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Research Article

Estimating soil erosion and identifying erosion hotspots for conservation priority in Bidara watershed, upper catchment of Lake Ziway, central Rift Valley of Ethiopia

Melese Abula[1], Kebede Wolka[2*], Mikias Biazin [3]

Article Info

[1] Office of Agriculture, Mareqo Special Woreda, Central Ethiopia Regional State, Koshe, Ethiopia.
[2] Department of Soil Resource and Watershed Management, Wondo Genet College of Forestry and Natural Resources, Hawassa University, Wondo Genet, Ethiopia.
[3] Department of Geographic Information Science (GIS), Wondo Genet College of Forestry and Natural Resources, Hawassa University, Wondo Genet, Ethiopia.

***Corresponding author**: kebedewolka@gmail.com

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Abstract

Soil erosion poses a global challenge on the environment and agriculture. Understanding soil loss in a specific watershed could assist in planning effective conservation measures. The objective of this study was to estimate annual soil loss, identify erosion hot-spots, and prioritize management strategies using Revised Universal Soil Loss Equation with Geographic Information System and Remote Sensing. Meteorology record (rainfall), lab analysis of soil properties, digital elevation model analysis of topography, normalized difference vegetation index-based land cover analysis, and field observation of conservation practices were inputs of the model. In the watershed, the annual soil loss ranged from 0–1129.47 t ha-1 yr-1, surpassing the tolerable limit. Approximately 74.6% of the study area exhibited low to moderate soil loss (¡20 t ha-1 yr-1), while 25.4% faced high to extremely severe erosion (¿20 t ha-1 yr-1). Upstream regions were identified as areas with high soil erosion risk mainly due to cultivation and grazing on steep slopes. The areas with ¿20 t ha-1 yr-1 soil loss require immediate, intensive and integrated soil and water conservation measures including bunds, terraces and tree planting. Implementation of soil and water conservation measures are required to reduce erosion particularly in the highly susceptible southern parts of the watershed. Implementing contour plowing, grass strips and bunds can reduce erosion in areas experiencing low erosion(¡10 ha-1 yr-1). Mapping erosion hotspots provides valuable insights for the development and execution of effective and sustainable conservation plans. Planners and decision makers should prioritize implementation of integrated soil and conservation measures in areas with intolerable erosion.

Keywords: Erosion risk; Hotspot area; Slope; Conservation priority; Land degradation

1 Introduction

Soil erosion by water is among major processes that significantly and negatively affecting soil quality and global food production in recent decades (Hu et al., 2021; Ighodaro et al., 2013; Kim et al., 2005; Pimentel, 2006; Pimentel & Burgess, 2013; Van Oost et al., 2005). Globally, soil loss from cultivated land can vary widely, ranging from zero to exceeding100 t ha-1 yr-1, leading to an annual reduction in crop productivity of 15–30% (Borrelli et al., 2020;

Morgan, 2005). Annual soil erosion increment of 0.22 Mg ha-1 was reported (Hu et al., 2021), showing its severity. Aggravated soil erosion removes nutrient-rich topsoil, declining its nutrient concentration and ecological functioning. Continuous soil erosion can reduce cultivable area due to abandoning low productivity lands and formation of gullies (Morgan, 2005; Mukanov et al., 2019). Approximately 80–85% of agricultural land is estimated to be affected by soil erosion of certain extent, resulting in the annual loss of six million hectares of fertile land due to water erosion and associated degradation processes (Rodrigo-Comino et al., 2018). Global economic activities and land management practices contribute to soil erosion and its impacts. The climate and land use changes are predicted to escalating soil erosion (Borrelli et al., 2020; Eekhout & de Vente, 2022).

Highland areas of Ethiopia are subjected for extensive soil and land cover manipulations due to concentration of the country's agriculture and population. As a result, soil erosion rates exceeding soil formation (about 11 t ha-1 yr-1) were reported in many areas (Ali & Hagos, 2016; Fenta et al., 2024; Hurni et al., 2010; Wolka et al., 2021; Zerihun et al., 2018). A study conducted in Ethiopia reported significant soil loss rates in the highlands land, reaching as high as 170 t ha1 yr1 (Hurni et al., 2010), and 300 t ha1 yr1 (Gadisa & Midega, 2021) . This poses a significant threat to agricultural productivity and land sustainability. Conventional cultivation on sloping lands, inadequate soil and water conservation measures, and excessive vegetation removals are among important human activities that aggravated erosion. soil erosion can increase food insecurity and socio-economic challenges, primarily in rural areas where majority of the nation lives. The severity of erosion expected to vary spatially due to natural topography, land management and rainfall differences. It is crucial to estimate soil loss spatially and assess the extent of soil erosion risk at watershed scale to implement effective erosion control measures.

At watershed scale, soil erosion can be estimated using different models. The Revised Universal Soil Loss Equation (RUSLE) has been widely used soil erosion estimation method in various landscapes, including steep slopes and rugged terrain, and can be applied in GIS interface. Since it developed many years back (Wischmeier & Smith, 1978), this model has been applied in different areas across the world (Borrelli et al., 2020; Eekhout & de Vente, 2022), and in Ethiopian highlands (Ali & Hagos, 2016; Wolka et al., 2015; Zerihun et al., 2018). The model combines rainfall, soil physical properties and organic matter content, topographic characteristics, vegetation cover and conservation practices to estimate annual soil loss ha1 yr1. Models help soil erosion estimation in large areas, which are otherwise expensive and time taking to estimate erosion and to plan conservation measures. Applying models is also important to estimate erosion for areas with limited data availability, which is a common problem in the country.

In Bidara watershed, where this study focuses, soil erosion has not been estimated to assist planning for soil and water conservation at local scale. However, in some other sub-watersheds of Lake Ziway, soil erosion was estimated (Aga et al., 2018; Negasa & Goshime, 2024; Woldesenbet et al., 2020). In the Bidara watershed different initiatives including public campaign invest on watershed-based soil and water conservation activities. There are some signs of soil erosion including gullies and rills in the area. However, soil erosion risk areas are not identified and mapped for conservation planning. Thus, this study aimed: (i) to estimate the mean annual soil loss rate; and (ii) to identify and prioritize hotspot areas that are particularly susceptible to erosion. This study could provide spatial information on areas prone to erosion, enabling better planning and management of the Bidara watershed.

2 Methods and Materials

2.1 Description of the study area

The study was conducted in the upper catchment of Lake Ziway, situated in the central Rift Valley Basin (Figure 1). The study watershed is within Mareqo district, which is located approximately 165 km from Addis Ababa city and 25 km from Ziway town. The Bidara watershed is geographically positioned between 38º 24' 00" E to 38º 36' 00" E longitude and 7º 55' 12" N to 8º 4' 48" N latitude (Figure 1). The annual rainfall in the watershed varies between 700 and 1400 mm, while the mean minimum and maximum temperatures are recorded at 12.8 °C and 28 °C, respectively. The area is situated within a dry, semi-arid lowland.

Bidara watershed covers approximately 3,966.32 ha on a topography characterized by mountains, deep incised valleys, and escarpments on altitudinal range of 1796 to 2059 meters above sea level. The land use consists of cultivated (85%), and grazing (10%) lands. The agricultural land holdings are typically small and degraded. Crop production, including wheat, maize, pepper, barley, and sorghum, is the primary economic activity. Livestock production is also an integral part of the farming activity.

