Panagos et al., 2015; Schmidt et al., 2019). Slope length refers to the horizontal distance from the starting point of overland flow to where the slope gradient decreases sufficiently for deposition to occur, or where runoff becomes focused into a defined channel. Meanwhile, the slope steepness factor (S) indicates how the slope gradient affects erosion (Belayneh et al., 2019; Schmidt et al., 2019). Both the slope length (L) and slope steepness (S) have a significant impact on sheet and rill erosion as estimated by the Revised Universal Soil Loss Equation (RUSLE), which expresses the ratio of soil loss (Degefu et al., 2017). The LS factors are usually evaluated together (Wischmeier & Smith,1978; Panagos et al., 2015; Degefu et al., 2017; Adem et al., 2020; Girma & Gebre, 2020). This is dimensionless, with higher values indicating a greater risk of erosion (Schmidt et al., 2019). The LS factor calculated from the DEM and combined to create the topographical factor grid following Desmet and Govers (1996), Benzer (2010), Usman et al. (2023), and Getahun et al. (2024) equation Eqs. (4, 5, 6 &7).

$$LS = L * S \quad (4)$$

$$L = \left(\frac{\lambda}{22.13}\right)^{m} \quad (5)$$

Where: L is slope length factor, S is slope steepness factor, λ is slope length (m), m is slope length exponent.

$$m = \frac{F}{1 + F'} \quad (6)$$

$$F = \frac{sin/0.0896}{3(\sin)0.8 + 0.56} \quad (7)$$

Where F is the ratio between rill erosion and inter rill erosion, $\beta, slope\ angle$ (°)
The S factor in the RUSLE equation, which represents the ratio of soil erosion loss from a field slope compared to that from a 9% slope under specific conditions, is illustrated in the equations below (Kimberlin & Moldenhauer, 1977) equation Eqs. (8 &9).

$$S = 10.8 \times \sin\theta + 0.03\,\sigma \leq 9\% \quad (8)$$
$$S = 16.8 \times \sin\theta - 0.50\,\sigma > 9\% \quad (9)$$

Where θ: is the slope angle and σ is the slope gradient in percentage.
The slope steepness factor (S) is simpler to calculate than the slope length factor (L) (Ouyang and Bartholic 2001). Additionally, a 10% error in slope length leads to a 5% error in the estimated soil erosion, whereas the same error in slope steepness results in a 20% error in the calculated soil loss (Morgan, 2005). This method offered

valuable insights into the interplay between slope length, steepness, and the likelihood of soil erosion across the study area.

Factors related to cover and management (C)

The vegetation cover and management factor indicate how ground cover from crops in agricultural settings or from trees and grass in non-agricultural areas, along with their associated management practices, contributes to the reduction of soil loss (Tessema et al., 2020). C factor values range from 1 to 0, where 1 indicates lack of cover and values near zero indicate strong cover (Haseeb et al., 2024). C values for different land covers are assigned by selecting representative values from the tables provided by Wischmeier and Smith (1965). In the study, the C-factor value was obtained using satellite images to compute the Normalized Difference of Vegetation Index (NDVI), which measures vegetation abundance. We selected time series data from Landsat 8 Operational Land Imager (OLI) imagery featuring a 30-meter resolution, specifically from path 170, row 51, for the year 2024. Using the Supervised Classification method in ArcGIS 10.8, a detailed analysis of the land surface was performed by evaluating NDVI data (Essaadia et al., 2022). Consequently, the watershed's land use-cover map was carefully divided into five categories: settlement, forestland, cropland, grassland, and bare land. The comprehensive C-factor map offers insights into the erosive potential of various land cover and usage categories in the study areas (Getachew & Woldemariam, 2024).

Furthermore, the C-factor was calculated applying the formula suggested by van der Knijff et al. (2000) and Pandey et al. (2021), which represents a relationship characterized by an exponential function, deemed more realistic than a linear equation, expressed in Eq. (10).

$$C = 1.2 - 1.21 * \mathrm{NDVI} \quad (10)$$

This method allowed for the estimation of each pixel's C value, enabling the exploration of seasonal trends in soil erosion risk associated with the C-factor (Mahapatra et al., 2018; Pandey et al., 2021)

Supporting the conservation practice factor (P)

The conservation practice factor (P) in the RUSLE is defined as the ratio of soil loss under a specific management practice compared to the soil loss observed with straight-row tillage, both upslope and downslope (Wischmeier and Smith 1978; Girma & Gebre, 2020; Getachew Abebe & Woldemariam, 2024).This factor considers management practices that mitigate the erosion potential of runoff by influencing drainage patterns, runoff concentration and velocity, and the hydraulic forces that runoff applies to the soil (Phinzi & Ngetar, 2019). Contouring, strip cropping, and terracing are examples of supporting practices. Consequently, the soil erosion management practice factor is determined by the soil management practices implemented in a specific area Hurni (1985), Farhan et al. (2013), Nurhussen and Desale (2016) conducted studies to establish P values for various supporting practices, as well as for land use and cover. Therefore, the land use and land cover map classified for C-factor estimation, along with the slope map developed from the DEM, were used for P-factor estimation. Both maps are converted into vector files to enable their union, allowing for the identification of attributes containing both slope and land use/land cover (LULC) values. Using union analysis in ArcGIS 10.8, the slope and LULC maps of the watershed were combined, and values were assigned accordingly (Wischmeier and Smith, 1978). The general methodological flow chart of the study is shown in Figure 2.

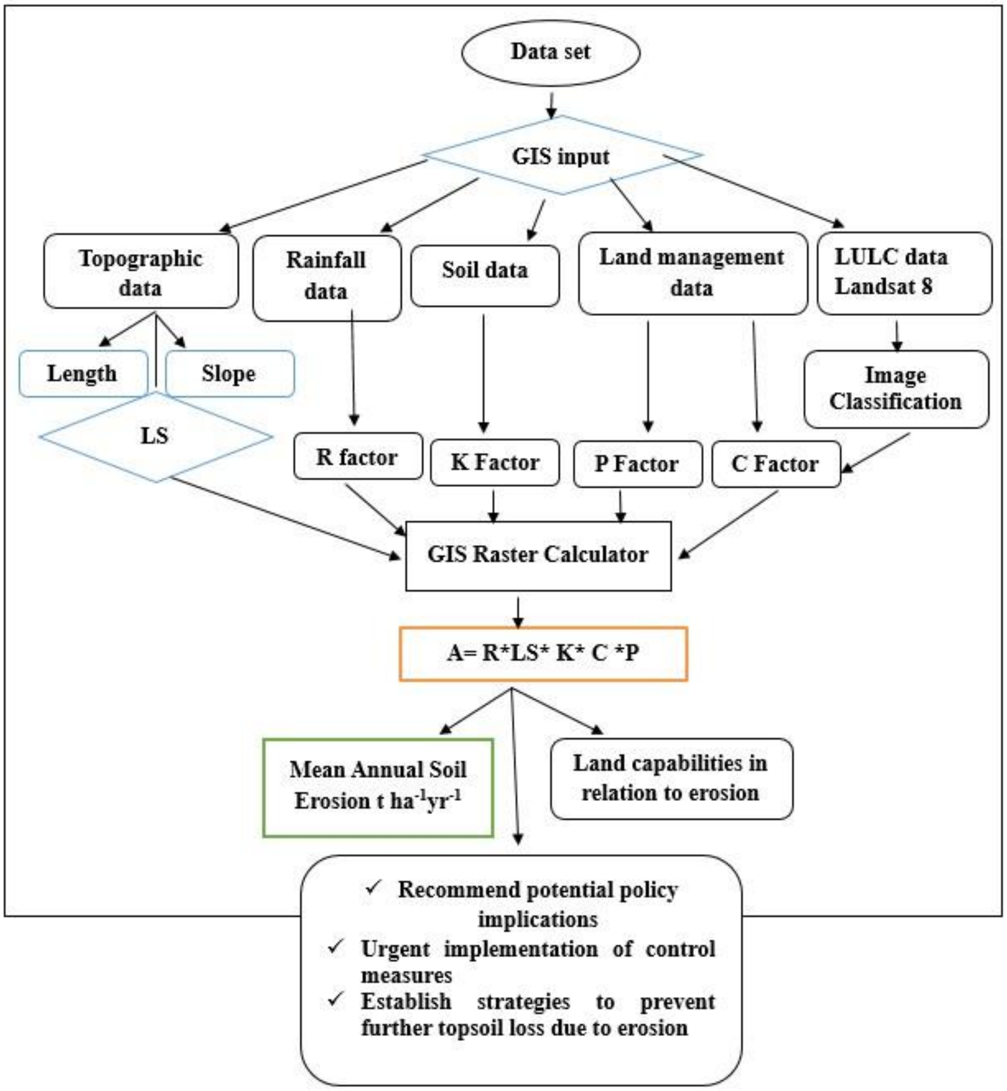


Figure 2. The flowchart of the methodology

3. Results and Discussion

3.1. Estimation of average annual soil loss

3.1.1. Rainfall erosivity factor

To obtain spatially averaged rainfall, interpolation using the DEM was applied. The DEM and rainfall exhibited a high correlation value of -0.425 (Table 1). To verify the mean rainfall, a standard linear regression model utilizing the DEM was employed, and the output is shown in Table 2.

$$\text{Mean Rainfall } = \alpha + (\beta * \text{DEM})$$

Where α signifies the mean rainfall intercept (constant), β indicates the slope coefficients for the predictor (DEM) values in the regression equation, and DEM refers to the digital elevation model.

