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Research Article

# Assessing Soil Erosion and Sediment Yield in the Aguat Wuha Dam Catchment, Northwest Ethiopia Using RUSLE and GIS

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## Abstract

One crucial metric for estimating a reservoirs and dam's lifespan is sedimentation. It is dependent upon sediment output, which in turn is dependent upon soil erosion. The study area, the Aguat Wuha Dam, was located in Simada woreda, of northwestern parts of Ethiopia. And the study's goal was to use Arc GIS and RUSLE adjusted to Ethiopian conditions to assess potential soil erosion and sediment output from the watershed and identify hotspot locations for appropriate planning for erosion and sedimentation problem management techniques to make the outputs of the dam project more productive and effective for the proposed and suggested purpose of the dam. To predict the geographical patterns of soil erosion in the watershed, the Geographic Information System (GIS) was combined with the revised universal soil loss equation (RUSLE). A soil erosion map was produced using ArcGIS by utilizing all of the model's parameters, including Erosivity, erodibility, steepness, land use, land cover, and supportive practice factors. The watershed's yearly soil loss varies from 0 to 413.86 tons/ha. In order to determine the erosion hotspot area, the average annual soil loss value was discovered to be 9.24 tons/ha/year and was categorized into six erosion severity classes: low, moderate, high, very high, severe, and very severe. These findings indicated that 162.57 ha and 699.17 ha of the watershed were considered to be extremely and severely vulnerable to soil erosion, respectively. It was discovered that the anticipated sediment yield supplied to the outlet varied from 0 to 104.94 tons/ha/year. By standing from the implications of the assessments of the geological, geotechnical, topographical, and socioenvironmental considerations Watershed management is the most effective way to reduce the amount of sediment produced and the amount that enters the reservoir among the several reservoir sedimentation control options that are available.

## Keywords

Aguat Wuha Dam Catchment, RUSLE, Sedimentation, Sediment Delivery Ratio, Sediment Yield, Soil Loss, Watershed

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## 1. Introduction

Soil erosion and the resulted sedimentation are of the most important environmental concerns throughout the world which, causing great damage to life and ecosystems [1-3]. These phenomena, while demonstrating both positive and negative impacts, entail adverse consequences like depletion of nutrients-rich topsoil, diminished agricultural productivity, and alterations on river channels affecting floodplain farmlands. In irrigation initiatives, soil erosion and sedimentation contribute to diminish conveyance capacities and storage volumes in reservoirs, as well as a decline in irrigation water quality due to high water turbidity. More than 40,000 large reservoirs worldwide are affected by sedimentation, leading to an estimated annual loss of 0.5% to 1% of their total storage capacity. The global sediment load carried by rivers is estimated to range between 24 and 30 billion tons per year, with a total water inflow of 40,000 km $^3$ However, these figures can vary significantly depending on the specific river and its discharge [4]. But the process in reservoirs causes not only the loss of storage capacity but also has an environmental impact [5]. In low-lying areas, the deposition of eroded soil from higher elevations alters river channels, elevating flood vulnerability of floodplain farmlands and residential zones. However, it's essential to note that soil erosion and sedimentation are not universally negative. In certain instances, these processes can yield downstream benefits, such as the deposition of fertile sediments conducive to agricultural activities. Examples of such positive outcomes include the Nile basin irrigation systems in Egypt and the Juba and Shabelle irrigation projects in Somalia [6].

Soil erosion, encompassing processes like sheet erosion, gully erosion, and stream bank erosion, is a critical global challenge influenced by a complex interplay of factors, including climate, land use, and soil characteristics. Simultaneously, sedimentation, involving the transport and deposition of soil particles in water bodies, presents challenges to the longevity of reservoirs and downstream water management. The accumulation of sediment in reservoirs is a multifaceted phenomenon influenced by sediment yield, transport rate, reservoir operation, and variations in stream flow [3, 7-9].

Dams disrupt the natural flow of sediment within river systems, leading to the accumulation of sediments in the reservoir. This adversely affects reservoir operation, diminishes storage capacity, and deprives downstream areas of crucial sediments necessary for maintaining channel structure and supporting the riparian ecosystem. The prevailing debates on sediment-connected issues commonly revolve around the escalating of erosion and sediment loads due to inappropriate land usage practices and the expansion of human activities into untouched areas [10].

According to [11], the accumulation of sediment in reservoirs poses a significant challenge, impacting the longevity of dams. It is crucial to possess data on both the rate and manner of sedimentation within reservoirs to anticipate potential issues. This information empowers decision-makers to formulate strategies and solutions to address future challenges. The buildup of sediments in reservoirs is a multifold phenomenon due to numerous factors such as sediment yield, sediment transport rate, sediment characteristics, reservoir operation, reservoir geometry, and variations in stream flow. The information gathered from extended records of sediment load suggests that the flow of sediments in rivers is responsive to various factors. These factors entail activities such as the creation of reservoirs, deforestation, alterations in land usage, various forms of land disruptions like mining, implementation of soil and water conservation practices, sediment control initiatives, and the impacts of climate change [12]. The processes of reservoir sedimentation are intricate and influenced by factors such as sediment production in the watershed, the speed of sediment transportation, and the manners in which deposition takes place. The phenomenon leads to a decrease in the storage capacity of reservoirs, impacting their abilities to regulate flow and consequentially affecting water supplies, flood control, hydropower generation, navigation, recreation, and environmental benefits derived from stored water release. Apart from the loss of storage capacity, various issues related to sediment can arise both upstream and downstream of dams [13]. In many parts of the world, sedimentation causes serious problems concerning water management, flood control, and production of energy [14].

Kanito stated that, soil erosion and the resulting sediment yield pose current constraints and potential future threats to agriculture, water resources, and hydropower initiatives, especially in developing nations [15]. It is vital to assess the scopes and understand the spatial distributions of areas prone to these issues to implement evidence-based soil management strategies. Identification of areas vulnerable to soil erosion is crucial in applying soil conservation measures, especially in river basins [16]. Erosions are multifold phenomena involving intricate and interconnected natural mechanisms that result in the loosening, dissolution, and displacement of earth or rock materials. This process entails the gradual wearing down of the land surface, achieved through the detachment and transportation of soil and rock substances by various geological agents such as flowing water, wind, or other natural forces [17]. Several key elements impact soil erosions, including climates (in the form of rainfall/precipitation or winds), the topography of the landscape, the properties of soils and bedrock, vegetation coverings, and human activities. Climates, in particular, are instrumental in delineating various forms of soil erosion, such as wind and raindrop erosion. Rainfall-induced erosion occurs when raindrops hit the surfaces, overpowering the forces that bind soil particles together [6].

Though a number of studies have been done by researchers on soil loss based on the suitability of the regions by incorporating the different models. The worldwide issues of erosion and sedimentation pose a persistent threat to reservoir capacity, endangering the dependability of essential services like water supplies, flood control, hydropower generation, and other benefits crucial to our water-dependent society. The diminishing capacity of reservoirs directly jeopardizes our capacity to ensure consistent water supplies for both agricultural and urban purposes. Furthermore, it hampers various other functions such as flood control, hydropower generation, navigation, and fisheries. The repercussions of sediment trapping extend beyond reservoirs, impacting downstream areas and reaching all the way to the coastlines [18].

In case of Ethiopia Previous studies have revealed that our country grapples a multifaceted challenge concerning erosion and sedimentation, which has far-reaching implications for its hydroelectric power and irrigation reservoirs [19]. These critical infrastructures confront substantial threats due to the accumulation of excessive sediment, resulting in reduced storage capacity, and shortened lifespan, compromised water quality, and heightened operational costs for sediment removal and upkeep. Consequently, the functionality of these dams is compromised, failing to deliver the intended services effectively [20].