2.2 Data Sources and Collection

The RUSLE model requires inputs for rainfall erosivity, soil erodibility, topography, land cover and conservation practices. Satellite images, observation and laboratory analysis were used to acquire relevant data.

2.2.1 Watershed delineation

To delineate watershed, Digital Elevation Model (DEM) with resolution of 30m*30m was acquired from United States Geological Survey (USGS) Earth Explorer website (https://earthexplorer.usgs.gov/). The watershed was delineated using QGIS 3.16. To ensure accurate watershed delineation, the DEM was processed to fill sinks in areas of internal drainage. This process involved identifying depressions within the DEM and adjusting the elevation values to create a depression-less elevation grid. From the filled DEM, flow direction and flow accumulation maps were generated. In principle, flow direction indicates the path water would take from each cell, while

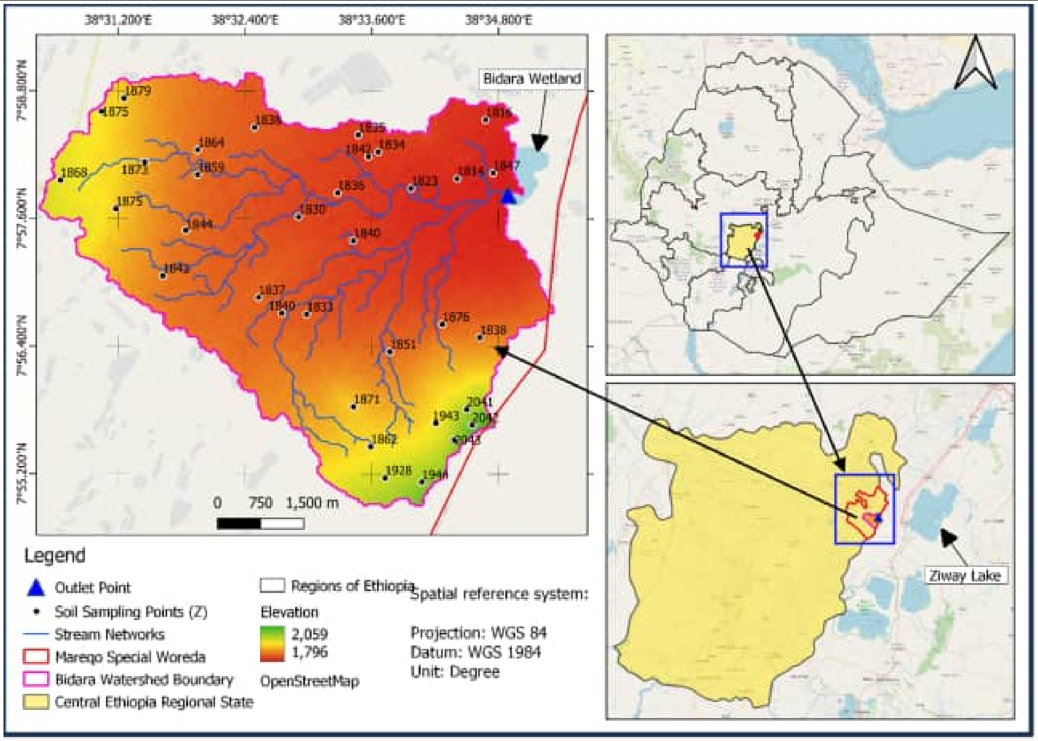

Figure 1: Location map of Bidara Watershed in Ethiopia

flow accumulation represents the accumulated flow from upstream cells. The watershed boundary was delineated based on the filled DEM and the flow accumulation map.

2.2.2 *Rainfall erosivity (R-factor) data*

The rainfall erosivity was estimated using 25 years (1996-2020) records of precipitation at meteorological stations of Ziway, Mareqo/Koshe, Butajra, and Hosana (Table 1). The R-factor, representing rainfall erosivity, was calculated using mean annual rainfall data from those four weather stations. The precipitation data from those stations, which are available meteorology stations near the watershed, were used due to the lack of rainfall stations within the study watershed, and the calculated R-factor values could provide reasonable information on rainfall erosivity in the watershed.

The normal ratio method was followed to estimate the missing rainfall records as described in equation (1). The normal ratio method is applied when the normal annual rainfall from surrounding station exceeds 10% of the considered gauge (Miller & Singh, 1994; Samuel et al., 2014). Since the normal annual rainfall of the meteorological station in the study area exceeded the specified threshold, the missing data were estimated and reconstructed using the normal ratio method. The specific method is given as follows:

$$P_X = \frac{A_x}{M}\left(\frac{P_1}{A_1} + \frac{P_2}{A_2} + \frac{P_3}{A_3} + \cdots + \frac{P_i}{A_i}\right) \quad (1)$$

Where: PX = is normal annual precipitation at station X to be estimated; Ax = is annual precipitation at station X; M = total number of stations (N) other than station X (N-1); and Pi /Ai = ratio of normal annual precipitation to annual precipitation of each station. After filling the missing data that collected from the National Meteorological Agency for stations mentioned above, in this study, Hurni's model for Ethiopia's highland, equation 2 (Hurni, 1985), was applied for estimating R-factor. The mean annual rainfall was interpolated using the IDW interpolation tool in ArcGIS 10.8 to generate continuous rainfall data for each grid cell. The R-value was then derived based on the spatially interpolated mean annual rainfall of the watershed.

$$R = 0.55MAR - 4.7 \quad (2)$$

Where R is the rainfall erosivity factor and MAR is the mean annual rainfall (mm).

2.2.3 *Soil erodibility*

The K factor in soil erosion modeling represents the susceptibility of different soil particle types to erosion caused by rainfall and runoff (Williams et al., 2000). To estimate the K factor, fractions of the topsoil layer, including sand, clay, silt, and organic carbon, were considered. Researchers often focus on the topsoil layer when calculating the K factor because it is directly affected by the energy of raindrops and surface runoff. Soils with high infiltration capacities and moderate structural stability typically have K factors ranging

Table 1: Mean annual rainfall of the meteorological stations considered in the study.

5Name of stations	Longitude	Latitude	Elevation (m)	Rainfall (mm)
5Ziway	7.93639	38.7147	1876	767.802
5Koshe	8.01083	38.5314	1646	753.958
5Butajra	8.1225	38.3758	2074	1024.65
5Hosana	7.56778	37.8561	2306	1203.85

from 0.2 to 0.3, while easily erodible soils with low infiltration capacities may have K factors of 0.3 or higher (Brady & Weil, 2008). Soil erodibility (K) values generally range between 0 and 1 (Farhan et al., 2013), where the lesser value indicates low sensitivity to erosion, while a higher value implies greater susceptibility to water erosion.

The soil organic carbon indicates its erodibility as it contributes to particle aggregation through the presence of chelating agents and water infiltration (Rao et al., 2014; Zakerinejad & Maerker, 2015). Walkley and Black method was used to determine soil organic carbon concentration of the soil samples collected for this study (Benavidez et al., 2018). The fractional proportion (sand, silt and clay) is another essential characteristic of soil that determines erodibility of soil through its impact, among others, on water infiltration rate.