The R-factor is expressed as: $R = -8.12 + (0.562 \times P)$ where R represents the rainfall erosivity factor and P denotes the mean annual rainfall (mm/year) (Figure 3a and b). Consequently, the mean annual rainfall of the Womba watershed was 1,821.66 mm, leading to a computed rainfall erosivity (R factor) of 998.21 MJ mm ha^{-1} h^{-1} yr^{-1}.

Table 1. Rainfall and elevation data and their relationship

Pointed	Elevation*	Rainfall**	Item		Rainfall	Elevation
1	2551	146.59	Pearson Correlation	Rainfall	1.00	-.425
2	2539	161.23		Elevation	-.425	1.00
3	2522	160.57	Sig. (1-tailed)	Rainfall		.127
4	2500	144.51		Elevation	.127	
5	2478	134.86	N	Rainfall	9	9
				Elevation	9	9

*and ** Source: - Ethiopia Meteorological Agency and https://gis.ucar.edu/gis-climatedata, ASTER DEM

Table 2. Linear regression model

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
	B	Std. Error	Beta			Lower bound	Upper bound
(Constant)	171.284	9.180		18.658	.000	149.576	192.991
Elevation	-.005	.004	-.425	-1.242	.254	-.015	.005

3.1.2. Soil erodibility factor (K)

The predominant soil types in the watershed include dystric Nitisols, primarily located in the eastern and western peripheries, whereas dystric Cambisols are prevalent in the central and eastern regions (Figure 3c).

Additionally, Orthic Acrisols are mainly located in the northern and western, and southwestern parts of the watershed (Figure 3c). The calculated soil erodibility (K) values for the Womba watershed ranged from 3.763 (dystric Nitisols) to 4.652 (dystric Cambisols) t MJ mm h−1 ha −1 yr−1 (Table 3 and Figure 3d). The K factor shows an increasing trend in order of dystric cambisols > orthic acrisols > dystric nitisols (Table 3). This indicates that an increase in the K-value corresponds to a heightened susceptibility to soil erodibility. For instance, within the studied watershed, dystric cambisols are more prone to erosion compared to orthic acrisols and dystric nitisols. Studies elsewhere have indicated that soil type is one of the fundamental factors influencing soil erosion (Nurhussen & Desale, 2016; Buraka et al., 2022; Usman et al., 2023).

Table 3. Estimated values of the soil erodibility (K) factor in the study area

Soil Type	Sand %	Silt %	Clay %	OC %	Fsand	Fc-silt	Forg	Fsand	K-factor
Dystric Nitisols	38.9	17.6	43.6	1.57	0.96	0.68	0.92	46.51	3.763
Dystric cambisols	39.9	34.1	26	4.26	0.97	0.84	0.92	46.48	4.652
Orthic Acrisols	53.6	15.8	30.6	2.25	1.02	0.72	0.92	46.11	4.106

3.1.3. Slope length and slope steepness (LS) factor

The LS factor value reflects the relative erodibility associated with specific slope lengths and steepness (Schmidt et al., 2019; Haseeb et al., 2024). Literature reviews indicate that steeper slopes correspond to higher LS values, while gentler slopes exhibit lower LS values, assuming all other parameters remain constant (Bayabil et al., 2015; Woldemariam et al., 2018; Yirgu, 2022; Tesema et al., 2024). As illustrated in Figures 4g and 4f, the lengths of the slopes (L) range from a minimum of 44.246 m to a maximum of 239.33 m, with slope steepness (S) in the Womba watershed varying between 0.029% and 15.58%. Consequently, the estimated combined LS factor values span from 1.328 for level slopes to 1400.86 for steep slopes (Figure 4h).

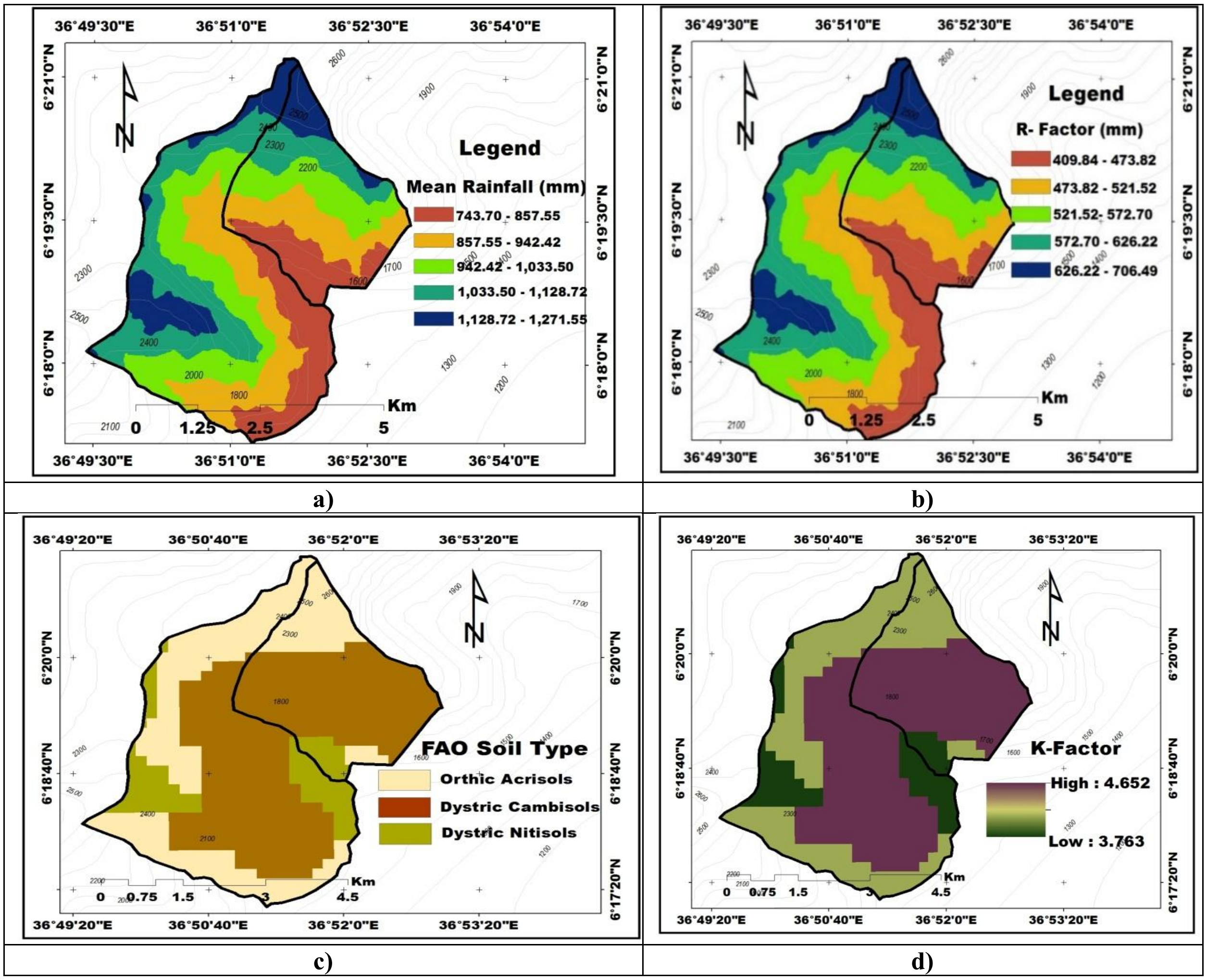


Figure 2. Maps of mean rainfall (a), R factor (b), soil type (c), and K factor (d) of Womba watershed

3.1.4. Cover and management factor (C)

Utilizing the 2024 Landsat 8 Operational Landsat Imager and Thematic Infrared Sensor (OLI-TIRs), six dominant LULC categories were discerned within the Womba watershed (Table 4 and Figure 4i).