The big problem of accelerated soil damage caused by water severely influences environmental wellness, agricultural production, and worldwide food certainty [21]. Additionally, it brings unfavorable outcomes to the natural water storage capability of watersheds and longevity of man-made reservoirs and dams, leading to major expenses for digging. It also undermines the caliber of surface water origins, diminishes the visual attractiveness of landscapes, and disrupts ecological stability [22, 23].

Ethiopia has been recognized as among the countries most negatively impacted by soil erosion on a global scale [24]. Soil erosion and the consequent sediment yield from catchments pose significant obstructions to accomplishing sustainable land usage practices and preserving water excellence in rivers, lakes, and other marine environments in the country [25]. Numerous hydroelectric and irrigation reservoirs in the country, like Aba-Samuel, Koka, Angereb, Melka Wakena, Borkena, Adarko, and Legedadi, are confronting significant menaces from superfluous sedimentation. Consequently, these dams have encountered reduced capability and lifetime, deterioration in water superiority, and demand expensive maintenance operations for sediment elimination, which finally diminishes their intended functions and services [20, 26]. The deposition of the sediment is controlled by different factors, including sediment characteristics, discharge of the water system, sediment inflow amount, and the shape, size, and operational mode of the reservoir's [11]. In cultivated regions, the extent, severity, and likelihood of soil erosion are primarily influenced by human actions such as deforestation, grazing, urban development, inadequate agricultural practices, and controlled burning. Nevertheless, the fundamental mechanisms that drive these activities leading to soil erosion in specific locations may not be immediately apparent [27]. The potential for soil loss in basin areas is influenced by factors such as the basin's configuration, soil attributes, local climate conditions, and the land use and management practices adopted within the basin [28]. Precise assessments of soil erosion play a crucial role in understanding various environmental factors, including diminished soil fertility, heightened flood susceptibility, nutrient loss, and deterioration of water quality [29].

The major reasons for carrying out the research in the area are as follows:

There is no previously published or unpublished work of assessing or estimating soil erosion and sediment yield in the study area before this research, The nearly developed and constructed Dam of Aguat Wuha, which is located in the northwestern part of Ethiopia, Simada woreda, is suitable for different agricultural and domestic needs and seems at risk due to the problem of soil erosion and sedimentation. These problems disturb the quality of the water, decrease the water storage capacity of the reservoirs, and affect the ecological downstream [14, 30]. Due to this, this study helped as an input tool for solving the problem firstly by accurately assessing and showing the phenomena, which makes aware of the community and the concerned respondent about the problem. Next to this after the study accurately conducted a detailed assessment and examination of the problem of soil erosion and sedimentation in the area an appropriate and acceptable management measures have been proposed based on the findings of this study result.

With this background, this study was conducted with the following general objective:

To Assess and address the challenges posed by soil erosion and sedimentation in the Aguat Wuha watershed, aiming to enhance the resilience and sustainability of the Aguat Wuha Water Dam

The following are the specific objectives of this study:

1) Identify the factors of soil erosion and sedimentation in the area.
2) Produce the spatial distribution map of soil erosion hotspot areas
3) Prepare sediment yield map in the Aguat Wuha dam site catchment
4) Evaluate the effectiveness of existing erosion control measures in the watershed.
5) Propose sustainable watershed management practices based on the assessment.

The study was conducted on the dam, Aguat Wuha, which is found in Simada woreda, South Gondar zone, Amhara region. Its focuses were on detailed assessments of soil erosion and sediment yield estimation within the watershed of the dam, particularly in relation to the construction of the Aguat Wuha Water Dam. During the study, the topographical and land use characteristics of the area were exaggerated. The work is manipulated by advanced hydrological and environmental tools such as the Revised Universal Soil Loss Equation (RUSLE) model and GIS technology for precise modeling, allowing for detailed assessment of soil erosion risk factors.

Conducting soil erosion and sediment yield assessment using GIS and the Revised Universal Soil Loss Equation (RUSLE) model is crucial for sustainable land management and environmental conservation. This integrated approach enables precise spatial analysis of erosion-prone areas by leveraging GIS's geospatial capabilities and RUSLE's empirical framework, which considers rainfall patterns, soil properties, topography, land cover, and conservation practices. By identifying high-risk zones, policymakers and land managers can implement targeted soil conservation measures, reducing land degradation, maintaining agricultural productivity, and preserving water quality in watersheds. Additionally, this research supports climate change adaptation strategies by providing data-driven insights for erosion control and sustainable land-use planning.

## 2. Methods and Materials

### 2.1. Description of the Study Area

The study dam site is situated in the Simada Woreda in the northwestern part of Ethiopia, within the South Gondar Administrative Zone of the Amhara National Regional State. It is positioned approximately 205 kilometers southeast of Bahir Dar, the regional capital. The dam shares borders with the South Wollo Zone to the southwest, the Abay (Nile) river to the west (which separates it from East Gojjam Zone), and East Este, Lay Gayint, and Tach Gayint Woredas within the same Administrative Zone to the west, north, and northeast, respectively. The study area watershed covers about 16.25 km2.

The district is characterized by four distinct seasons, such as winter, spring, summer, and autumn. These different seasons experience different temperatures and rainfall patterns. The summer rainfall starts from June to August and sometimes extends to the end of September, while the spring rainfall starts from March to May. The summer rainfall is more reliable in terms of onset and in its total amount. However, the rainfall pattern of the area was irregular and high, fluctuating from year to year. Early cessation and late onset and declining trend characterized the nature of rainfall in the area. There is a strong correlation between temperature and altitude. The high land (2001-2880 meters above mean sea level) has an average annual temperature of 17.5 ℃, and it comprises about 10% of the total area. The midland (1880 - 2000 meters above mean sea level), on the other hand, has an average annual temperature of 22 ℃ by having a share of about 30% of the total area, and below 1880 meters above sea level, it has an average annual temperature of 23.4 ℃ and comprises about 60% of the district [31].

The region is physiographically defined by a variety of features, comprising hills (40 percent), plateaus/plains (20 percent), valleys (10 percent), hilly terrain (20 percent), and other landforms (10 percent). The territory is elevated between 2398 and 3290 meters above sea level; according to Gebrie & Minch (2020), roughly 11% of the area is classed as dega (highland), 42% as woinadega (midland), and 47% as kola (lowland). The region has between 1000 and 1500 mm of rainfall on average annually, along with an average temperature of roughly 23 degrees Celsius. At precisely 11°23'35'N latitude and 38°15'08'E longitude, the dam is situated at an elevation of 2303 meters above sea level.