For this study, soil erodibility parameter was estimated following the lab analysis of soil that collected from systematically distributed locations within the watershed. To collect representative soil samples, the watershed was divided into three slope classes viz lower (¡8%), medium (8-15%), and steep slopes (¿15%). Within each slope class of the watershed, agriculture, forest/woodland, and grassland were considered for soil sampling. From each land use/cover type within the respective slope class, three soil sampling points were selected. From entire watershed, a total of 36 soil samples were collected using auger at 0–20 cm depth. Using lab procedures, the soil samples were analyzed in the lab to determine silt, sand, and clay fractions and soil organic carbon. The K factor was determined using equations below.

$$K = f_c^{\text{sand}} \cdot f_c^{\text{l-si}} \cdot f^{\text{orgC}} \cdot f_h^{\text{isand}} \tag{3}$$

$$f_c^{\text{sand}} = \left(0.2 + 0.3 \cdot \exp\left[-0.256 \cdot m_s \cdot (1 + m_{100}^{\text{silt}})\right]\right) \tag{4}$$

$$f_c^{\text{l-si}} = \left(\frac{m^{\text{silt}}}{m^c + m^{\text{silt}}}\right)^{0.3} \tag{5}$$

$$f^{\text{orgC}} = 1.0 - \frac{0.256 \cdot \text{orgC}}{\text{orgC} + \exp\left[3.72 \cdot \text{orgC} - 2.95 \cdot \text{orgC}\right]} \tag{6}$$

$$f_h^{\text{isand}} = 1 - \frac{0.7 \cdot (1 - m_s/100)}{(1 - m_s/100) + \exp\left[5.51 + 22.9(1 - m_s/100)\right]} \tag{7}$$

Where the factor fcsand represents the effect of coarse sand content on lowering the K factor in soils The factor fcl-si accounts for the clay-to-silt ratio and assigns low soil erodibility factors to soils with a high clay-to-silt ratio. The factor forgC reduces the K values in soils with a high organic carbon content. The calculations for fcsand, fcl-si, forgC, and fhisand were performed using Equations 3–7.

2.2.4 *Topographic data*

Topographic characteristics of the land such as slope gradient and length are important in estimating erosion as well as in planning soil and water conservation measures. The slope length factor (L) represents the length of a slope at upslope of water way or barrier for surface runoff, while the slope steepness factor (S) reflects the influence of the slope gradient. Both factors affect the rate of soil erosion by water due to their effect on volume and speed of surface runoff. Initially, the LS factor supposed to provide the expected ratio of soil loss per unit area of a field slope compared to the loss from a standardized 22.13 m length of a uniform 9% slope under equivalent conditions (Wischmeier & Smith, 1978).

For this study, the LS factor was estimated to be using DEM in ArcGIS 10.8 and spatial analysis tools. Initially, the restored and repaired DEM of the watershed was used to analyze the slope (in degrees) across the study area. Next, the flow direction was generated from the filled DEM of the watershed. Flow accumulation was then derived from the flow direction. Finally, the LS factor was calculated in the raster calculator (Equation 8).

$$LS = \left(\text{Flow accumulation} \times \frac{\text{cell size}}{2.13}\right)^{0.4} \times \left(\frac{\sin(\text{slope} \times 0.01745)}{0.0896}\right)^{1.3} \tag{8}$$

2.2.5 *Land cover data*

Land cover data was derived from a Landsat image captured in May 2022, which was obtained from the USGS website (https://earth.explorer.usgs.gov), then transformed to the WGS-84 datum and Universal Transverse Mercator Zone 37 North coordinate system. The pre-processing of Landsat 8 imagery involved atmospheric corrections using the respective algorithms within QGIS 3.16. Prior to land cover classification, pre-processing and post-processing tasks such as sub-setting, layer stacking, and image enhancement were completed. Those steps were aimed to enhance image quality and remove any atmospheric interference for accurate land cover classification. Major land covers considered in the study are defined in Table 2 below.

Table 2: Description of land cover types classified.

Land cover type	Description	Source
Cultivated	Cultivated land includes area used to grow annual crops. Cultivated lands are plowed continuously or periodically depending on quality of soil and interest of farmers.	Desta and Hurni (2011)
Grazing	Grass and herb cover with scattered trees and shrubs, and are areas supposedly with permanent grass cover used for livestock grazing. Grazing land tends also to be open areas with good visibility on flat areas and hill slopes and are relatively homogeneous, with little pattern compared to cultivated land.	Desta and Hurni (2011)
Forest	The land area dominantly covered with trees and shrubs, mainly with dense canopy (¿30%).	Girmay et al. (2020)

The integration of field data with the original Landsat 8OLI allowed for the identification and delineation of these land cover types. Field observations, including direct assessments and surveys within the study watershed, provided valuable ground-truth data for understanding the composition and characteristics of the land cover. To perform the image classification, the Normalized Difference Vegetation Index (NDVI) approach was adopted. This approach allowed the classification algorithm to learn the spectral characteristics and patterns associated with each land cover class based on the NDVI values.

A Landsat 8 satellite image that acquired for the study area provided the necessary spectral bands for calculating NDVI. To minimize computational requirements and to focus on the study area, a subset of the Landsat 8 image covering the specific region of interest was selected, which contains the necessary spectral bands for NDVI calculation. The near-infrared (NIR) and red bands of Landsat 8 were extracted from the selected subset. These bands are essential for calculating NDVI because they capture the reflectance in the red and near-infrared portions of the electromagnetic spectrum. Finally, the NDVI value was determined by using eq. 9. The NDVI was computed using the extracted NIR and red bands.

$$\text{NDVI} = \frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}} \tag{9}$$

Where NIR represents the reflectance in the near-infrared band and Red represents the reflectance in the red band. The calculation of NDVI provides a quantitative measure of vegetation health and density, allowing for the analysis of vegetation dynamics and monitoring changes over time (Jensen, 2009).

The value of the C factor depends on various factors, including vegetation type, growth stage, and percentage of cover (Gitas et al., 2009). The C factor of 0 represents a condition where soil erosion is negligible due to high plant cover, while a C factor of 1 indicates a greater potential for soil loss due to extensive tillage, leaving a smooth surface that generates significant runoff and renders the soil susceptible to erosion (Rabia, 2012; Renard et al., 1997). The Normalized Difference Vegetation Index (NDVI) was used to derive the C factor as it positively correlates with the amount of green biomass and indicates variations in green vegetation coverage (Van der Knijff et al., 2000). Higher C factor values imply greater vulnerability to soil erosion, as they indicate unprotected barren land. The calculation of the NDVI spectral index follows the equations proposed by Ahmed et al. (2013).

$$C = \exp\left[-\alpha\left(\frac{\text{NDVI}}{\beta} - \text{NDVI}\right)\right] \tag{10}$$

The parameters α and β are unitless parameters that determine the shape of the curve representing the relationship between NDVI and the C factor. For the parameters and , values of 2 and 1 were chosen, respectively. This equation has been effectively employed by numerous researchers to determine the spatial distribution of the C factor (Kouli et al., 2009; Prasannakumar et al., 2011) .