Table 4 Land Use/Land Cover types (2024) and the corresponding C values

No	Land use/Land cover type	Area in (ha)	%	C-value	Reference (C-value)
1	Forest	306.4	11.6	0.03	Wischmeier & Smith, 1978).
2	Shrub land	224.8	8.5	0.03	
3	Cultivated Land	695	26.4	0.21	
4	Settlement	823	31.2	0.05	
5	Grass/Grazing Land	470.8	17.9	0.01	
6	Bare Land	116	4.4	0.45	
Total		2,636	100	-	-

The most prevalent category was settlement, comprising 31.2% of the area, followed by cultivated land at 26.4%, grazing land at 17.9%, and forest land at 11.6% (Table 4). The least represented category was bare land, which constituted a mere 4.4% of the whole area of the watershed. Each LULC type was allocated specific C-values, as shown in Table 4. The C-factor is dimensionless with a value ranging from

0, which signifies very strong coverage effects, to 1, which indicates the absence of cover and treats the surface as barren land (Molla & Sisheber, 2017; Negese et al., 2021). In this study, values vary from 0.01 for grazing land to 0.45 for bare land (Table 4 & Figure 4j). The results suggest that an increase in C-values correlates with a diminished ability of the area to resist erosion. For example, bare land exhibits a higher C-value while forested areas have a lower C-value, indicating that degraded areas (bare land) are more susceptible to soil erosion compared to vegetated or plantation areas. The forest and shrubland areas were assigned C values that suggest these land use categories exhibit somewhat comparable characteristics. Overall, the results indicate that improved vegetation cover and effective management practices are linked to a decrease in soil erosion. Likewise, previous research has demonstrated that higher C factor values are associated with an increased ability to resist soil loss (Liu et al., 2000; Dotterweich et al., 2013; Nurhussen & Desale, 2016; Panagos et al., 2018; Girma & Gebre, 2020).

3.1.5. Supporting the conservation practice factor (P)

The land use classes were categorized into agricultural lands, which were further divided into five slope categories, while the remaining land use types were classified as non-agricultural and assigned a P-value of 1 (Table 5 and Figure 5k).

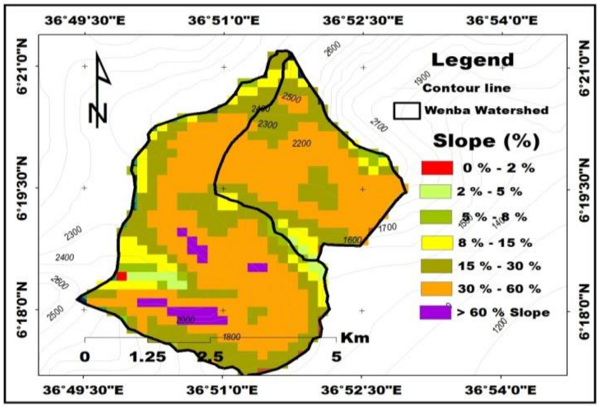
Table 5. Cover and management factor values for slope

Land use type	Slope %	P- value	Reference (P values)
Agricultural land use	0–7	0.55	Wischmeier and Smith (1978)
	7–11.3	0.55	
	11.3–17.6	0.80	
	17.6–26.8	0.95	
	> 26.8	1.00	
Nonagricultural land use	ALL	1.00	

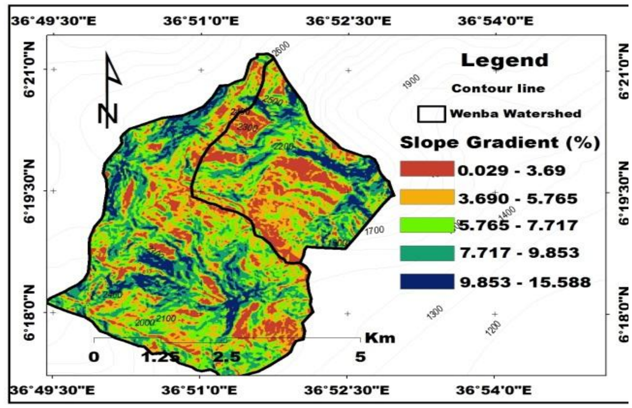
The results indicated that the correlation between slope percentage and land use/land cover (LULC) classes in the Womba watershed had P-values ranging from 0.55 to 1 (Figure 5k). As illustrated in Figure 5k, a P-value of 1 was observed in the south-central, north-central, and eastern edges of the watershed, whereas lower P-values were concentrated in the western and eastern edges. This suggests that higher P-values are associated with poor land management, which contributes to increased soil erosion rates. Previous studies have also highlighted that areas with elevated P-values are more susceptible to soil erosion, indicating the need for improved land management practices to address these challenges (Desalegn et al., 2018; Thapa, 2020; Getachew & Woldemariam, 2024).

3.1.6. Estimated average annual soil loss from the Womba watershed

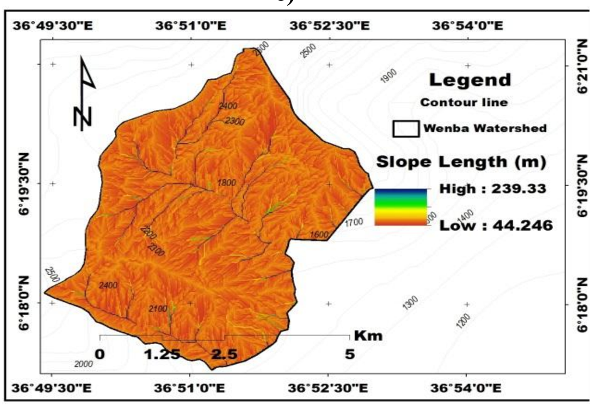
By integrating the RUSLE factors R (rainfall erosivity), K (soil erodibility), LS (slope length and steepness), C (land cover), and P (conservation support practices), the estimated annual soil loss in the study watershed ranged from 2.18 t ha^{-1} yr^{-1} (less severe) to 163.58 t ha^{-1} yr^{-1} (extremely severe) (Table 6 and figures l & m). The overall average soil loss rate was determined to be 10.84 t ha^{-1} yr^{-1}, and the total estimated soil loss from the study watershed was 28,552.96 tons per year (Table 6).



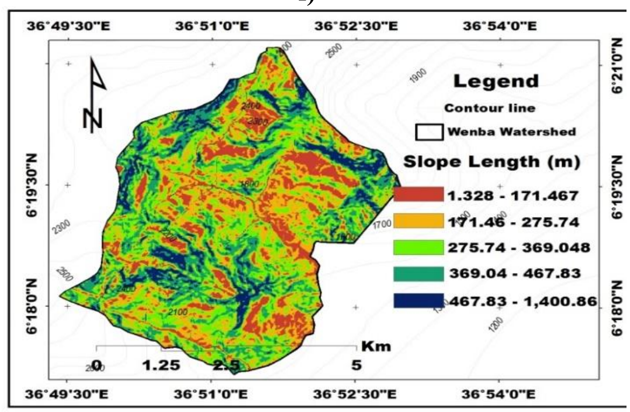
e)



f)

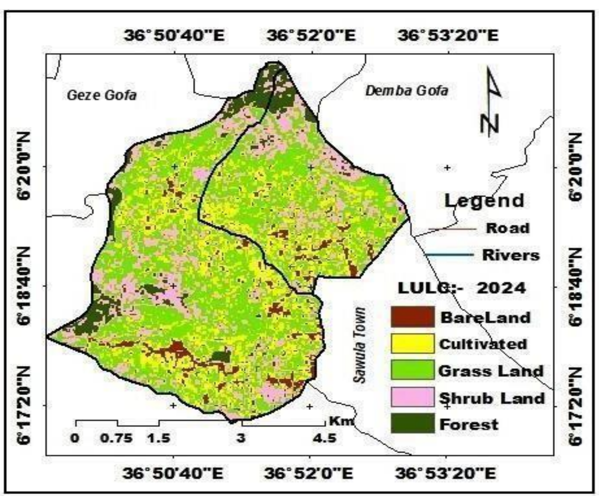


g)

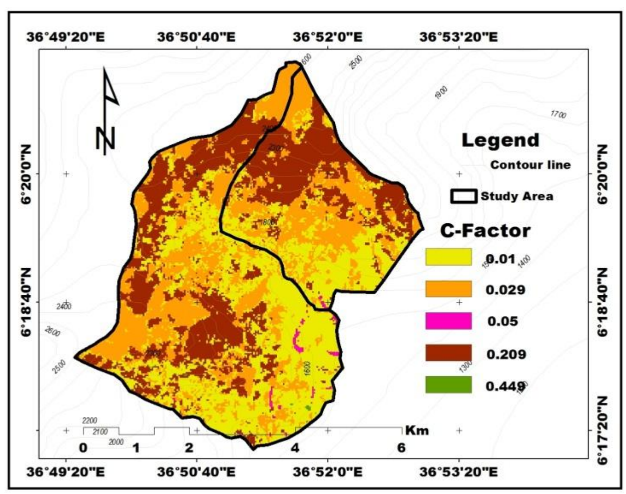


h)

Figure 3. Map of slope classification (e), Maps of slope steepness (f), slope length (g), LS factor (h), LULC, 2024 year (i), and C factor (j)



i)



j)

Figure 4. cont. Map of slope classification (e), Maps of slope steepness (f), slope length (g), LS factor (h), LULC, 2024 year (i), and C factor (j)