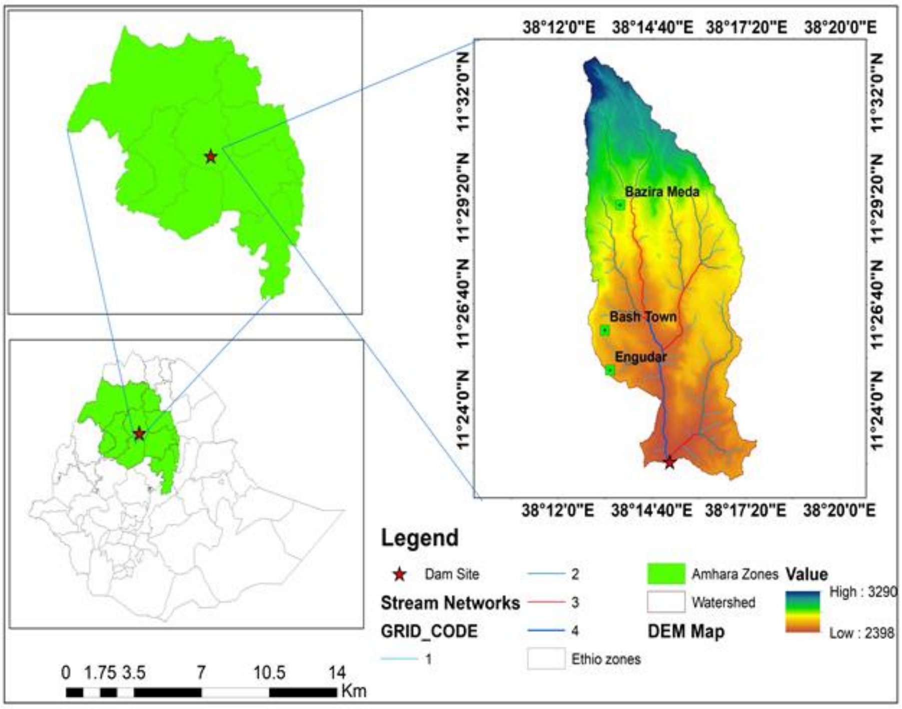


*Figure 1. Location map of the study area.*

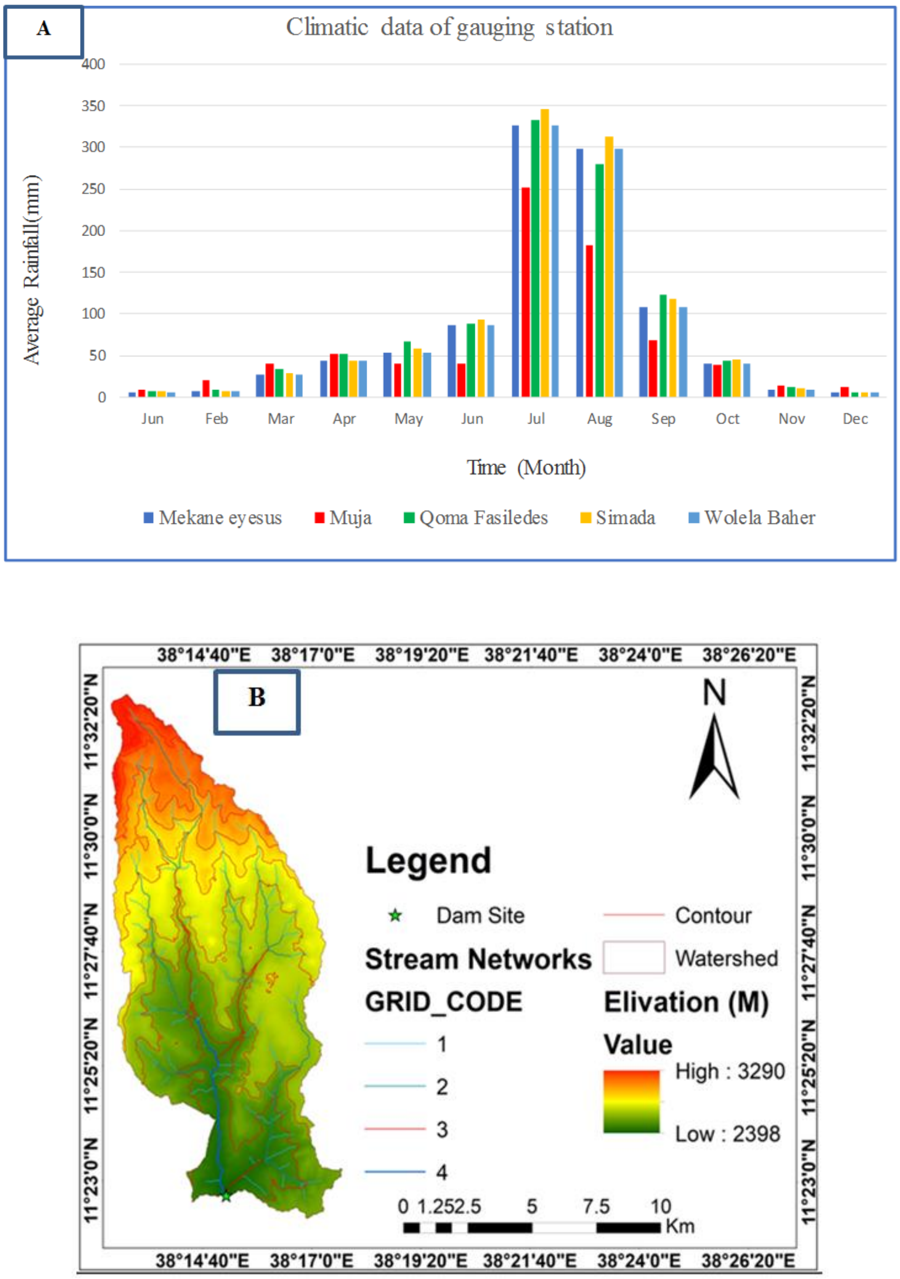


*Figure 2.* *(A) Average monthly rainfall of selected stations around the area, (B) Elevation map of the watershed.*

Vertic Cambisol, Eutric cambisol, and Pellicisol are the predominant soil types in the research region, according to data from the Ministry of Water, Irrigation, and Energy (MWIE). These soil types are found within the catchment. High clay concentration and distinctive shrink-swell behavior where the soil expands and contracts in response to variations in moisture content are characteristics of Vertic Cambisol. Usually, these soils grow in areas where the seasons alternate between being wet and dry. However, the surface layer of Pellicisols is rich in organic materials. This layer forms in moist or marshy areas when decomposing plant and animal material accumulates. The Eutric cambisols are characterized by a very shallow profile with sandy and loamy texture and are usually formed in areas of sloping areas. This condition makes the soil highly susceptible to erosion problems than the two predefined soil types, especially during the condition of rainfall [32-34].

The land use land cover map for this study was created using satellite imagery from the Copernicus Sentinel 2A satellite, and the analysis was conducted using ArcGIS 10.8. The map delineates four primary land-use categories, namely sparsely vegetated land, bare land, agricultural land, shrub land, and built area, as illustrated in Figure 9B. And agricultural land represents the predominant land cover type in the area.

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*Geological Settings of the Study Area*

Northwestern Ethiopia is characterized by folded and foliated basement rocks, which are part of the Arabian-Nubian Shield. This basement is overlain by a thick sub-horizontal alternation of continental sandstones and marine sediments, such as limestones and shales, deposited between the Triassic and Cretaceous periods and separated by a regional unconformity. During the Eocene and Late Oligocene, the region experienced intense magmatic activity, leading to the emplacement of continental flood basalts, also known as the Trap series. The magmatic activity in the Eocene was predominantly centered in southern Ethiopia but gradually shifted northward during the Oligocene and Early Miocene [35]. The lithological units consisted in the study area are upper basalts and trachyte, aphanitic fine-grained basalts, pyric basalts, horizontally stratified basalts and lower lava flows. In some parts of the area stratified flood basalts, intercalated with scoria flows and trachyte basalt rocks in the study area.

The lineament Density map of the study area was prepared from DEM image of 12.5meter resolution. The extracted lineaments changed into lineament density map with the use of spatial analysis tool of line density function in ArcGIS environment. It is a geological structure that can control stability of slope, may be faults, joints, lineaments. The geological structure can reduce the strength of slope material when it acts as a conduit for fluids through it. Lineament reflects invisible structure of the rock basement, that can be identified as a line of landscape.