To calculate the C-factor values for the study area, obtained a Landsat 8 OLI/TIRS C1 image covering PATH 168 and ROW 55 downloaded from the United States Geological Survey (USGS) Earth Explorer (https://earthexplorer.usgs.gov). Only images with cloud cover below 6% were selected, and data from May 2022 was utilized. The accuracy of the image was validated through ground truth data obtained from field observations.

2.2.6 *Conservation practices (P-factor)*

The P-factor quantifies the ratio of soil loss with a specific conservation support practice to the corresponding soil loss (Dabral et al., 2008; Renard et al., 1997; Wischmeier & Smith, 1978). Various factors, such as contour plowing, strip-cropping, and terracing, were taken into account when assigning P-factor values, which reflect the effectiveness of erosion control measures. table 3 below displays the support practice factor values corresponding to different cultivation methods and slope conditions (Morgan, 2005; Pesaran et al., 1999). The values range from 0 to 1, where a value of 0 indicates excellent conservation practices implemented to control erosion, while a value of 1 indicates the absence of any erosion control mechanism.

In the study area, there are few terraces. Thus, to calculate the P-factor, slope and contouring values were used (Wischmeier & Smith, 1978). The P-factor values were then calculated considering the effectiveness of contouring in reducing soil erosion based on slope and

Table 3: Values for conservation practices under different slope classes considered for the study (Morgan, 2005).

Slope (%)	Contouring	Strip-cropping	Terracing
0–7	0.55	0.27	0.10
7–11.3	0.60	0.30	0.12
11.3–17.6	0.80	0.40	0.16
17.6–26.8	0.90	0.45	0.18
>26.8	1.00	0.50	0.20

contouring practices. This analysis helps assess the potential risk of soil erosion in different areas, considering the challenges of the limited terracing and the less common strip-cropping practices in the study area.

2.2.7 Combining the RUSLE inputs

Soil loss estimation and erosion risk assessment were conducted by the RUSLE model in a raster GIS environment (grid-based approach). Individual GIS files were built for the rainfall erosivity, soil erodibility, topography (slope length and steepness), land use/land cover, and conservation practice (denoted by RKSLCP) combined by cell grid modeling procedures in GIS software to predict soil loss in spatially. After completing the data input procedure and preparing the necessary maps of RUSLE factors with a pixel size of 30 m *30 m, they were combined and analyzed using the raster calculator in ArcGIS 10.8. The average annual erosion expected on the field slopes was estimated (fig. 2) (Wischmeier & Smith, 1978).

$$A = R \times K \times LS \times C \times P \tag{11}$$

3 Results

3.1 Rainfall erosivity

The IDW interpolation technique in ArcGIS revealed a range of R-factor values from 407.044 to 393.039 MJ mm-1 ha-1 yr-1, indicating spatial variations in rainfall within the study watershed. Higher R-factor values were observed in the southern areas of the watershed, while lower values were found in the northwestern parts of the watershed (Table 4; Figure 3). The R-factor value implies the possible rainfall force that could generate surface runoff and exert power to detach and transport soil particles.

3.2 Soil erodibility factor

According to this study, a high soil erodibility (K-factor) value was recorded in agricultural land (0. 179 t h MJ-1 mm-1), while a low value was found in vegetation-covered land (0.146 t h MJ-1 mm-1) in the upper and central parts of the watershed (Figure 4). A higher K-value indicates a greater susceptibility to soil erosion (Figure 4b). The low K-value was observed in the western parts of the watershed, while the high soil erodibility was identified in the northeastern and in the southeastern parts of the study watershed.

3.3 Topographic factor

In this study, the LS values ranged from 0 (indicating low erosion potential) to a high value of 49.24. The areas with higher LS values were observed in the mountainous regions characterized by steep slopes, particularly in the southern and western parts of the watershed **??** Conversely, lower LS values were observed in the northeastern and southwestern parts of the study watershed. The variability in LS values can be attributed to the complex and rugged natural landforms found within the study watershed. Higher LS values were predominantly observed in areas prone to erosion within the Bidara watershed. However, it is worth mentioning that most of the catchment area, approximately 79.46% (3,151.59 ha), is in the western to eastern parts of the watershed (Table 5; Figure 5a).

3.4 Land cover factor

The land cover indicates the protective effect of vegetation in reducing soil erosion vulnerability. The estimated NDVI values within the watershed ranged from 0.06481 to 0.3486, with higher values indicating areas with abundant vegetation (table 5). The analysis showed a range of C-factor values within the watershed, with lower values (0.3428) in vegetated areas and higher values (0.864) in agricultural land. This suggests that areas with less vegetation and absence of dense shrubs have higher erosion vulnerability in the watershed.

3.5 Supportive conservation practice

The P values within the watershed exhibit variation, ranging from 0.55 in the northern, eastern, and central parts of the watershed to 0.9 in steep slope areas located in the southern and the northwest parts of the study watershed (fig. 7,table 6). Notably, the P factor map highlights elevated P values in areas characterized by vegetation and dense shrub land.

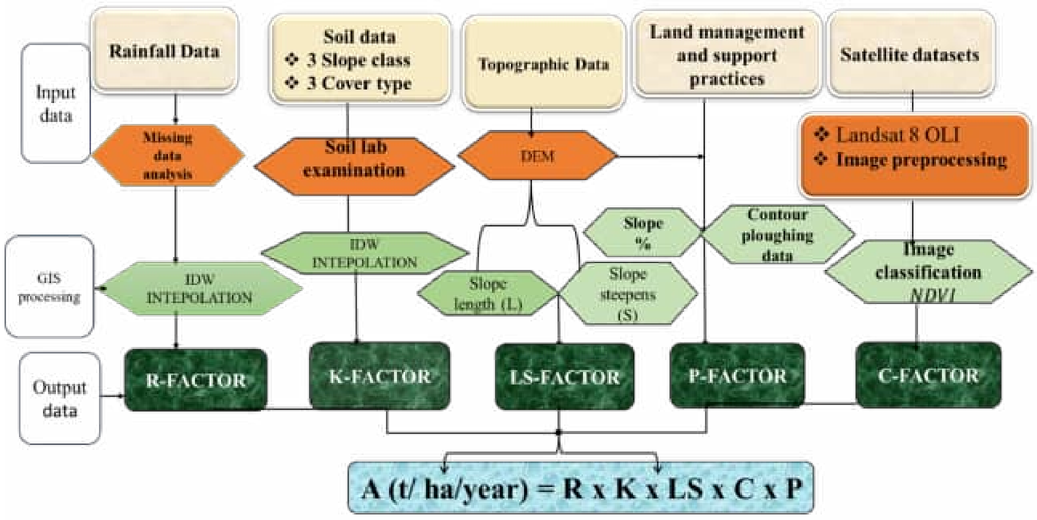

Figure 2: Input data combination in RUSLE

Table 4: R-Factor within station.

Mean Annual Rainfall (mm)	R-Factors (MJ mm/ha/yr)
760.09	393.039
772.45	400.179
777.85	403.145
784.57	407.044

3.6 Soil loss estimation in Bidara watershed

The findings of this investigation revealed that the watershed is currently experiencing a high soil erosion rate with significant spatial variation. Soil loss ranges from zero in flat terrain to $1129.47\ \mathrm{t\,ha^{-1}\,yr^{-1}}$ in sloping areas of the watershed, with a mean annual soil loss of $16.41\ \mathrm{t\,ha^{-1}\,yr^{-1}}$. In total, an estimated 65 087.47 t of top fertile soil is lost annually from the entire watershed of the Bidara (Figure **??**; Table **??**).