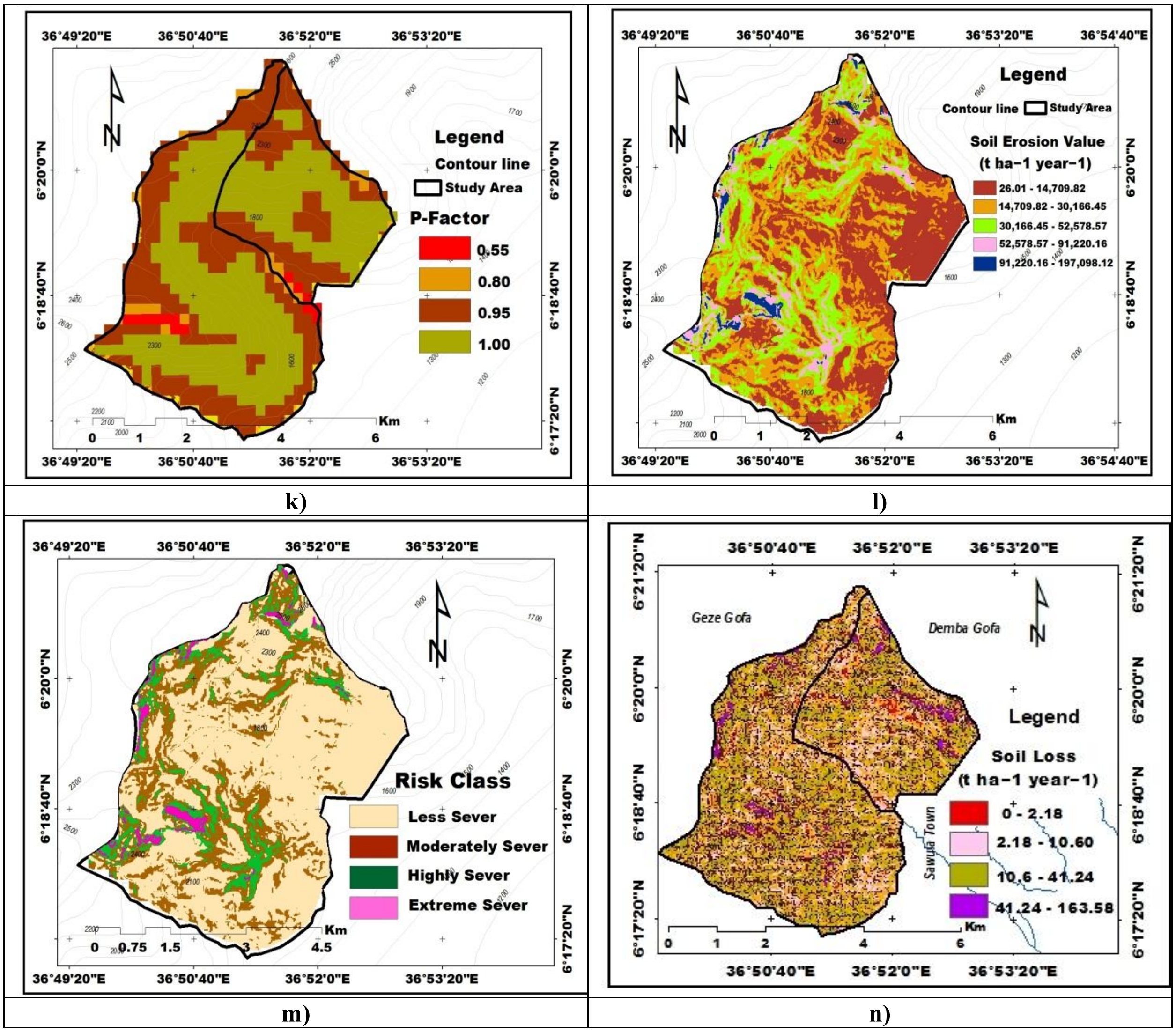


Figure 5. Maps of P factor (k), soil erosion value (l), soil erosion risk classes (m), and soil loss (n)

3.1.6. Estimated average annual soil loss from the Womba watershed

By integrating the RUSLE factors R (rainfall erosivity), K (soil erodibility), LS (slope length and steepness), C (land cover), and P (conservation support practices), the estimated annual soil loss in the study watershed ranged from 2.18 t ha^{-1} yr^{-1} (less severe) to 163.58 t ha^{-1} yr^{-1} (extremely severe) (Table 6 and figures l & m). The overall average soil loss rate was determined to be 10.84 t ha^{-1} yr^{-1}, and the total estimated soil loss from the study watershed was 28,552.96 tons per year (Table 6). Approximately 64.3% of the area experiences less severe erosion, quantified at 2.18 t ha^{-1} yr^{-1}, which results in a total soil loss of 3,709.82 tons per year. This suggests that while a considerable portion of the area is classified as less severe, the overall contribution to soil loss from this category is significant, highlighting that even lower severity levels can have a meaningful impact on total erosion. Nearly 25.6% of the watershed is classified as moderately severe, with a soil loss rate of 10.60 t ha^{-1} yr^{-1}, leading to a total contribution of 7,166.45 tons per year (Table 6). Despite the small coverage of the highly severe (7.8%) and extremely severe (2.3%) categories, these classes exhibit significant soil loss rates of 41.24 t ha^{-1} yr^{-1} and 163.58 t ha^{-1} yr^{-1}, contributing a total soil loss of 8,578.57 tons per year and 9,098.12 tons per year, respectively (Table 6). This highlights the need for targeted interventions in these areas to prevent further degradation.

The findings revealed that average yearly soil loss rates in the Womba watershed for the less severe and moderately severe categories fell within the tolerable soil limit estimated for Ethiopian conditions by Hurni (1985) (2–18 t ha^{-1} yr^{-1}), whereas the rates for the highly severe and extremely severe categories exceeded this limit. Soil erosion rates in the extreme severe category for Womba watershed reached 168.53 t ha^{-1} yr^{-1}, which is higher than the mean soil loss rates of 62.98 t ha^{-1} yr^{-1} for the Ghibe I Dam basin (Tesfaye, 2018) 69 t ha^{-1} yr^{-1} for the Omo-Ghibe basin (Girma and Gebre. 2020); 51.04 t $ha^{-1}yr^{-1}$ for the Gobele watershed, East Hararghe Zone (Woldemariam et al., 2018); and 45.35 t ha^{-1} yr^{-1} in 2021 year for Didessa sub-basin (Usman et al., 2023). The mean annual soil loss rate under the extreme severity class was also higher than the findings of

(Shiferaw, 2011), who reported 80 t ha^{-1} yr^{-1} in the South Wollo highlands of Ethiopia (Bewket & Teferi, 2009), who found 93 t ha^{-1} yr^{-1} for the Chemoga watershed in the Blue Nile Basin; Balabathina et al. (2020) recorded 156.83 t ha^{-1} yr^{-1} in the northern catchment of the Lake Tana sub-basin and Buraka et al. (2022) 62.15 t ha^{-1} yr^{-1} in the Coka watershed. According to previous studies indicate that higher annual mean soil loss rates were attributed to deforestation, sparse land cover, shallow soil depth, steep slopes, intense rainfall, intensive agriculture and climate variability (Negese, 2021; Temesgen, 2021; Mengie et al., 2022; Mathewos et al., 2023); Workie & Teku, 2025). On the contrary, the soil loss rates for the Womba watershed, classified as extremely severe, were notably lower than those reported in several studies. For instance, (Gashaw et al., 2018) indicated a much higher rate of 237 t ha^{-1} yr^{-1} in the hilly terrain of the Geleda watershed, while Girmay et al. (2020) reported 897 t ha^{-1} yr^{-1} in the hilly terrains of the Agewmariayam watershed in northern Ethiopia. Additionally, Sahle et al. (2019) found a rate of 165 t ha^{-1} yr^{-1} for the Wabe River catchment in Ethiopia, and Tadesse and Abebe (2014) reported 504.6 t ha^{-1} yr^{-1} in the Jabi Tehinan district, Ethiopia.

The study revealed significant variability in soil erosion across different areas of the watershed. Specifically, the northern and western edges, as well as the central southern parts, exhibited high to extreme erosion potential (Figure 5m). In contrast, the eastern and southern parts showed lower and moderately severe erosion potential (Figure 5m). Contributing factors to these differences may include variations in climate, altitude, topography, drainage density, soil characteristics, geology, sediment transport, sub catchment sizes, overgrazing, deforestation, expansion of cultivated land, urban development, fuel demand, and land use practices, as reported (Abebe et al., 2019; Desalegn et al., 2020; Yadeta et al., 2022; Usman et al., 2023). Moreover, Usman et al. (2023) noted that the escalating soil erosion rates are because of a lack of integrated sound management practices aimed at reducing soil loss in their respective study area.