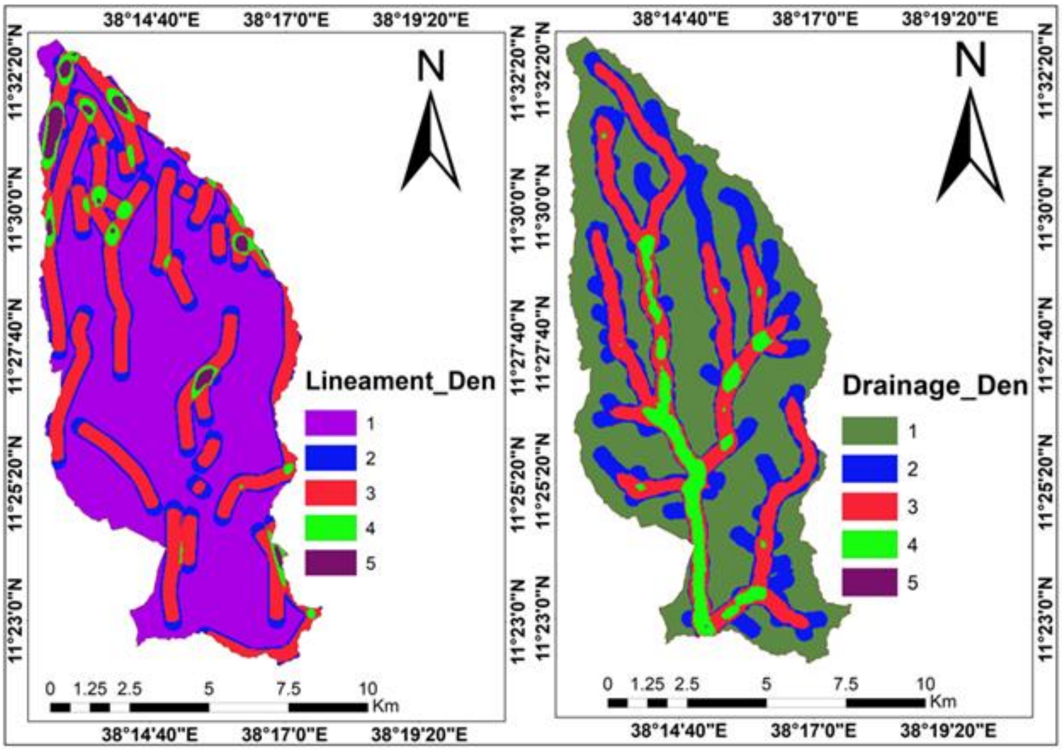


***Figure 3.*** *Lineament density (A) and Drainage density (B) map.*

It is the total length of all stream channels in a given area. It is usually used for giving the quantitative representation of the extent of development of drainage. The drainage density depends on factors such as geology, topography, climate, and land use. Areas of high relief and steep slopes with highly permeable rock or soil will have higher drainage. Density On the other hand, areas with generally low relief, gentle slopes, and impermeable surfaces have lower drainage density. The relation between drainage density and landslides is intricate, probably under the control of topography, geology, climate, and human activities. However, there are some general patterns and observations: Areas of high drainage density are characterized by a dense network of streams and rivers. These areas. More often exhibit high water flow rates and runoff subsequent to rainfall events. The increased water flow can lead to erosion and slope destabilization, therefore potentially increasing landslide susceptibility; Steep Slopes: Areas with steep slopes tend to have high drainage density. Steeper slopes would increase the concentration of runoff water, thus leading to increased erosive forces on the slopes.

## 2.2. Research Methodology

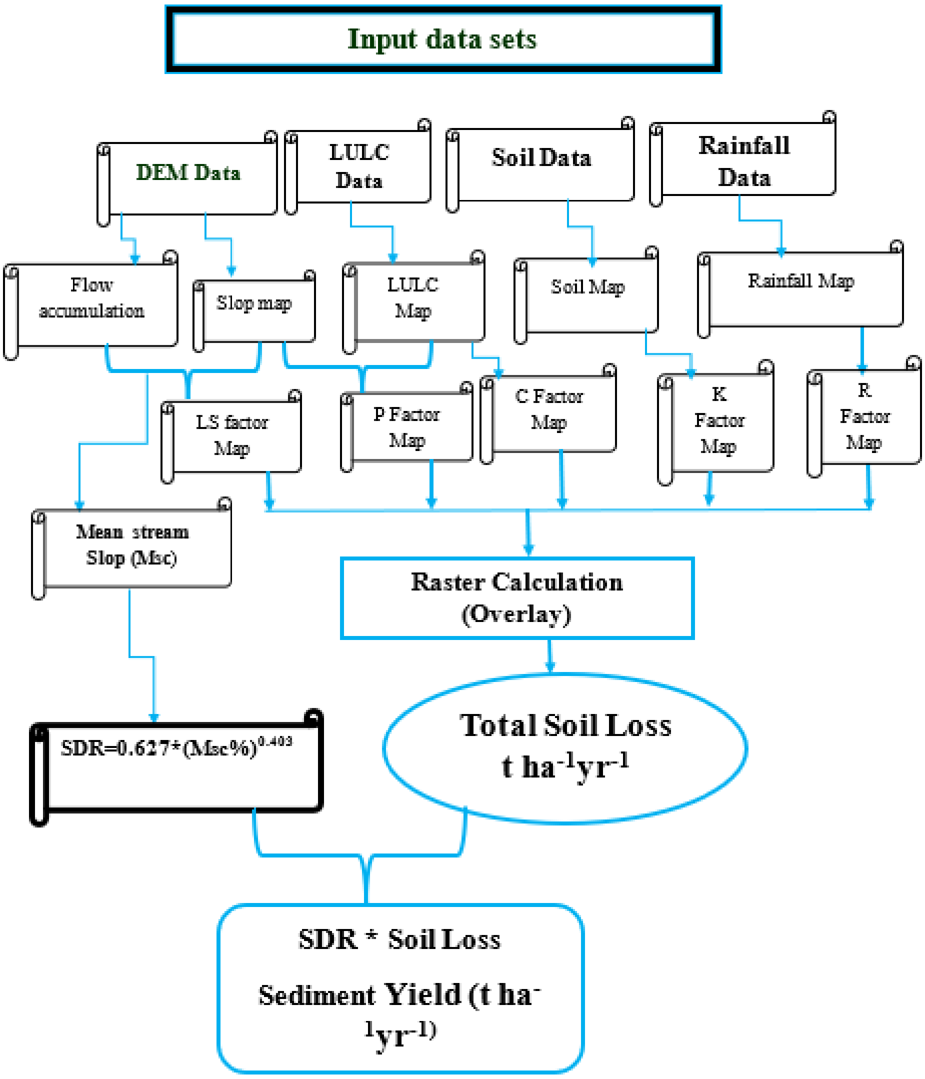


***Figure 4.*** *General methodological framework or flow chart.*

*Sources of Data and Data Types*

To achieve the objectives outlined in the introduction section, several key data types and methodologies have been essential. Soil data, which included parameters such as texture, organic matter content, and infiltration rates, has been critical for understanding soil erosion processes. The primary data (data collected from the field) and secondary data (from different organizations, freely available remote sensing data, and different literature) were collected. Rainfall data, encompassing both temporal and spatial variations, has been indispensable for assessing erosive forces and modeling sediment yield. Land use and land cover data have been pivotal in identifying anthropogenic factors influencing erosion, while Digital Elevation Model (DEM) data has aided in characterizing the topographical features affecting runoff and soil movement.