From the total area of the study watershed, the distributions of soil loss are 55.92% (2217.77 ha) of the land experiences soil loss ranging from 0-10 t ha-1 yr-1 of fertile topsoil, 17.27% (685.08 ha) experiences loss ranging from 10–20 t ha-1 yr-1 ; 10.55% (452.61 ha) experiences loss ranging from 20–30 t ha-1 yr-1; 7.58% (301.3 ha) experiences loss ranging from 30–45 t ha-1 yr-1ha); 3.5% (138.22 ha) experiences loss ranging from 45–60 t ha-1 yr-1 ; 2.66% (107.06 ha) experiences loss ranging from 60–80 t ha-1 yr-1 and the remaining 1.62% (64.295 ha) experiences loss exceeding 80 t ha-1 yr-1 of fertile topsoil. These findings are consistent with a previous study (Fenta et al., 2021), which reported a mean annual soil loss of 16.5 t ha-1 yr-1 based on the agro ecological zones of Ethiopia.

The results of this study indicated significant soil loss in the upstream mountainous and hilly areas of the study watershed as well as in the middle-slope areas of the catchment (Table 8). In contrast, relatively lower mean annual soil loss rates ranging from 0–10 t ha-1 yr-1 were observed in the bottom areas of the watershed, specifically in the eastern part, enclosing the centers of the watershed. Based on these findings, it is recommended to prioritize the development of a management plan to reduce soil and nutrient losses in the steep and middle slope areas of the watershed. Furthermore, the results reveal that the low soil loss category covers a substantial portion of the study area, accounting for 55.92% (2217.77 ha) of the total land area (Table 8 Figure 10).

3.7 Identifications and prioritization of hotspot areas

3.7.1 Identifications of hotspot areas in Bidara watershed

Based on the soil loss and erosion rates observed in the study area, the hotspot areas were classified into seven categories: low (0–10 $\mathrm{t\,ha^{-1}\,yr^{-1}}$), moderate (10–20 $\mathrm{t\,ha^{-1}\,yr^{-1}}$), high (20–30 $\mathrm{t\,ha^{-1}\,yr^{-1}}$), very high (30–45 $\mathrm{t\,ha^{-1}\,yr^{-1}}$), severe (45–60 $\mathrm{t\,ha^{-1}\,yr^{-1}}$), very severe (60–80 $\mathrm{t\,ha^{-1}\,yr^{-1}}$), and extremely severe (>80 $\mathrm{t\,ha^{-1}\,yr^{-1}}$). The low to moderate soil loss category covered 73.262% (2,902.8518 ha), while the high to extremely severe classes accounted for a total of 26.812% (1,063.487 ha) of the study area (Table **??**). This area is extensively grazing and has experienced a relatively high level of degradation and relatively high steep slope areas (Figure **??**). The mean annual soil loss rate in this study was 16.41 $\mathrm{t\,ha^{-1}\,yr^{-1}}$, which exceeds the soil loss tolerance level of 1–16 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ specified by **Hurni1985**.

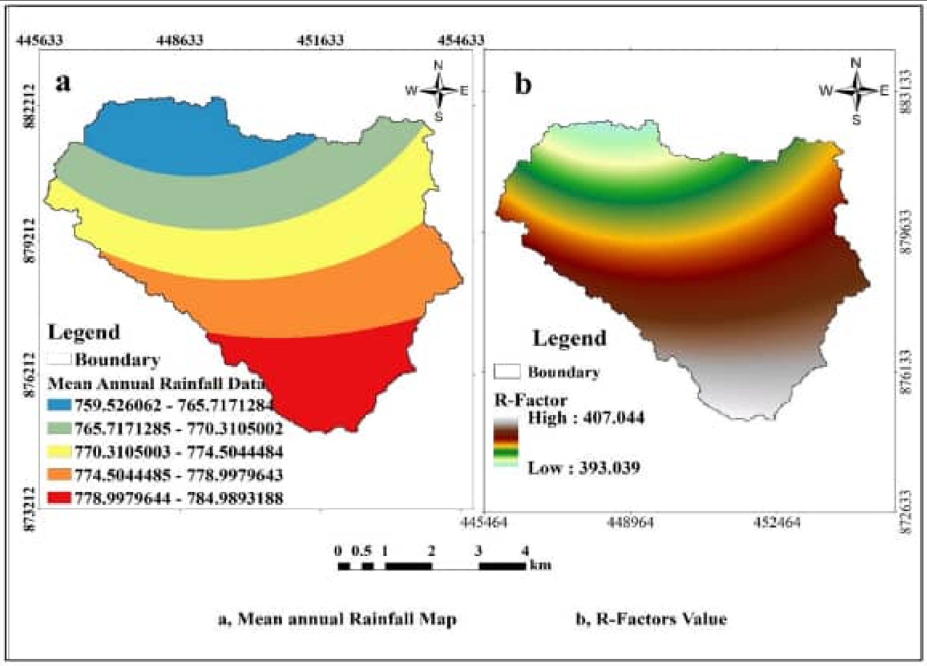

Figure 3: Rainfall erosivity factor in Bidara watershed.

Table 5: Area under slope classes in the Bidara watershed.

No	Slope Class (%)	Description	Area (ha)	Area (%)
1	0–0.5	Flat-Level	592.44	14.94
2	0.5–1	Nearly Level	267.001	6.73
3	1–2	Very gently sloping	342.142	8.63
4	2–5	Gently sloping	1950.01	49.17
5	5–10	Sloping	758.001	19.11
6	10–15	Strongly sloping	51.52	1.30
7	15–30	Moderate Steep	5.16	0.13
	Total		3966.3	100

3.7.2 *Prioritization for specific conservation plans of Bidara watershed*

Proper identification of vulnerable areas to soil loss is crucial for effective soil and water conservation (SWC) planning (Wischmeier & Smith, 1978). The study area, Bidara watershed, was ranked into seven conservation priority levels based on soil erosion severity and risk. Approximately 1.62% (64.29 ha) is extremely severe (priority level I), 2.699% (107.06 ha) is very severe (priority level II), and 3.49% (138.22 ha) is severe (priority level III) (Table **??**). Topography has significantly contributed to high soil loss rates. Other areas with high and very high soil levels covered 19.01% (753.91 ha) of the total area.

The results of the soil loss analysis indicated that approximately 55.92% (2,217.77 ha) of the watershed was categorized as a low erosion risk area, which falls within tolerable values adapted for the highlands of Ethiopia (Rizeei et al., 2016). The expansion of bare land and cropland on sloping land was identified as the primary drivers of land cover change, contributing to high soil loss rates in areas experiencing non-tolerable erosion. Across the Bidara Watershed, 65,087 tons of soil is lost annually. The watershed necessitates site-specific planning for conservation and restoration of fertile topsoil.