Table 6. Annual soil loss rates, severity class, and area coverage

Soil loss rate (t $ha^{-1}yr^{-1}$)	Severity classes*	Area coverage based on severity (ha)	Area (%)	Estimated annual soil loss (tone)	Priority class for conservation
2.18	Less severe	1,697.33	64.3	3,709.82	4th
10.60	Moderately severe	675.13	25.6	7,166.45	3rd
41.24	Highly severe	208.02	7.8	8,578.57	2nd
163.58	Extreme severe	55.52	2.3	9,098.12	1st
Total		2636	100	28,552.96	

* Severity class based on Balabathina et al. (2020), Mustefa et al. (2020), and Mengie et al. (2022)

Table 7. Land capability classes in relation to soil erosion severity

LCLF	Soil loss t ha^{-1} year^{-1})	LCC	Area coverage based on severity (ha)	Estimated soil loss (t yr^{-1})	Suitable land use
Past soil erosion	2.18 less severe	I	1,697.33	3,709.82	Agriculture, annual crops
	10.60 (moderately severe)	II	675.13	7,166.45	
	41.24 (highly severe)	IV	208.02	8,578.57	Perennial crops, urbanization grazing
	163.58 (Extreme severe)	VI	55.52	9,098.12	Forest development, wildlife

LCLF, Land capability limiting factors, MSL, LCC. Land Capability Class

3.2. Land capability classification based on soil erosion severity in the Womba watershed

Land Capability Classification (LCC) is a methodical framework used to evaluate the appropriateness of land for various uses, including agriculture, forestry, and urban development. Owing to, the criteria established by the Food and Agriculture Organization's Land Capability Classification (LCC) (Neitsch et al., 1997; Oluwatosin et al., 2006; Atalay, 2016), the land in the Womba watershed was categorized into four classes: Class I, Class II, Class IV, and Class VI, in relation to severity of erosion (Table 7 and figure n). Therefore, the analysis of satellite imagery for the Womba watershed revealed that of the total area, 1,697.33 ha (64.3%) are classified as Class I, while approximately 675.13 ha (25.6%) and 208.02 ha (7.8%) are designated as Class II and Class IV, respectively (Table 7). Additionally, around 55.52 ha (2.3%) fall into Class VI (Table 7). The results show that although Classes IV and VI occupy a small portion of the watershed, these classes experience significant soil erosion compared to Classes I and II (Table 7).

According to soil erosion assessments, the areas classified as Class I (less severe) and Class II (moderately severe) are regarded as highly suitable for agriculture and annual crops (Table 7 and Figure n). These typically exhibit high productivity potential, making them valuable for farming. Class IV (highly severe) is appropriate for perennial crops, urban development, and grazing purposes, while Class VI (extremely severe) is designated for forest development and wildlife conservation (Table 7 and Figure n).

Table 8. Land capability classes in relation to soil erosion severity

LCLF	Soil loss t ha^{-1} year^{-1})	LCC	Area coverage based on severity (ha)	Estimated soil loss (t yr^{-1})	Suitable land use
Past soil erosion	2.18 less severe	I	1,697.33	3,709.82	Agriculture, annual crops
	10.60 (moderately severe)	II	675.13	7,166.45	
	41.24 (highly severe)	IV	208.02	8,578.57	Perennial crops, urbanization grazing
	163.58 (Extreme severe)	VI	55.52	9,098.12	Forest development, wildlife

LCLF, Land capability limiting factors, MSL, LCC. Land Capability Class

Previous research has indicated that Classes I and II are predominantly located on gentle to moderately sloped terrains, which experience lower levels of erosion. These areas are suitable for agricultural activities, particularly for annual crop cultivation (Selassie et al., 2014; Tesfay et al., 2017; Girma & Gebre, 2020). In contrast, Classes IV and VI are situated on steep slopes that are subject to high and extreme erosion rates, making them more appropriate for perennial crops, urban development, grazing, and forest management, as well as wildlife (Girmay et al., 2018; Yesuph & Dagnew, 2019; Gashaw et al., 2021; Balabathina et al., 2020; Getu et al., 2022). The satellite imagery analysis results indicated that areas classified as having high extreme severe and high severe erosion risks in the Womba watershed were assigned first and second priority, respectively, for soil conservation planning.

4. Conclusions

Water-induced soil erosion is recognized as a primary factor in degradation processes. Assessing its severity and spatial distribution is crucial for enhancing sustainable land management, particularly in resource-limited settings such as Ethiopia, especially within the Womba watershed. Therefore, estimating average annual soil loss rates and assessing land capability classes in relation to the severity of soil erosion in the Womba watershed are essential for informing policymakers and planners. The integration of RUSLE factors revealed annual soil loss rates ranging from 2.18 t ha^{-1} yr^{-1} in less severe areas to 163.58 t ha^{-1} yr^{-1} in extremely severe areas, with an overall average of 10.84 t ha^{-1} yr^{-1} and a total annual soil loss of approximately 28,552.96 tons. Notably, 64.3% of the area falls under less severe erosion, contributing significantly to total soil loss. However, areas classified as moderately severe also show considerable erosion rates, emphasizing the need for targeted interventions. The findings indicate that while the less severe and moderately severe categories align with tolerable soil limits, the highly severe and extremely severe categories exceed these thresholds, necessitating immediate attention. Spatial analysis indicated that high erosion potential is concentrated in the northern and western edges of the watershed, underscoring the importance of tailored management strategies to mitigate degradation and enhance land productivity.

Areas experiencing high and extreme soil erosion require urgent implementation of control measures to improve the livelihoods of local communities. Therefore, it is essential for both the government and local stakeholders to establish strategies to prevent further topsoil loss due to erosion. Adopting integrated landscape restoration and land management practices combining physical, biological, and agronomic approaches should be prioritized in these areas. This will help improve soil fertility and productivity, ultimately supporting food security for the local population in the study watershed and beyond.

5. Limitations of the study

The RUSLE model does not specifically incorporate gully erosion. To achieve a more thorough evaluation of erosion risks, it is crucial to identify and assess gullies within the watershed. Doing so will improve the precision of soil loss calculations and support more effective conservation strategies, planning, and management moving forward. Furthermore, this study used soil erosion severity as a criterion for classifying land capability. Consequently, future land capability assessments should also consider variables such as slope, drainage density, soil depth, and texture.

Acknowledgments

The authors would like to thank Arba Minch University for its financial support during the course of this research. They would also like to express their appreciation to the natural resource management experts of the Womba watershed.

Competing interests

The authors of this study declared that no potential conflict of interest was reported.

Availability data

Data available upon request

Authorship contribution statement

All authors of this project contributed to the writing of the original draft, study design, review and editing, creation of data collection instruments, verification and coding of the data, formal analysis, data curation, and conceptualization. Additionally, they provided valuable feedback and supervision on the manuscript.

Funding

There is no funding was received for this research work.

References

Abebe, M. S., Derebew, K. T., & Gemeda, D. O. (2019). Exploiting temporal-spatial patterns of informal settlements using GIS and remote sensing technique: a case study of Jimma city, Southwestern Ethiopia. Environmental

Systems Research, 8(1). doi: 10.1186/s40068-019-0133-5

Addis, H. K., & Klik, A. (2015). Predicting the spatial distribution of soil erodibility factor using USLE nomograph in an agricultural watershed, Ethiopia. International Soil and Water Conservation Research, 3(4), 282–290. doi: 10.1016/j.iswcr.2015.11.002

Adem, A. A., Dile, Y. T., Worqlul, A. W., Ayana, E. K., Tilahun, S. A., & Steenhuis, T. S. (2020). Assessing digital soil inventories for predicting streamflow in the headwaters of the blue nile. Hydrology, 7(1), 1–19. doi: 10.3390/hydrology7010008

Adugna, A., Abegaz, A., & Cerdà, A. (2015). Soil erosion assessment and control in Northeast Wollega, Ethiopia. Solid Earth Discussions, 7(4), 3511–3540. doi: 10.5194/sed-7-3511-2015

Aga, A. O., Chane, B., & Melesse, A. M. (2018). Soil erosion modelling and risk assessment in data Scarce Rift Valley Lake Regions, Ethiopia. Water (Switzerland), 10(11). doi: 10.3390/w10111684

Ahmad, I., Dar, M. A., & Andualem, T. G. (2020). Assessment of soil loss rate—Lake Tana basin, Ethiopia. Arabian Journal of Geosciences, 13(1). doi: 10.1007/s12517-019-5013-9

Amasi, A., Wynants, M., Blake, W., & Mtei, K. (2021). Drivers, impacts and mitigation of increased sedimentation in the hydropower reservoirs of East Africa. Land, 10(6). doi: 10.3390/land10060638

Ashraf, A., Abuzar, M. K., Ahmad, B., Ahmad, M. M., & Hussain, Q. (2017). Modeling risk of soil erosion in high and medium rainfall zones of pothwar region, Pakistan. Proceedings of the Pakistan Academy of Sciences: Part B, 54(2), 67–77.