The methodology has involved integrating the Revised Universal Soil Loss Equation (RUSLE) model with GIS technology to achieve precise modeling of soil erosion and sediment yield. This has entailed the spatial analysis of soil, rainfall, land use, and DEM data within a GIS framework. For this research, a Sentinel-2A level-c satellite image with a 10-meter resolution was obtained from the Copernicus Hub Alaska satellite (https://search.asf.alaska.edu/) to create a thematic layer map for land use and land cover. Additionally, a 12.5-meter resolution ALOS PALSAR DEM was acquired from the same source for preparing thematic layer maps related to slope, drainage density, and elevation. To generate a rainfall map for the study area, CHIRPS data was downloaded from https://data.chc.ucsb.edu/products/chirps-2.0. In general, to achieve the objectives of this study, data collection was conducted in three stages.

The first stage involved pre-fieldwork data collection, which included a literature review of both published and unpublished papers. Additionally, a 10-meter resolution Sentinel-2 satellite image was downloaded from the Copernicus Open Access Hub, and rainfall data were gathered from both the Ethiopian Meteorological Agency and Open Power Access Climate Data. The second stage took place during fieldwork, where activities included identifying and recording soil erosion hotspot areas, assessing slope materials and causative factors such as slope steepness in actively eroding areas, and examining human activities like farming practices and terracing. In the final stage, after completing the field investigation, the collected data were systematically processed and analyzed using Microsoft Word, Microsoft Excel, and GIS software.

#### 2.2.1. Precipitation Data

For the precipitation data, the five actively recorded meteorological stations have been selected and used for the study, which are located around the study dam site area. And then the rainfall data were obtained from the National Meteorological Agency (NMA) of Ethiopia and NASA power for selected representative rainfall stations in the study area, namely Mekane Eyesus, Muja, Qoma Fasiledes, Simada, and Wala Baher stations. The data collected spanned a period of 30 years from 1993 to 2022 and consisted of daily recorded rainfall measurements from each meteorological station. Table 1, *below* provides details on the locations of these stations along with their respective average rainfall values.

***Table 1.*** *Rain gauge stations with respective annual average rainfall (mm).*

| | Location | | Altitude (m) | Ave.annual rainfall (mm) |
|---|---|---|---|---|
| | Latitude (N) | Longitude (E) | | |
| Koma fasiledes | 11.18 | 38.06 | 2366 | 1056.84 |
| Mekane eyesus | 11.58 | 37.90 | 2430 | 1014.13 |
| Muja | 12.01 | 39.29 | 2744 | 856.05 |
| Simada | 11.30 | 38.18 | 2548 | 1079.19 |
| Walala baher | 11.56 | 38.22 | 2404 | 1014.31 |

#### 2.2.2. Soil Data

There are three main types of soil in the research region that have a big impact on how the soil behaves in terms of how it responds to erosion and deposits silt in the dam. Data from extensive field surveys and statistics from Ethiopia's Ministry of Agriculture were used to generate a map of the types of soil. As shown in Figure 6B, the study carried out in ArcGIS 10.8 revealed three primary soil types: Pellic Verticsols, Eutric cambisols and Vertic Cambisols. These soil types are important because they influence how the soil reacts to sediment buildup inside the dam and erosion processes.

#### 2.2.3. Digital Elevation Model (DEM)

Digital elevation models (DEMs) are virtual files containing point elevation records that may be freely downloaded from the internet. These datasets include x and y grid coordinates at the side of the point elevation, or z values. DEMs are raster datasets created in numerous approaches to aid one-of-a-kind map resolutions or scales [36]. They are a not unusual supply of virtual elevation statistics and play an essential role in watershed characterization [36, 37]. Numerous corporations provide DEM information at resolutions of 200, 90, 30, 12.5, and 10 meters. For this particular examine, a resolution of 12.5 by means of 12.5 meters is used. These factor elevation data are surprisingly treasured as inputs to GIS, allowing the generation of crucial spinoff products consisting of slope, float accumulation, and drift direction that are crucial for watershed delineation. In the case of this have a look at, DEM data turned into applied to delineate the watershed and to generate key RUSLE elements, including the LS and P-factors.

The ArcGIS interface was used to define the watersheds around the dam using data from the digital elevation model (DEM). The DEM dataset has a spatial resolution of 12.5 meters and was retrieved from https://search.asf.alaska.edu/. This DEM was used to extract topographic information necessary for the watershed study. It is georeferenced and aligned to the Ethiopian projected coordinate system parameters, WGS_1984_UTM_ZONE 37N (UTM Zone 37 North). Since the DEM's initial geographic scope was greater than that of the particular watershed being modeled, a masking approach was used to narrow the study to concentrate only on the catchment region of interest.

### 2.2.4. Land Use Land Cover (LU/LC)

The Copernicus Sentinel 2A satellite image of, columns 66148 and row 88695, acquired on 10, April 2024 was used to classify the current land use and land cover map of the study watershed of the dam.

*Table 2. Satellite image used for the study.*

| Imagery type | Date of Acquisition | column | Raw | Resolution | Image format |
|---|---|---|---|---|---|
| Sentinel 2A | 01/04/2024 | 66148 | 88695 | 10m | TIFF |

*Table 3. Summary of data types, sources, description and the purpose of the data.*

| Type of data | Source | Description | Purpose |
|---|---|---|---|
| Rainfall data | Obtained from EMA, NASA power and CHIRPS | 30 years data from five rain fall stations near the study area (1993-2022) | To extract R-factor |
| Soil data | Gathering data from (WALRIS) | Water and Land Resource Information System (WALRIS) Ethiopia and Ethiopian Ministry of Agriculture | To extract K-factor |
| Land use land cover data | Copernicus Sentinel 2A satellite image | 2022 land use land cover map | To extract C-factor Map |
| DEM data | Downloaded ALSOPLASAR data from (https://search.asf.alaska.ed u/) | 12.5 m resolution | Watershed delineation, slope map generation and LS- factor generation |
| Land use practice information | Natural resource responsible bodies in the study area | | To extract P-factor |

## 2.3. Methods of Data Processing Analysis

The data analysis and interpretation were carried out in the ArcGIS software by using the following methods and equations:

1) Revised Universal Soil Loss Equation (RUSLE)
2) Sediment Delivery Ratio (SDR) method

To develop the average soil loss map and sediment delivery ratio map, thematic layers of (soil type, slope, land use/land cover, rainfall), elevation and hydrological maps were prepared from the soil map, 12.5m DEM, satellite image analysis, meteorological rainfall data, field survey data, Google Earth imagery analysis, and from the total collected data. The sediment yield estimation map was generated from the early prepared average annual soil loss map and sediment delivery ratio, were conducted by raster calculation of the two thematic map layers in the spatial analysis toolbar of the ArcGIS software.

### 2.3.1. Checking Consistency of Data

The consistency of rainfall data was assessed by the method of double mass curve analysis. A plot of accumulated rainfall data at a station of interest against the accumulated average at the surrounding stations was generally used to check consistency of rainfall data. Therefore, for this study, each of the station was checked for consistency of the rainfall series by using a double mass curve.

### 2.3.2. Filling of Missing Data

Recording precipitation data accurately is an important issue in hydrological tasks and modeling, but different difficulties lead to improper recording of rainfall measurements in the stations. These difficulties include logistical necessities preventing regular station visits, destruction of recording instruments, or physical/electrical failures that can lead to missing data in precipitation records. To resolve these gaps, missing precipitation data at a station can be estimated using observations from available stations in the study area. A Variety of techniques are available for evaluating missing rainfall records, such as the arithmetic mean method, the normal ratio method, and the inverse distance weighting method.