3.8 Soil erosion susceptibility class for decision-makers

Bidara watershed has been classified into three major erosion susceptibility classes. The first class, situated in the southern parts of the watershed, exhibits extremely severe soil loss exceeding 80 t ha-1 yr-1. Immediate mitigation measures are deemed necessary for this area due to its high susceptibility to soil erosion. The second class comprises areas located on the northwestern part of the watershed, which have been identified as requiring second-level mitigation. The planners and decision-makers must prioritize and implement appropriate and effective measures to address soil erosion (Figure 12).

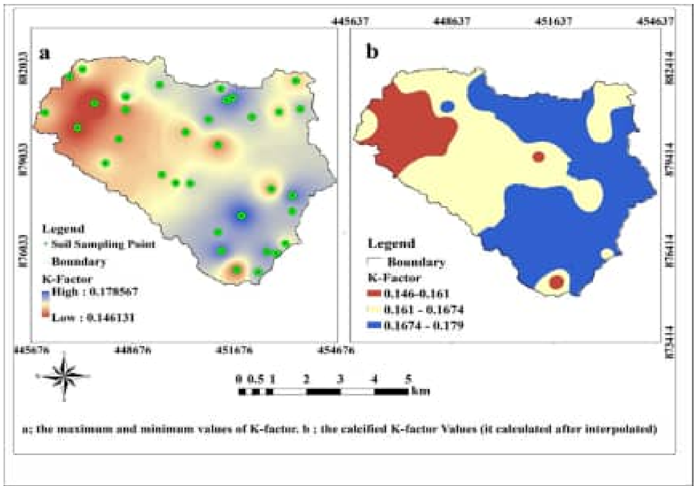

Figure 4: Soil sampling point and erodibility (K factor) for Bidara watershed.

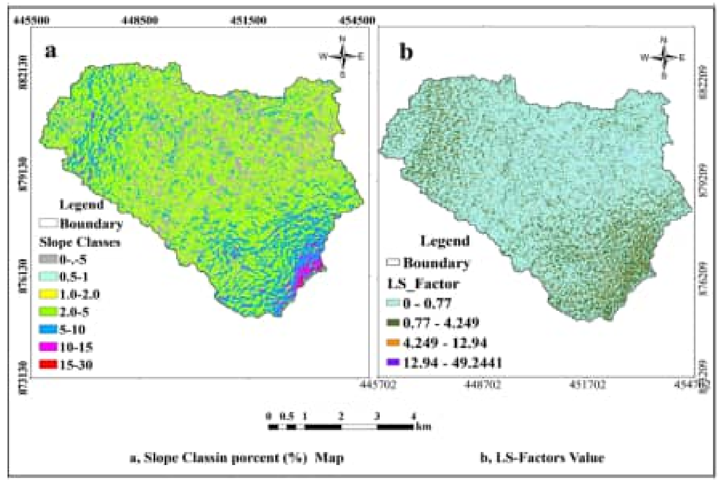

Figure 5: Map showing the topography (LS-factor) of the Bidara watershed.

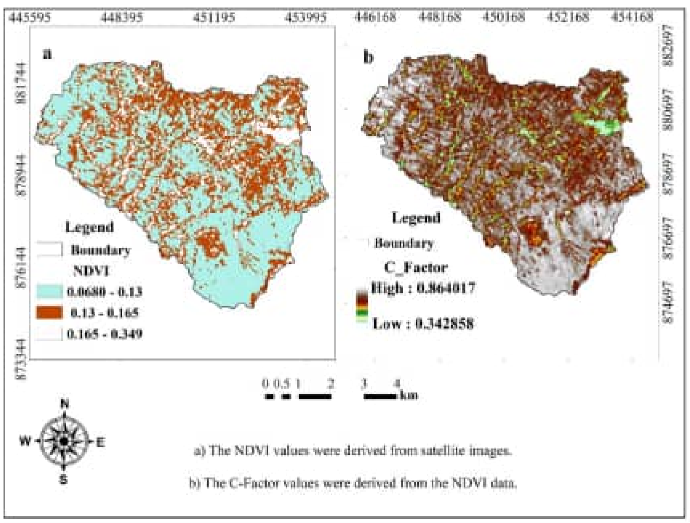

Figure 6: NDVI and C-Factor for the Bidara watershed.

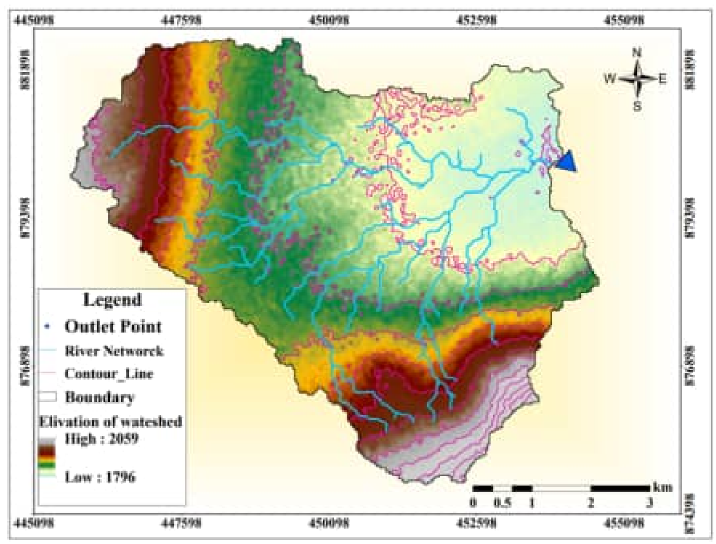

Figure 7: Slope class and P factor map of the Bidara watershed.

Table 6: The conservation practice (P Factor value) for Bidara watershed

Slope (%)	P Factor Value	Area (ha)	Area (%)
0–7	0.55	224.484	5.66
7–11.3	0.6	3711.39	93.57
11.3–17.6	0.8	29.7364	0.75
17.6–26.8	0.9	0.710 44	0.018
Total		3966.320 84	100