Atalay, I. (2016). A New Approach to the Land Capability Classification: Case Study of Turkey. Procedia Environmental Sciences, 32, 264–274. doi: 10.1016/j.proenv.2016.03.031

Balabathina, V. N., Raju, R. P., Mulualem, W., & Tadele, G. (2020). Estimation of soil loss using remote sensing and GIS-based universal soil loss equation in northern catchment of Lake Tana Sub-basin, Upper Blue Nile Basin, Northwest Ethiopia. Environmental Systems Research, 9(1). doi: 10.1186/s40068-020-00203-3

Barbosa, W. C. de S., Guerra, A. J. T., & Valladares, G. S. (2024). Soil Erosion Modeling Using the Revised Universal Soil Loss Equation and a Geographic Information System in a Watershed in the Northeastern Brazilian Cerrado. Geosciences (Switzerland), 14(3). doi: 10.3390/geosciences14030078

Bayabil, H. K., Tebebu, T. Y., Stoof, C. R., & Steenhuis, T. S. (2015). Spatial and temporal runoff processes in the degraded Ethiopian Highlands: The Anjeni Watershed. Hydrology and Earth System Sciences Discussions, 12(4), 4387–4411. doi: 10.5194/hessd-12-4387-2015

Bekele, M. (2021). Geographic information system (GIS) based soil loss estimation using RUSLE model for soil and water conservation planning in anka_shashara watershed, southern Ethiopia. International Journal of Hydrology, 5(1), 9–27. doi: 10.15406/ijh.2021.05.00260

Belayneh, M., Yirgu, T., & Tsegaye, D. (2019). Potential soil erosion estimation and area prioritization for better conservation planning in Gumara watershed using RUSLE and GIS techniques'. Environmental Systems Research, 8(1). doi: 10.1186/s40068-019-0149-x

Benzer, N. (2010). Using the geographical information system and remote sensing techniques for soil erosion assessment. Polish Journal of Environmental Studies, 19(5), 881–886.

Bewket, W., & Teferi, E. (2009). Assessment of soil erosion hazard and prioritization for treatment at the watershed level: Case study in the Chemoga watershed, Blue Nile basin, Ethiopia. Land Degradation and Development, 20(6), 609–622. doi: 10.1002/ldr.944

Borrelli, P., Robinson, D. A., Panagos, P., Lugato, E., Yang, J. E., Alewell, C., Wuepper, D., Montanarella, L., & Ballabio, C. (2020). Land use and climate change impacts on global soil erosion by water (2015-2070). Proceedings of the National Academy of Sciences of the

United States of America, 117(36), 21994–22001. doi: 10.1073/pnas.2001403117

Buraka, T., Elias, E., Suryabhagavan, K. V., & Lelago, A. (2022). Assessment of soil erosion risks in response to land-use and land-cover changes in Coka watershed, Southern Ethiopia. Geology, Ecology, and Landscapes, 00(00), 1–14. doi: 10.1080/24749508.2022.2109825

Darmawan, Y., Munawar, Atmojo, D. A., Wahyujati, H., & Nainggolan, L. (2023). Accuracy assessment of spatial interpolations methods using ArcGIS. E3S Web of Conferences, 464. doi: 10.1051/e3sconf/202346409005

Degefu, M. A., Rowell, D. P., & Bewket, W. (2017). Teleconnections between Ethiopian rainfall variability and global SSTs: observations and methods for model evaluation. Meteorology and Atmospheric Physics, 129(2), 173–186. doi: 10.1007/s00703-016-0466-9

Desalegn Chanie, Daniel Azaze, Teshome Yirgu, & A. Z. (2020). Soil Loss and Its Impact on Crop Productivity Under Varying Land Uses in Demba-Gofa District, Southern Ethiopia. Ethiopian Journal of Business and Social Scienc, 3(1), 57–89. doi: 10.59122/23502lk

Desalegn, A., Tezera, A., & Tesfay, F. (2018). Developing GIS-Based Soil Erosion Map Using RUSLE of Andit Tid Watershed, Central Highlands of Ethiopia. Journal of Scientific Research and Reports, 19(1), 1–13. doi: 10.9734/jsrr/2018/40841

Desmet and Govers. (1996). Two dimensional modelling of the within field variation in rill and gully geometry and location related to topography. CATENA, 29(1997), 283_306. doi: PII so341-8162(96)00074-4

Dotterweich, M., Stankoviansky, M., Minár, J., Koco, Š., & Papčo, P. (2013). Human induced soil erosion and gully system development in the Late Holocene and future perspectives on landscape evolution: The Myjava Hill Land, Slovakia. Geomorphology, 201, 227–245. doi: 10.1016/j.geomorph.2013.06.023

Duan, X., Shi, X., Li, Y., Rong, L., & Fen, D. (2017). A new method to calculate soil loss tolerance for sustainable soil productivity in farmland. Agronomy for Sustainable Development, 37(1). doi: 10.1007/s13593-016-0409-3

Essaadia, A., Abdellah, A., Ahmed, A., Abdelouahed, F., & Kamal, E. (2022). The normalized difference vegetation index (NDVI) of the Zat valley, Marrakech: comparison and dynamics. Heliyon, 8(12), e12204. doi: 10.1016/j.heliyon.2022.e12204

FAO. (2006). Guidelines for Guidelines. In Enhanced Recovery After Surgery. Management Service Information Division Rome, Italy. doi: 10.1007/978-3-030-33443-7_3

Farhan, Y., Zregat, D., & Farhan, I. (2013). Spatial Estimation of Soil Erosion Risk Using RUSLE Approach, RS, and GIS Techniques: A Case Study of Kufranja Watershed, Northern Jordan. Journal of Water Resource and Protection, 05(12), 1247–1261. doi: 10.4236/jwarp.2013.512134

Firoozi, A. A., & Firoozi, A. A. (2024). Water erosion processes: Mechanisms, impact, and management strategies. Results in Engineering, 24(September), 103237. doi: 10.1016/j.rineng.2024.103237

Gashaw, T., Bantider, A., Zeleke, G., Alamirew, T., Jemberu, W., Worqlul, A. W., Dile, Y. T., Bewket, W., Meshesha, D. T., Adem, A. A., & Addisu, S. (2021). Evaluating InVEST model for estimating soil loss and sediment export in data scarce regions of the Abbay (Upper Blue Nile) Basin: Implications for land managers. Environmental Challenges, 5(November), 100381. doi: 10.1016/j.envc.2021.100381

Gashaw, T., Tulu, T., & Argaw, M. a. (2018). Erosion risk assessment for prioritization of conservation measures in Geleda watershed, Blue Nile basin, Ethiopia. Environmental Systems Research, 6(1), 1–14. doi: 10.1186/s40068-016-0078-x

Getachew Abebe, T., & Woldemariam, A. (2024). Erosion spatial distribution mapping and sediment yield estimation using RUSLE and Arc GIS of Ayigebire watershed, North Shewa zone of Amhara region, Ethiopia. Water-Energy Nexus, 7, 124–134. doi: 10.1016/j.wen.2023.12.002

Getachew, B., Manjunatha, B. R., & Bhat, G. H. (2021). Assessing current and projected soil loss under changing land use and climate using RUSLE with Remote sensing and GIS in the Lake Tana Basin, Upper Blue Nile River Basin, Ethiopia. Egyptian Journal of Remote Sensing and Space Science, 24(3), 907–918. doi: 10.1016/j.ejrs.2021.10.001

Getahun, Y. S., Tesfay, F., Kassegne, A. B., & Moges, A. S. (2024). Geospatial based soil loss rate and land degradation assessment in Debre Berhan Regio-Politan city, Upper Blue Nile Basin, Central Ethiopia. Geomatics, Natural Hazards and Risk, 15(1). doi: 10.1080/19475705.2024.2359993

Getu, L. A., Nagy, A., & Addis, H. K. (2022). Soil loss estimation and severity mapping using the RUSLE model and GIS in Megech watershed, Ethiopia. Environmental Challenges, 8(May). doi: 10.1016/j.envc.2022.100560

Girma, R., & Gebre, E. (2020). Spatial modeling of erosion hotspots using GIS-RUSLE interface in Omo-Gibe river basin, Southern Ethiopia: implication for soil and water conservation planning. Environmental Systems Research, 9(1). doi: 10.1186/s40068-020-00180-7

Girmay, G., Moges, A., & Muluneh, A. (2020). Estimation of soil loss rate using the USLE model for Agewmariayam Watershed, northern Ethiopia. Agriculture and Food Security, 9(1), 1–12. doi: 10.1186/s40066-020-00262-w

Girmay, G., Sebnie, W., & Reda, Y. (2018). Land capability classification and suitability assessment for selected crops in Gateno watershed, Ethiopia. Cogent Food and Agriculture, 4(1). doi: 10.1080/23311932.2018.1532863

Haile, D. C., Bizuneh, Y. K., & Bedhane, M. D. (2024). Determinants of land management technology adoptions by rural households in the Goyrie watershed of southern Ethiopia : Multivariate probit modeling estimation. Heliyon, 10(11), 1–18. doi: 10.1016/j.heliyon.2024.e31894

Haileslassie, A., Priess, J., Veldkamp, E., Teketay, D., & Lesschen, J. P. (2005). Assessment of soil nutrient depletion and its spatial variability on smallholders' mixed farming systems in Ethiopia using partial versus full nutrient balances. Agriculture, Ecosystems and Environment, 108(1), 1–16. doi: 10.1016/j.agee.2004.12.010

Haregeweyn, N., Tsunekawa, A., Poesen, J., Tsubo, M., Meshesha, D. T., Fenta, A. A., Nyssen, J., & Adgo, E. (2017). Comprehensive assessment of soil erosion risk for better land use planning in river basins: Case study of the Upper Blue Nile River. Science of the Total Environment, 574, 95–108. doi: 10.1016/j.scitotenv.2016.09.019

Haseeb, M., Tahir, Z., Mahmood, S. A., Batool, S., & Farooq, M. U. (2024). Spatial soil loss prediction impacted by long-term land use/land cover change: a case study of Swat District. Environmental Monitoring and Assessment, 196(1). doi: 10.1007/s10661-023-12200-x

He, L., Shan, Y. Q., Liu, C., Cao, H., Liu, X. N., & Guo, Y. (2024). Prediction of bedload transport inside vegetation canopies with natural morphology. Journal of Hydrodynamics, 36(3), 556–569. doi: 10.1007/s42241-024-0033-7

Heyder, S. M., Beza, S. A., & Demissie, S. T. (2023). Optimization of land management measures for soil erosion risk using GIS in agricultural landscape of western Hararghe highlands, Ethiopia. Scientific African, 21(August 2022), e01853. doi: 10.1016/j.sciaf.2023.e01853

Hurni, H. (1985). Erosion-productivity-conservation systems in Ethiopia Conservation Systems in Ethiopia IV International Conference on Soil Conservation, Maracay, Venezuela. October.