### 2.3.3. Model Input Map Preparation

Each RUSLE model component, rainfall Erosivity, soil erodibility, slope length and steepness, cover and management, and erosion support practices was examined separately in the context of RUSLE and GIS parameterization by developing distinct thematic layers within a GIS framework on a cell-by-cell basis [38]. In order to do this, GIS layers were created, with each cell representing a unique value or property of a certain RUSLE factor, such as the kind of soil for erodibility or the intensity of rainfall for Erosivity. A thorough evaluation of the possibility of soil erosion across landscapes was made possible by GIS by dissecting the model into these thematic layers and assessing them spatially.

### 2.3.4. Rainfall Erosivity (R) Factor

Rainfall is a significant factor influencing soil erosion and sedimentation, contributing to various forms of water erosion like splash erosion, sheet erosion, rill erosion, and gully erosion caused by water flow. Soil particles are detached and transported by water flow due to the impact of rainfall. Hence, the potential for erosion can be assessed based on the intensity of rainfall and the duration of storms [39]. The R-factor quantitatively represents the erosive power of local average annual precipitation and runoff that contributes to soil erosion [40]. It is about quantifying the erosive impact of a particular rainfall. RUSLE and its precursor, USLE, were created to consider how raindrops hitting the ground and resulting overland flow affect soil erosion. Consequently, the speed of soil loss is heavily influenced by the intensity, duration, and patterns of rainfall during a storm series, as well as the rate and volume of runoff it generates. This erosion occurs because raindrops detach soil particles upon impact and contribute to runoff [41].

To calculate the R-factor for soil erosion, an erodent map (rainfall erosivity map) of the study region is essential [39]. Alternatively, this factor can be derived from rainfall kinetic energy and the 30-minute rainfall intensity, which can be obtained from measurements using an autographic recorder. In areas lacking such maps or detailed data, soil scientists have developed various empirical equations based on average annual rainfall to estimate this factor. These empirical 35 formulas were formulated and applied in different parts of the world [42].

In many regions worldwide, obtaining detailed rainfall intensity data can be challenging, particularly in developing countries where there is limited spatial coverage of pluviographic data [43]. Consequently, many studies rely from the available data, rainfall records for a longer period of time are accessible on a monthly, seasonal, and yearly basis and can thus be used to estimate the R-factor for the erosion. In this paper, the erosivity factor has been computed using the rainfall data collected from five rain gauge stations because data on rainfall kinetic energy and intensity were not available. (Mekane Eyesus, Muja, Qoma Fasiledes, Simada, and Wala Baher) located near the Aguat Wuha dam site in Ethiopia. For this purpose, the empirical formula created by Hurni (1985) was utilized to estimate R-values specific to the Ethiopian soil context, as shown in *Equation (1)*:

$$R = 0.562 \times P - 8.12 \quad (1)$$

Here, $R$ represents Erosivity Factor, and P denotes mean annual precipitation. The average annual rainfall data from these stations were used as input parameters for calculating the R-factor in the RUSLE model.

### 2.3.5. Soil Erodibility (k) Factor

The soil erodibility (K) factor reflects how prone soil is to erosion and how rainfall, runoff, and infiltration collectively influence soil loss during storms in upland areas. It considers soil properties that affect soil loss during these events [44]. The erodibility of a specific soil is determined by its texture, organic matter content, structure, and permeability. These factors collectively influence how susceptible the soil is to erosion and its ability to withstand the impact of rainfall and runoff [44]. However, soil data in Ethiopia often lacks detailed information about these soil parameters [42]. To assign K-factor values based on soil color in the study area, a qualitative index of soil color adapted by Kaltenrieder (2007) was employed. This index links soil color, believed to reflect soil properties, to specific K-factor values. The recommended K-factor values corresponding to recognized soil colors (black, brown, red, yellow, grey, and white) are 0.15, 0.2, 0.25, 0.3, 0.35, and 0.4, respectively, in sequential order.

After modifying the attribute table of the clipped soil map by adding K-factor values, the data was converted into a raster format with a grid cell size of 30 x 30 meters resolution using the spatial analysis tool of ArcGIS 10.8. This transformation was done to generate the erodibility factor map.

### 2.3.6. LS-Factor estimation

Slope magnitude and decline are the main essentials in soil erosion calculations, which originated from a Digital Elevation Model (DEM) [45]. The LS stuff, depicting soil erodibility, is being impacted by the combined impacts of slope extent and steepness compared to a standard plot. This stuff mirrors how topography, particularly the extent and steepness of hillslopes, induces soil erosion, with steeper and longer slopes contributing to upper LS values. To make a topographic grid, a filled DEM is needed, which includes spotting and fixing cavities (holes) in elevation by increasing their values to coordinate with the bordering terrain. The incline steepness and extent are then calculated from the DEM and utilized to compute the topographical factor grid. The joint factor, identified as the LS factor, lets out the relation of soil loss from a field's slope extent and steepness to a standard extent of 22.1 meters and a steepness of 9%. This relation determines how the current slope features (length and steepness) of a field equate to the standard conditions, impacting the speed of soil erosion. A larger LS factor points to heightened vulnerability to erosion because of longer or steeper slopes compared to the standard reference slope. This factor helps in appreciating and forecasting erosion speeds according to specific topographic conditions relative to a regulated benchmark [39, 46].

For this research, the LS-factor was calculated using a 12.5-m resolution digital elevation model (DEM) brought from Copernicus for the study location. Utilizing ArcGIS spatial analysis tools, an incline raster layer was produced to stand for terrain steepness, while recreation direction and flow accumulation maps were derived from the filled DEM using Arc Hydro tools inside the ArcGIS extension. This fill operation corrected DEM depressions to guarantee precise flow calculations. These flow-combined maps are vital inputs for computing an LS-factor, which merges slope extent and steepness to evaluate soil erodibility according to the study location's topographic features. The use of ArcGIS tools facilitated the formation and handling of these spatial datasets, enabling supplemental analysis and modeling of soil erosion factors. To make LS-factor map, the subsequent *equation (2)* that was constructed by Mitasova [47] was used in the raster calculator of Arc GIS.

$$LS = Power\,(''flowacc'' * (cell\ size)/\,(22.1), 0.6) * pow\,(sin\,(''slope'') * 0.01745))/0.09, 1.4) \quad (2)$$

### 2.3.7. C-factor Estimation

The Land Use/Land Cover (LU/LC) factor quantifies the influence of land cover and its management practices on soil erosion and is recognized as the second most significant factor, following topography [40], in controlling soil erosion [26, 46]. The cover-management factor is used in a rough attempt to represent the impacts of cropping and other management on erosion rates. Agronomic practices and land cover condition changes are integrative variables. The temporal and spatial variation of land use and land cover is an important factor when considering soil erosion and sediment yield. Land use/cover classification maps, and normalized difference vegetation index are the most frequently adopted methods for estimating the C-value. However, the land use/cover classification map approach normally gives more accurate C-value in comparison to the NDVI method. [45]. To account for the influence of surface cover on erosion rates and spatial patterns, a Sentinel-2A satellite image with a 10-meter resolution was utilized to create a land use and land cover map of the study area. This image was acquired on April 10, 2024, from the Ethiopia Geospatial and Mapping Agency. Once the classified map was obtained, corresponding C-factor values for different land use and land cover (LU/LC) classes were assigned. These values were sourced from previous studies and matched to the appropriate LU and LC types. The C-factor map was then generated within an ArcGIS database by incorporating these values into the attribute table of the LU/LC map. Converting this map to raster format resulted in the C-factor map.