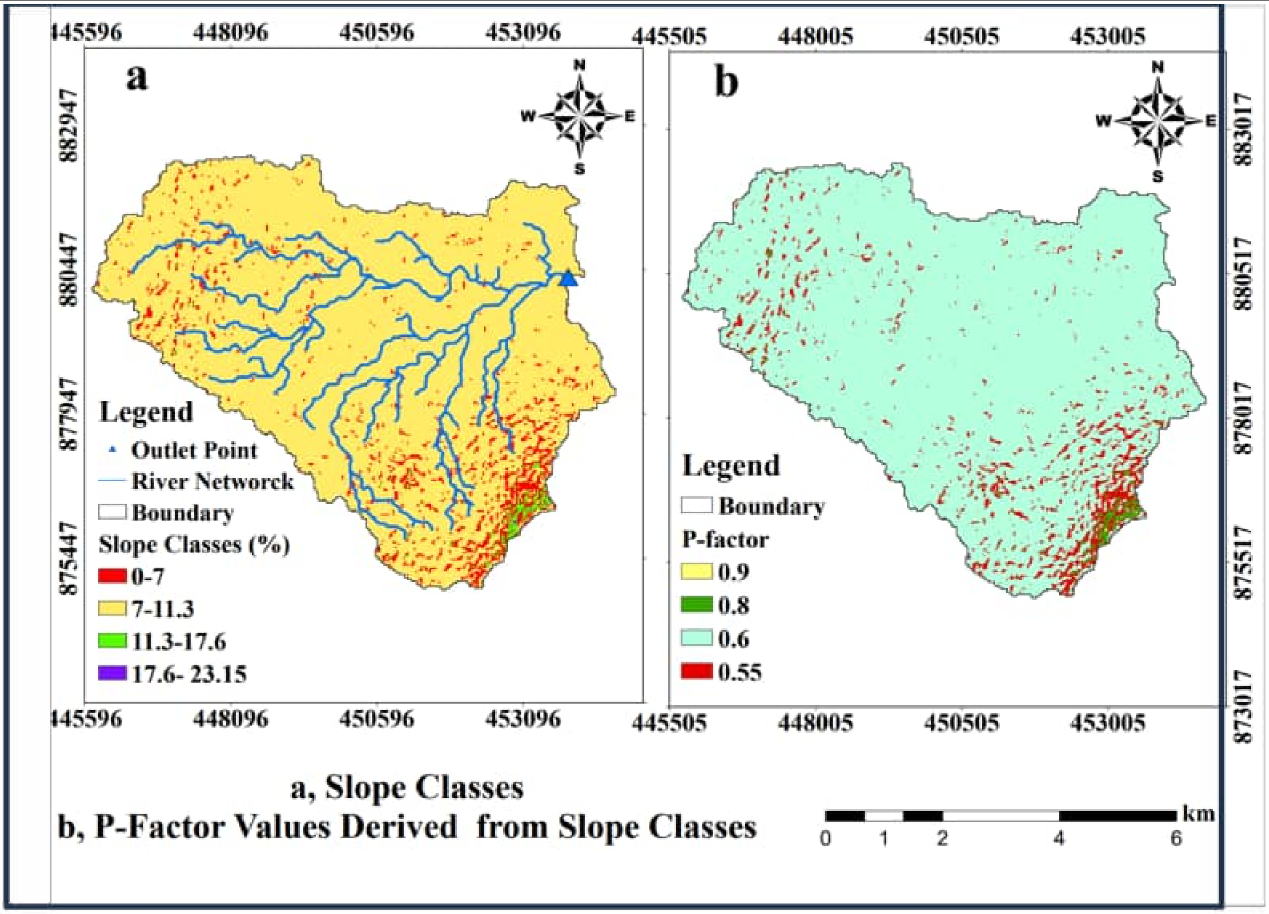

Figure 8: Slope class and P factor map of the Bidara watershed

4 Discussion

The mean annual soil loss rate of 16.41 t ha-1 yr-1 in the Bidara watershed is greater than the tolerable rate, 5 to 11 t ha-1 yr-1 (Renard et al., 1997) . A study by Nigatu (2014) in the Denki River catchment of Ankober woreda reported soil erosion rate of 0.006 to 505.7 t ha-1 yr-1 with a mean annual soil loss rate of 17.69 t ha-1 yr-1.. Mean annual soil loss of 18.7, 19.7, and 20 tons ha -1 yr-1 were reported by Belay and Mengistu (2021) for watersheds of Somodo, Muga, and Afa, respectively. The findings of those studies were in line with our results, demonstrating similar rates of soil loss in various watersheds in other parts of Ethiopia. It is important to note that the Bidara watershed experiences relatively lower soil loss rates compared to some other regions in the country. For instance, in the Chemoga watershed (Bewket & Teferi, 2009) an average soil erosion rate of 93 t ha -1 yr-1, while Moisa et al. (2022) found a mean annual soil loss of 83.7 t ha-1 yr-1. Also, less mean annual soil loss (9.63 t ha -1 yr-1) was reported for Medego watershed (Tripathi et al., 2003), which is less than the soil loss rates found in our study. Depending on erosion factors, which expected to vary with a specific locality, even within watershed, the magnitude of erosion observed could vary between watersheds. In the study area, the intolerable soil erosion could be due to land cover, topography, and lack of adequate and appropriate conservation measures. For instance, conventional agriculture is dominating and supposed to aggravate erosion, especially on steep sloping topography. As observed in the field, the soil and water conservation structures such as terraces are few and not sustainable to reduce soil erosion in the long run.

In this study, areas with high soil loss rates are identified and prioritized for SWC measures. This prioritization can greatly assist decision-makers and conservation planners in designing suitable SWC interventions based on the severity of soil loss. The first, second, and third priority levels encompass approximately 309.57 ha (7.8%) of the watershed area and require immediate, intensive and integrated SWC measures including bunds, terrace and tree planting. These priority areas are predominantly located in Washe Faka kebele in the northwest and Bidara Faka and Faka Repe kebeles in the southern parts of the watershed. These areas are characterized by steep slopes, with slope gradient ranging from 11.3% to 23.15%. A recent report by Karamage et al. (2016), for the Nyabarongo River Catchment in Rwanda and Chaleleka wetland watershed of Ethiopia Wolka et al. (2015) support our findings by demonstrating higher soil erosion in areas with steep slopes. Steep slopes contribute for the velocity of surface runoff and increase eroding force of the water.

Fortunately, about 56% of the Bidara watershed is estimated to experience tolerable erosion and thus, erosion controlling measures such as grass strips and contour plowing could control soil loss. Hence,

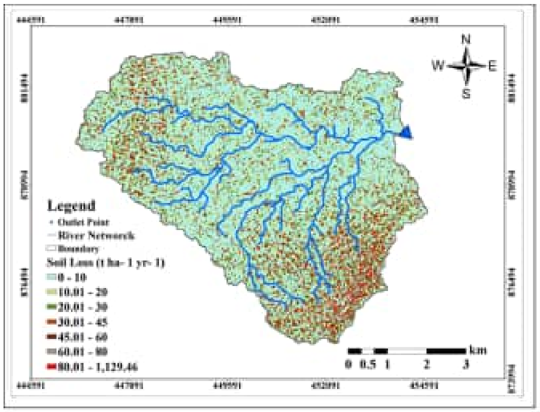

Figure 9: Estimated soil loss using the RUSLE in Bidara watershed.

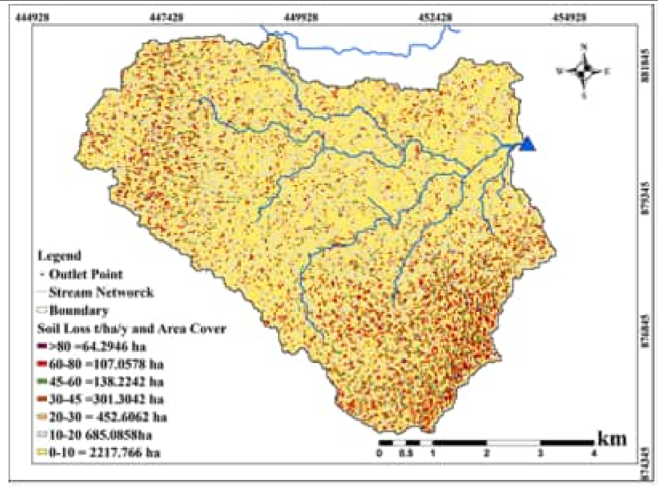

Figure 10: Soil loss classification map.