Hurni, H., Herweg, K., Portner, B., & Liniger, H. (2008). Soil erosion and conservation in global agriculture. Land Use and Soil Resources, 41–71. doi: 10.1007/978-1-4020-6778-5_4

Karimzadeh Motlagh, Z., Derakhshani, R., & Sayadi, M. H. (2023). Groundwater vulnerability assessment in central Iran: Integration of GIS-based DRASTIC model and a machine learning approach. Groundwater for Sustainable Development, 23(November), 101037. doi: 10.1016/j.gsd.2023.101037

Kebede, S., & Fufa, F. (2023). Estimation of average annual soil loss rates and its prioritization at sub-watershed level using rusle: A case of Finca'aa, oromiya, Western Ethiopia. Environmental Health Engineering and Management, 10(1), 41–50. doi: 10.34172/EHEM.2023.05

Kimberlin, L. W., & Moldenhauer, W. C. (1977). Predicting Soil Erosion. In ASAE Publ (Issues 4–77, pp. 31–42).

Lal, R. (2017). Soil erosion research methods (2nd ed.). CRC Press.

Lee, E., Ahn, S., & Im, S. (2017). Estimation of soil erosion rate in the Democratic People's Republic of Korea using the RUSLE model. Forest Science and Technology, 13(3), 100–108. doi: 10.1080/21580103.2017.1341435

Liu, B. Y., Nearing, M. A., Shi, P. J., & Jia, Z. W. (2000). Slope Length Effects on Soil Loss for Steep Slopes. Soil Science Society of America Journal, 64(5), 1759–1763. doi: 10.2136/sssaj2000.6451759x

Luzio, M. Di, Srinivasan, R., Arnold, J. G., & Neitsch, S. L. (2002). A RC V IEW I NTERFACE F OR SWAT2000 U SER ' S G UIDE. 193.

Mahapatra, S. K., Obi Reddy, G. P., Nagdev, R., Yadav, R. P., Singh, S. K., & Sharda, V. N. (2018). Assessment of soil erosion in the fragile Himalayan ecosystem of Uttarakhand, India using USLE and GIS for sustainable productivity. Current Science, 115(1), 108–121. doi: 10.18520/cs/v115/i1/108-121

Maimouni, S., Daghor, L., Oukassou, M., Moutaki, S. El, & Lhissou, R. (2021). Evaluate the Effect of Topographic Factors and Lithology on Forest Cover Distribution: a Case Study of the Moroccan High Atlas. Environmental Modeling and Assessment, 26(5), 787–801. doi: 10.1007/s10666-021-09785-3

Maqsoom, A., Aslam, B., Hassan, U., Kazmi, Z. A., Sodangi, M., Tufail, R. F., & Farooq, D. (2020). Geospatial assessment of soil erosion intensity and sediment yield using the Revised Universal Soil Loss Equation (RUSLE) model. ISPRS International Journal of Geo-Information, 9(6). doi: 10.3390/ijgi9060356

Masha, M., Yirgu, T., & Debele, M. (2021). Impacts of Land Cover and Greenness Change on Soil Loss and Erosion Risk in Damota Area Districts, Southern Ethiopia. Applied and Environmental Soil Science, 2021. doi: 10.1155/2021/9148138

Mathewos, M., Tsegaye, M., & Wondrade, N. (2023). Soil erosion variations along land use and land cover dynamics in Matenchose watershed, Rift Valley Basin, Southern Ethiopia. Natural Resource Modeling, 36(4). doi: 10.1111/nrm.12379

Mekuriaw, A. (2017). Assessing the effectiveness of land resource management practices on erosion and vegetative cover using GIS and remote sensing techniques in Melaka watershed, Ethiopia. Environmental Systems Research, 6(1). doi: 10.1186/s40068-017-0093-6

Mengie, M. A., Hagos, Y. G., Malede, D. A., & Andualem, T. G. (2022). Assessment of soil loss rate using GIS–RUSLE interface in Tashat Watershed, Northwestern Ethiopia. Journal of Sedimentary Environments, 7(3), 617–631. doi: 10.1007/s43217-022-00112-8

Millward, A. A., & Mersey, J. E. (1999). Adapting the RUSLE to model soil erosion potential in a mountainous tropical watershed. Catena, 38(2), 109–129. doi: 10.1016/S0341-8162(99)00067-3

Moisa, M. B., Gabissa, B. T., Wedajo, Y. N., Gurmessa, M. M., Deribew, K. T., Negasa, G. G., Negassa, M. D., & Gemeda, D. O. (2023). Analyzing the correlation of forest and wetland with land surface temperature by using geospatial technology: a case of Yayo district, Southwestern Ethiopia. Geocarto International, 38(1). doi: 10.1080/10106049.2023.2256300

Molla, T., & Sisheber, B. (2017). Estimating soil erosion risk and evaluating erosion control measures for soil conservation planning at Koga watershed in the highlands of Ethiopia. Solid Earth, 8(1), 13–25. doi: 10.5194/se-8-13-2017

Morgan, R. (2005). Soil Erosion and Conservation, 3rd edition. Blackwell Publishing, Oxford. doi: 10.1111/j.1365-2389.2005.0756f.

Mustefa, M., Fufa, F., & Takala, W. (2020). GIS estimation of annual average soil loss rate from hangar river watershed using rusle. Journal of Water and Climate Change, 11(2), 529–539. doi: 10.2166/wcc.2019.181

Negese, A. (2021). Impacts of Land Use and Land Cover Change on Soil Erosion and Hydrological Responses in Ethiopia. In Applied and Environmental Soil Science (Vol. 2021). Hindawi Limited. doi: 10.1155/2021/6669438

Negese, A., Fekadu, E., & Getnet, H. (2021). Potential Soil Loss Estimation and Erosion-Prone Area Prioritization Using RUSLE, GIS, and Remote Sensing in Chereti Watershed, Northeastern Ethiopia. Air, Soil and Water Research, 14. doi: 10.1177/1178622120985814

Neitsch, C., Golden, M., & Hossner, L. R. (1997). Land Capability Classification. Journal American Society of Mining and Reclamation, 1997(1), 141–151. doi: 10.21000/jasmr97010141

Nurhussen Ahmed Mohammed and Desale Kidane Asmamaw. (2016). Remote Sensing and GIS-Based Soil Loss Estimation Using RUSLE in Bahir Dar Zuria District, Ethiopia. Intech, 11(tourism), 13. https://www.intechopen.com/books/advanced-biometric-technologies/liveness-detection-in-biometrics

Oluwatosin G.A, O.D. Adeyolanu, A. O. O. and O. J. I. (2006). From Land Capability Classification To Soil Quality: an Assessment. Tropical and Subtropical Agroecosystems, 6(2006), 49–55.