### 2.3.8. Supportive Practice (P) Factor Estimation

The practice factors of conservation quantify the impact of soil conservation techniques that lessen water runoff, boost infiltration, and hence diminish erosion rates. In the RUSLE model, the P-factor is defined as the ratio of soil loss under a particular conservation practice against soil loss under no management or cultivation conditions along the slope [39], [48]. The mechanical practices that support this include the consequences of contouring, strip cropping, or terracing (Kim, 2006). The impact of this factor relies on the particular agricultural activities conducted by the stakeholders or farmers in the region. Crucial erosion control practices, like contouring, strip cropping, and terracing, greatly decrease the erosion force of rainwater runoff and boost infiltration by reducing slope steepness and length. These methods effectively fight erosion by halting the concentration of surface runoff in channels and reducing its velocity of flow. A variety of management practices illustrate varying levels of effectiveness in erosion reduction. In this context, researchers have endeavored to assess the effectiveness of common physical management practices, such as contouring solely and in conjunction with terracing.

## 2.4. Applicability of the RUSLE Model

The RUSLE modeling technique is well known and broadly available for evaluating the risk of soil erosion, with great acceptance and implementation in different contexts [49], [50]. It is a systematic tool available for predicting erosion rates over large areas and estimating sediment production, particularly in watersheds, farmlands, and pastures where runoff is influenced by rainfall exceeding infiltration levels [51]. The technique is conducted on the basis of data for climate, soil characteristics, topography, land cover, and conservation practices. And the data sets for these factors are sourced from available meteorological stations, soil surveys, topographic maps, and satellite imagery. RUSLE is specifically designed to estimate annual soil erosion caused by raindrop impact and overland flow on sloped agricultural fields and rangelands based on an equation developed by [46].

### 2.4.1. Descriptive Statistics in the RUSLE Model

The RUSLE model, an improved version of the USLE created by the United States Department of Agriculture (USDA) in 1978, was used to determine statistical significance. Because inter-rill and rill processes are influenced by a variety of factors, including land use, terrain, soil type, and climate, the RUSLE model is intended to forecast long-term average soil erosion on croplands. It provides direction for the creation of conservation plans meant to reduce erosion [52]. The U.S. Department of Agriculture (USDA) improved the technique for estimating soil erosion in 1996, going beyond test locations such as woods and pastures. This revised approach, called RUSLE, included a number of significant enhancements. The weather factor was revised, seasonal fluctuations in soil erosion factors were developed, a new technique for calculating the land use and land cover factor was devised, and the computations for slope length and gradient were refined. The improvements were made with the intention of offering more precise evaluations of soil erosion in a range of environments and settings [53].

In developing countries such as Ethiopia and others where essential erosion assessment data is often lacking, parametric models like the Universal Soil Loss Equation (USLE) and its revised versions are frequently employed to estimate annual soil loss using limited available data. These empirical equations provide a practical means to estimate soil erosion rates even when comprehensive data may be scarce, making them valuable tools for soil conservation and management in regions facing data constraints [45].

#### 2.4.2. Sediment Delivery Ratio (SDR) Analysis

The sediment delivery ratio is generally considered in a spatially aggregated manner. However, sediments are actually generated from various sources spread across the basin, each with distinct characteristics for sediment detachment, transport, and storage. Additionally, each source area has its own travel time, which is the duration taken for particles eroded from the source to be transported through the hillslope conveyance system to reach the channel network. The influence of local factors (such as sediment detachment, flow transport, and travel time) on sediment delivery processes highlights the necessity of employing a spatially distributed approach for modeling this phenomenon [54]. It's value tells the integrated capability of a catchment for storing and transporting the eroded soil [53]. It accounts for areas where sediment deposition becomes more significant as the catchment area grows. Thus, it evaluates the relative importance of sediment sources and their delivery. This assessment can be done in various aspects related to the physical features of the watershed: drainage area, slope, relief-length ratio, runoff and rainfall factors, land use and land cover, and sediment particle size [39].

The SDR of basins is influenced by topographic features. More sediment is supplied by landscapes with short, steep slopes than by long, fat slopes. Beside to this, the pace of sediment delivery to the watershed mouth is also influenced by the amount of floodplain sedimentation that is taking place and the existence of hydrologically controlled places like small ponds, reservoirs, lakes, and wetlands [20].

For this study, it has used SDR as calculated using the watershed's stream channel slopes by the equation,

$$\mathrm{SDR} = 0.627\ \mathrm{Msc\%}\ 0.403 \tag{3}$$

where Msc is the main stream channel slope expressed in percentage as suggested by [55]. The stream with the highest stream order is known as the mainstream. [53] proposed that the slope of the mainstream is determined by the stream profile and may be expressed as the elevation difference between the two mainstream end points divided by the horizontal distance along the mainstream channel. Where sediment data is insufficient, the estimation of SDR using steam channel slopes yields a realistic value for the watershed. Using an ArcGIS, the slope of the stream channels was produced using the DEM.

### 2.5. Materials Used

To effectuate the objective of this research, the following materials, software's and, equipment's were used, such as:

Global Positioning System (GPS), ArcGIS, Google earth software, Satellite image, Compass clinometer, computer (Pc), Excel sheet.

## 3. Results and Discussions

The evaluations of the RUSLE model parameters for the soil erosion and sedimentation yield estimation processes were performed by using early stated and well accepted hydrological formulas and equations. The generations of the parameters were employed after the available and necessary input datasets were obtained from the applicable and provided sources. This was done by the implementation of hydrological processes and steps.

### 3.1. Erosivity (R) - Factor

A characteristic of rainfall called the rainfall erosivity (R-factor) allows one to calculate how likely it is to produce erosion under specific conditions. Following the acquisition of each selected metrological station's mean 30-year rainfall data, ArcGIS 10.8 was used for interpolation. To turn this dispersed collection of point data into an approximated surface. Variation in rainfall erosivity was noted as a result of changes in the mean annual rainfall amount within the study area.

***Table 4.*** *Average annual Rainfall and the corresponding R- factor value.*

| Station | Precipitation (mm) | R-factor @gauge station |
|---|---|---|
| Koma fasiledes | 1056.84 | 585.86 |
| Mekane Eyesus | 1014.13 | 560.90 |

| Station | Precipitation (mm) | R-factor @gauge station |
|---|---|---|
| Muja | 856.05 | 472.79 |
| Simada | 1079.19 | 598.05 |
| Walala Baher | 1014.31 | 561.94 |

The rainfall erosivity values, thus, varied from 567.77 MJ mm ha-1 hr-1 yr-1 to 579.23 MJ mm ha-1 hr-1 yr-1 based on the mean annual rainfall of the chosen rainfall stations. Following this, the area has strong rainfall erosivity around the upper top parts of the watershed of the dam site and a relativly decreased rosivity factor in the lower portion of the watershed area of the dam.