Table 7: Annual soil loss in Bidara watershed

No	Area (ha)	Area (%)	Soil loss (t ha^{-1} yr^{-1})
1	2217.77	55.92	0–10
2	685.08	17.27	10–20
3	452.61	11.41	20–30
4	301.30	7.60	30–45
5	138.22	3.50	45–60
6	107.06	2.69	60–80
7	64.29	1.62	¿80
Total	**3966.33**	**100.00**	

the identification of priority areas considering the spatial variability in soil erosion risk within the Bidara watershed is crucial for effective planning and implementation of appropriate SWC measures (Adugna et al., 2015; Bhattacharyya et al., 2016; Keesstra et al., 2018). Soil and water conservation measures can address the varying levels of soil loss and erosion risk.

The proper prioritization of soil and water conservation areas in the Bidara watershed, taking into account the severity levels of soil loss, is essential for effective conservation planning. It is crucial to identify and address the high-priority areas characterized by steep slopes with urgent erosion protection measures. In the context of Ethiopia, specifically the Central Rift Valley area, some other studies have highlighted the significance of erosion protection measures and conservation planning. For example, Wolka et al. (2015) emphasized the importance of prioritizing soil and water interventions through improved vegetation cover and terrace based on the severity of soil erosion in the Central Rift Valley. They stressed the need for targeted measures in areas with higher erosion risk to prevent further soil degradation. Furthermore, studies by Gebregergs (2018) focused on SWC practices in the Central Rift Valley, emphasizing the effectiveness of terracing and other erosion control measures in reducing soil loss and enhancing soil conservation. In the region, soil and water conservation measures such as bunds and Fanya juu have positive effect on soils of cultivated and grazing lands due to their erosion protecting role (Dangiso & Wolka, 2024; Husen et al., 2017; Wolka et al., 2024). Planners and experts in the district could apply output of our study in designing watershed-based soil and water conservation measures.

In general, models are important and applied for estimating soil erosion as field experiments are expensive in terms of time and budget. In addition, monitoring erosion at watershed scale to choose soil and water conservation measures is difficult unless models are used. Still there are uncertainties in model and its output due to resolution and quality of spatial and temporal data. For instance, in the study area, we applied interpolation method for soil properties and rainfall parameters. This could have some uncertainties on output, but we believe this scientific method we applied can result in a reasonable range.

5 Conclusion and recommendations

The RUSLE model effectively evaluated soil erosion intensity and variability in the Bidara watershed. The findings revealed a mean annual soil loss rate of 16.41 t ha-1 yr-1, resulting in an estimated loss of 65,087.3 t of fertile topsoil annually across the watershed. Approximately 7.8% (309.57 ha) of the evaluated areas experienced severe to extremely severe soil erosion rates. Spatial distribution maps depicted varying soil loss patterns ranging from 0 to 1129.47

Table 8: Erosion hotspot area (severity class) in Bidara watershed

No	Area (ha)	Area (%)	Soil loss (t ha^{-1} yr^{-1})	Severity Class
1	2217.77	55.91	0–10	Low
2	685.09	17.23	10–20	Moderate
3	452.61	11.41	20–30	High
4	301.30	7.60	30–45	Very High
5	138.22	3.48	45–60	Severe
6	107.06	2.70	60–80	Very Severe
7	64.30	1.62	>80	Extremely Severe
Total	**3966.33**	**100.00**		

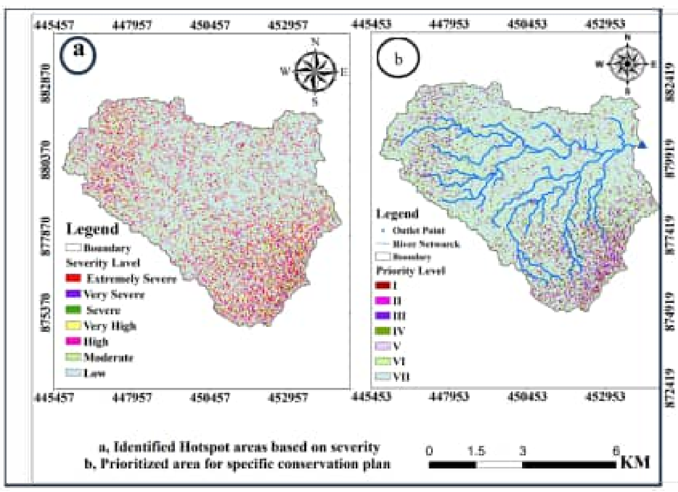

Figure 11: Severity class and priority level map in Bidara watershed.

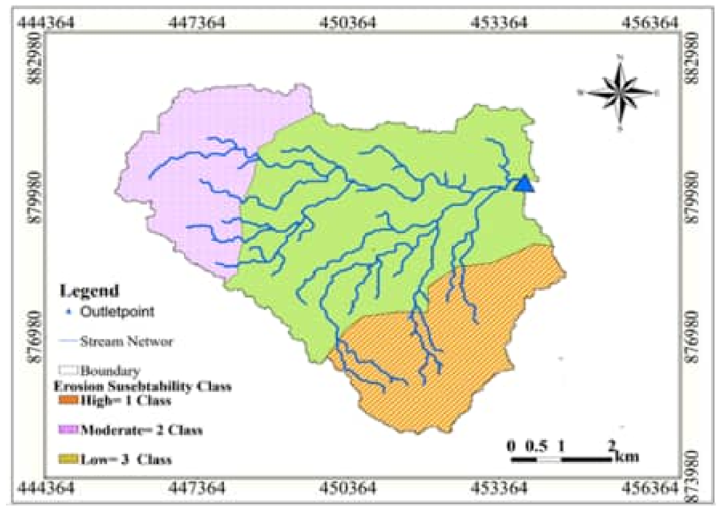

Figure 12: Soil erosion susceptibility map

t ha-1 yr-1 throughout the watershed. The mean annual soil loss exceeded the tolerable limit of 11 t ha-1 yr-1, primarily attributed to steep slopes. Urgent implementation of soil and water conservation practices is imperative, particularly in areas with high erosion rates. These research findings provide valuable insights for researchers seeking to address soil erosion challenges and promote effective conservation strategies in similar watersheds. The identified areas with high erosion risks should be prioritized for soil and water conservation measures. A comprehensive implementation plan for soil and water conservation should be prepared and executed in collaboration with local communities, government agencies, and non-governmental organizations. Multi-disciplinary integrated watershed management approach should be conducted to develop sustainable natural resource management in the study watershed for a healthy ecosystem by concerned stockholders. In the long, government should increase datasets that are important for natural resource research including establishing meteorology stations to monitor rainfall in the woreda.

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Table 9: Prioritized for conservation plan in Bidara watershed

No	Area (ha)	Area (%)	Soil loss (t ha^{-1} yr^{-1})	Severity class	Priority level
1	2217.76	55.91	0–10	Low	VII
2	685.08	17.27	10–20	Moderate	VI
3	452.60	11.41	20–30	High	V
4	301.30	7.59	30–45	Very high	IV
5	138.22	3.48	45–60	Severe	III
6	107.05	2.69	60–80	Very severe	II
7	64.29	1.62	>80	Extremely severe	I
Total	**3966.33**	**100.00**			

Competing interests

The authors declare that they have no conflicts of interest.

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