Panagos, P., Borrelli, P., & Meusburger, K. (2015). A new European slope length and steepness factor (LS-factor) for modeling soil erosion by water. Geosciences (Switzerland), 5(2), 117–126. doi: 10.3390/geosciences5020117

Panagos, P., Matthews, F., Patault, E., De Michele, C., Quaranta, E., Bezak, N., Kaffas, K., Patro, E. R., Auel, C., Schleiss, A. J., Fendrich, A., Liakos, L., Van Eynde, E., Vieira, D., & Borrelli, P. (2024). Understanding the cost of soil erosion: An assessment of the sediment removal costs from the reservoirs of the European Union. Journal of Cleaner Production, 434(September 2023), 140183. doi: 10.1016/j.jclepro.2023.140183

Panagos, P., Standardi, G., Borrelli, P., Lugato, E., Montanarella, L., & Bosello, F. (2018). Cost of agricultural productivity loss due to soil erosion in the European Union: From direct cost evaluation approaches to the use of macroeconomic models. Land Degradation and Development, 29(3), 471–484. doi: 10.1002/ldr.2879

Pandey, S., Kumar, P., Zlatic, M., Nautiyal, R., & Panwar, V. P. (2021). Recent advances in assessment of soil erosion vulnerability in a watershed. International Soil and Water Conservation Research, 9(3), 305–318. doi: 10.1016/j.iswcr.2021.03.001

Phinzi, K., & Ngetar, N. S. (2019). The assessment of water-borne erosion at catchment level using GIS-based RUSLE and remote sensing: A review. International Soil and Water Conservation Research, 7(1), 27–46. doi: 10.1016/j.iswcr.2018.12.002

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R., & Blair, R. (1995). Environmental and economic costs of soil erosion and conservation benefits. Science, 267(5201), 1117–1123. doi: 10.1126/science.267.5201.1117

Reith, J., Ghazaryan, G., Muthoni, F., & Dubovyk, O. (2021). Assessment of land degradation in semiarid Tanzania-using multiscale remote sensing datasets to support sustainable development goal 15.3. Remote Sensing, 13(9). doi: 10.3390/rs13091754

Reta Roba, Z., Moisa, M. B., Purohit, S., Tsegay Deribew, K., & Obsi Gemeda, D. (2025). Assessment of soil erosion and sediment yield in response to land use and land cover changes using geospatial techniques in Dumuga Watershed, Ethiopia. All Earth, 37(1), 1–18. doi: 10.1080/27669645.2025.2460917

Reusing, M., Schneider, T., & Ammer, U. (2000). Modelling soil loss rates in the Ethiopian Highlands by integration of high resolution MOMS-02/D2-stereo-data in a GIS. International Journal of Remote Sensing, 21(9), 1885–1896. doi: 10.1080/014311600209797

Saguye, T. S. (2017). An Empirical Analysis of Land Degradation Risk from Local Community Knowledge Perspective: the Case of Geze Gofa District, Southern Ethiopia. Global Journal of Science Frontier Research:

H Environment & Earth Science, 17(2), 59–75. https://core.ac.uk/download/pdf/234691250.pdf

Sahle, M., Saito, O., Fürst, C., Demissew, S., & Yeshitela, K. (2019). Future land use management effects on ecosystem services under different scenarios in the Wabe River catchment of Gurage Mountain chain landscape, Ethiopia. Sustainability Science, 14(1), 175–190. doi: 10.1007/s11625-018-0585-y

Schmidt, S., Tresch, S., & Meusburger, K. (2019). Modification of the RUSLE slope length and steepness factor (LS-factor) based on rainfall experiments at steep alpine grasslands. MethodsX, 6, 219–229. doi: 10.1016/j.mex.2019.01.004

Selassie, Y. G., Ayalew, G., Elias, E., & Getahun, M. (2014). Soil Characterization and Land Suitability Evaluation to Cereal Crops in Yigossa Watershed, Northwestern Ethiopia. Journal of Agricultural Science, 6(5). doi: 10.5539/jas.v6n5p199

Shiferaw, A. (2011). Assessment of Soil Erosion in the South Wollo Highlands of Ethiopia. Ethiopian Journal of Natural Resources. Ethiopian Journal of Natural Resources, 13(2), 139–163. doi: 10.1080/10962247.2015.1083913%0

Tadele, T. T., Gebremedhin, C. C., Markos, M. U., & Fitsum, E. L. (2022). Stunting and associated factors among 6–23 month old children in drought vulnerable kebeles of Demba Gofa district, southern Ethiopia. BMC Nutrition, 8(1), 1–11. doi: 10.1186/s40795-022-00501-2

Tadesse, A., & Abebe, M. (2014). GIS Based Soil Loss Estimation Using RUSLE Model: The Case of Jabi Tehinan Woreda, ANRS, Ethiopia Keywords GIS, Remote Sensing, Multi-Criteria Evaluation (MCE), RUSLE, Weighted Overlay, Land Use/Land Cover (LULC), Soil Loss. Natural Resources, 5, 616–626. http://www.scirp.org/journal/nr%0Ahttp://dx.doi.org/10.4236/nr.2014.511054%0Ahttp://creativecommons.org/licenses/by/4.0/

Temesgen, A. E. (2021). Land Degradation and Sustainable Land Management in the Upper Blue Nile : The Case of North Gojjam Sub-Basin Land Degradation and Sustainable Land Management in the Upper Blue Nile : The Case of North Gojjam Sub-Basin. July.

Tesema, M., Feyessa, F. F., Kebede, A. B., & Geresu, B. A. (2024). Evaluation of soil erosion rate using geospatial techniques for enhancing soil conservation efforts. Environmental Systems Research, 13(1). doi: 10.1186/s40068-024-00357-4

Tesfay, T., Biedemariam, M., Hagazi, M., & Gebretinsae, T. (2017). Land capability and suitability evaluation for rain-fed crops in semi-arid lowland area of north Ethiopia. Vegetos, 30(3), 18–22. doi: 10.5958/2229-4473.2017.00160.4

Tesfaye, G. (2018). Soil Erosion Modeling Using GIS Based RUSEL Model in Gilgel Gibe-1 Catchment, South West Ethiopia. International Journal of Environmental Sciences & Natural Resources, 15(5). doi: 10.19080/ijesnr.2018.15.555923

Tessema, Y. M., Jasińska, J., Yadeta, L. T., Świtoniak, M., Puchałka, R., & Gebregeorgis, E. G. (2020). Soil loss estimation for conservation planning in the welmel watershed of the Genale Dawa Basin, Ethiopia. Agronomy, 10(6), 1–19. doi: 10.3390/agronomy10060777

Thapa, P. (2020). Spatial estimation of soil erosion using RUSLE modeling: a case study of Dolakha district, Nepal. Environmental Systems Research, 9(1). doi: 10.1186/s40068-020-00177-2

Tundu, C., Tumbare, M. J., & Onema, J. M. K. (2018). Sedimentation and its impacts/effects on river system and reservoir water quality: Case study of Mazowe catchment, Zimbabwe. Proceedings of the International Association of Hydrological Sciences, 377, 57–66. doi: 10.5194/piahs-377-57-2018

Usman, K., Deribew, K. T., Alemu, G., & Hailu, S. (2023). Spatial modeling of soil loss as a response to land use-land cover change in Didessa sub-basin, the agricultural watershed of Ethiopia. Heliyon, 9(3), e14590. doi: 10.1016/j.heliyon.2023.e14590

Usman, S., & Onokebhagbe, V. (2017). Soil problems in dryland environment of sub-Saharan Africa: a review of the impact on soil erosion and desertification soil problems in dryland environment of sub-Saharan Africa. Biological and Environmental Sciences Journal for the Tropics, 14(1). doi: 10.13140/RG.2.2.13233.12641

van der Knijff, J. M., Jones, R. J. A., & Montanarella, L. (2000). Soil erosion risk assessment in Europe. Luxembourg: Office for Official Publications of the European Communities, EUR 19022, 32. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Soil+Erosion+Risk+Assessment+in+Italy#0

Wassie, S. B. (2020). Natural resource degradation tendencies in Ethiopia: a review. Environmental Systems Research, 9(1), 1–29. doi: 10.1186/s40068-020-00194-1

Wischmeier, W. H. and, & Smith, D. D. (1978). Predicting Rainfall Erosion Losses: A Guide to Conservation Planning. Department of Agriculture, Science and Education Administration, Washington, DC, USA,. 537, 1978.

Woldemariam, G. W., Iguala, A. D., Tekalign, S., & Reddy, R. U. (2018). Spatial modeling of soil erosion risk and its implication for conservation planning: The case of the gobele watershed, east hararghe zone, ethiopia. Land, 7(1). doi: 10.3390/LAND7010025

Workie, M. D., & Teku, D. (2025). Assessing soil erosion hotspots and land degradation extent in Beshilo Watershed, Northeastern Ethiopia: integrating geospatial and field survey techniques, for sustainable land management. Frontiers in Environmental Science, 13(March), 1–17. doi: 10.3389/fenvs.2025.1548881

Yadeta, T., Deribew, K. T., Getahun, K., Debesa, G., Abreha, G., & Hailu, S. (2022). Recent resettlement programs, as drivers for Afromontane forest loss in the Hawa-Galan district of Ethiopia. Cogent Social Sciences, 8(1). doi: 10.1080/23311886.2022.2088462

Yagaso, Z. S., Bayu, T. Y., & Bedane, M. D. (2024). Estimating soil erosion in response to land use/cover change around Ghibe III hydroelectric dam, Southern Ethiopia. Discover Sustainability, 5(1). doi: 10.1007/s43621-024-00608-5

Yesuph, A. Y., & Dagnew, A. B. (2019). Soil erosion mapping and severity analysis based on RUSLE model and local perception in the Beshillo Catchment of the Blue Nile Basin, Ethiopia. Environmental Systems Research, 8(1), 1–21. doi: 10.1186/s40068-019-0145-1

Yirgu, T. (2022). Assessment of soil erosion hazard and factors affecting farmers' adoption of soil and water management measure: A case study from Upper Domba Watershed, Southern Ethiopia. Heliyon, 8(6), 1–12. doi: 10.1016/j.heliyon.2022.e09536