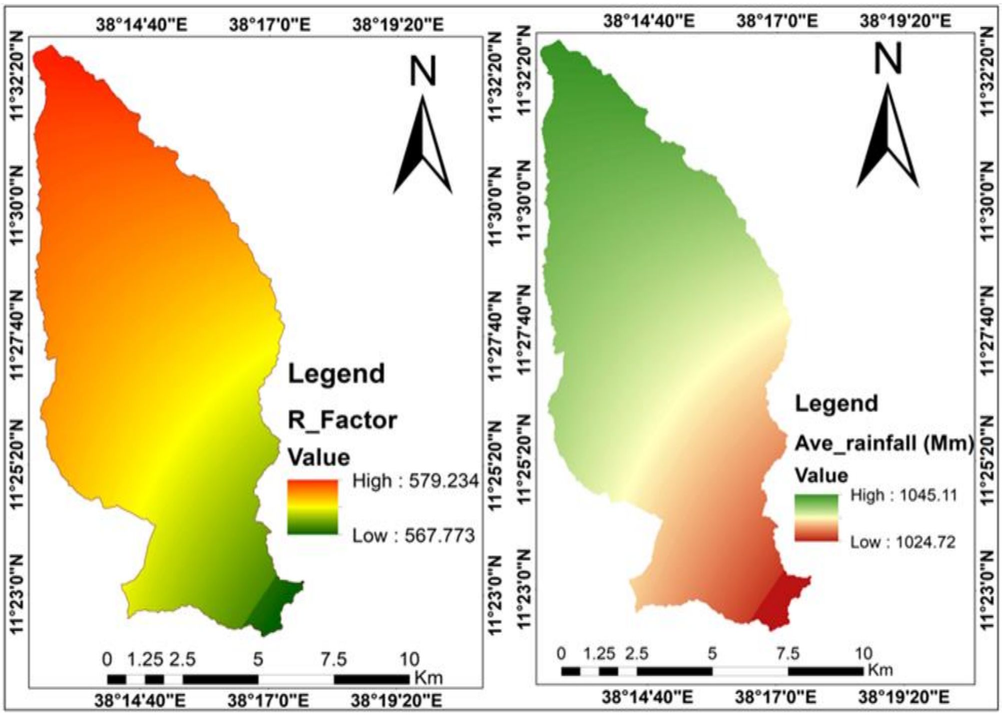


***Figure 5.*** *Erosivity (R) factor (A) and average rainfall map (B).*

## 3.2. Soil Erodablity (K) Factor

Soil erodibility, also known as the soil erodibility factor (K), is correlated with the combined impact of runoff, infiltration, and rainfall on soil loss. In RUSLE, the soil erodibility factor (K) takes into consideration how soil qualities affect soil loss in upland locations during storm occurrences. The approach of assigning K-factor values based on soil color is supported by [56] and others, who suggest experiment-based calibration to determine suitable K-factor values for Ethiopian soil conditions [20, 42, 57].

***Table 5.*** *Soil color and respective k-factor values (K. Hurni et al., 2015; MoA, 2016).*

| Soil color | Black | Brown | Grey | Red | Yellow | White |
|---|---|---|---|---|---|---|
| K-factor values | 0.15 | 0.2 | 0.25 | 0.25 | 0.35 | 0.4 |

The study area is predominantly covered by three major soil types, colored yellow, brown, and red, with cross-pond K-component values of 0.35, 0.2, and 0.25, respectively, based on the provided soil color-K-factor dating. Brown soil commonly carries organic matter and also oxidation of iron, which makes the soil have a good fertility character. The soil, which is composed of organic matter, can resist erosion under the condition that the ground has good vegetation cover by stabilizing the soil roots the ground cover. Beside these well-aggregated brown-colored soils having better ability to infiltrate in the ground, which reduces the erosion risk. Even though the soil may become susceptible to erosion due to the removal of vegetation cover from the area and when the area is steeply slop. On the other hand, red soil commonly carries iron oxide and clay minerals, suggesting proper structural balance but nonetheless susceptible to erosion, mainly underneath situations of limited natural be counted or floor cover.

Around 43.29% of the entire area is covered by the predominant vertice cambisol on the central areas of the dam, 33.28% of the upper top region of the watershed is covered with Eutric cambisols, and the remaining 23.39% of the entire base area of the dam is covered by Pellic verticsols. The soil is more susceptible to erosion when the K-factor value is closer to 1, and it has a higher capacity to withstand erosion when the K-factor value is closer to 0. The K-factor values of the existing soils in the research area were changed, ranging from 0.2 to 0.35 t hr MJ-1 mm-1 in terms of their erodibility features. The soil area covered around 33.28% of the study region by Eutric cambisols having erosivity values of 0.35, while the Pellic soils, which cover 23.39% of the area, account for a medium to high value of 0.25 erosivity, and the soil area of 43.29% by Vertic cambisols having erosivity values of 0.2 *(*Tables 6 and 7*)*.

This better K-aspect implies reduced infiltration potential and elevated ability for surface runoff and soil loss at some point of severe rainfall activities. While the brown-colored soils (K-factor of 0.2) are extremely much less erosive as compared to red soils, they too require interest in erosion control techniques, mainly on sloping terrain or areas at risk of heavy rainfall. While the yellow-colored Eutric cambisols are also moderately composed of organic maters and getting with iron oxides like goethite. The resulted k-factor values for these soil types are 0.35 due to the topographic and profile nature of the area, which enables the formation of these types of soils.

***Table 6****. Soil type and coverage area.*

| No | Soil type | Area ($Km^2$) | Coverage area in (%) |
|---|---|---|---|
| 1. | Vertic Cambisol | 46.83 | 43.29 % |
| 2. | Pellic verticsols | 24.86 | 23.39 % |
| 3. | Eutric cambisols | 35.36 | 33.28 % |

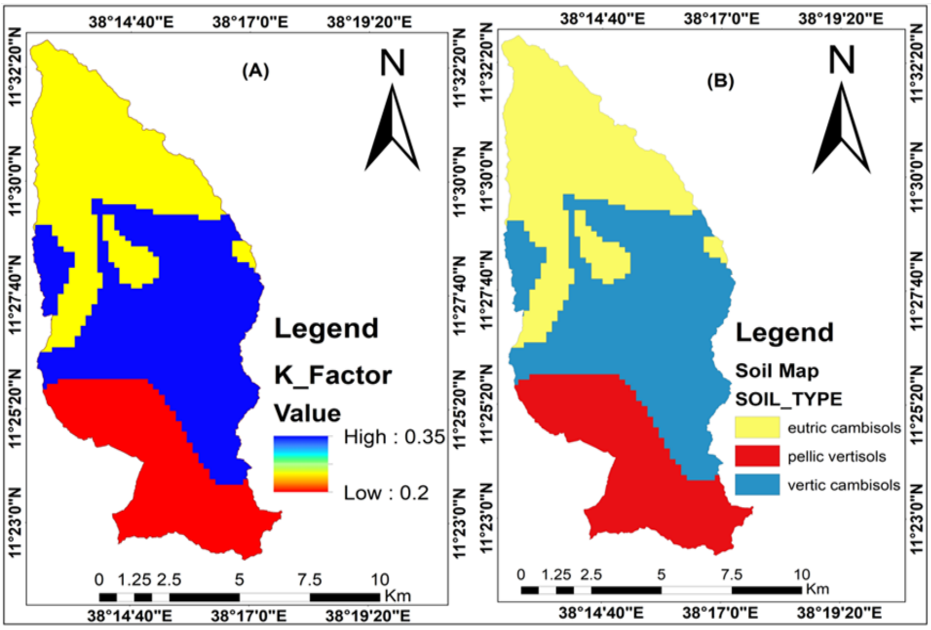


***Figure 6****. Soil erodibility (K) factor (A) and Soil type map (B).*

***Table 7****. Soil classes and provided k- factor value.*

| No | soil type | color | K- VALUE |
|---|---|---|---|
| 1 | Vertic Cambisol | brown | 0.2 |
| 2 | Pellic vertisols | red | 0.25 |
| 3 | Eutric cambisol | Yellow | 0.35 |

### 3.3. Length and Slope Steepness (LS) Factor

One of the key topographical characteristics utilized in soil erosion modeling is the LS-factor. It illustrates how the length and steepness of a slope affect the erosion process. The flow accumulation and slope in percentage were taken into account while calculating the combined LS factor value for each section.

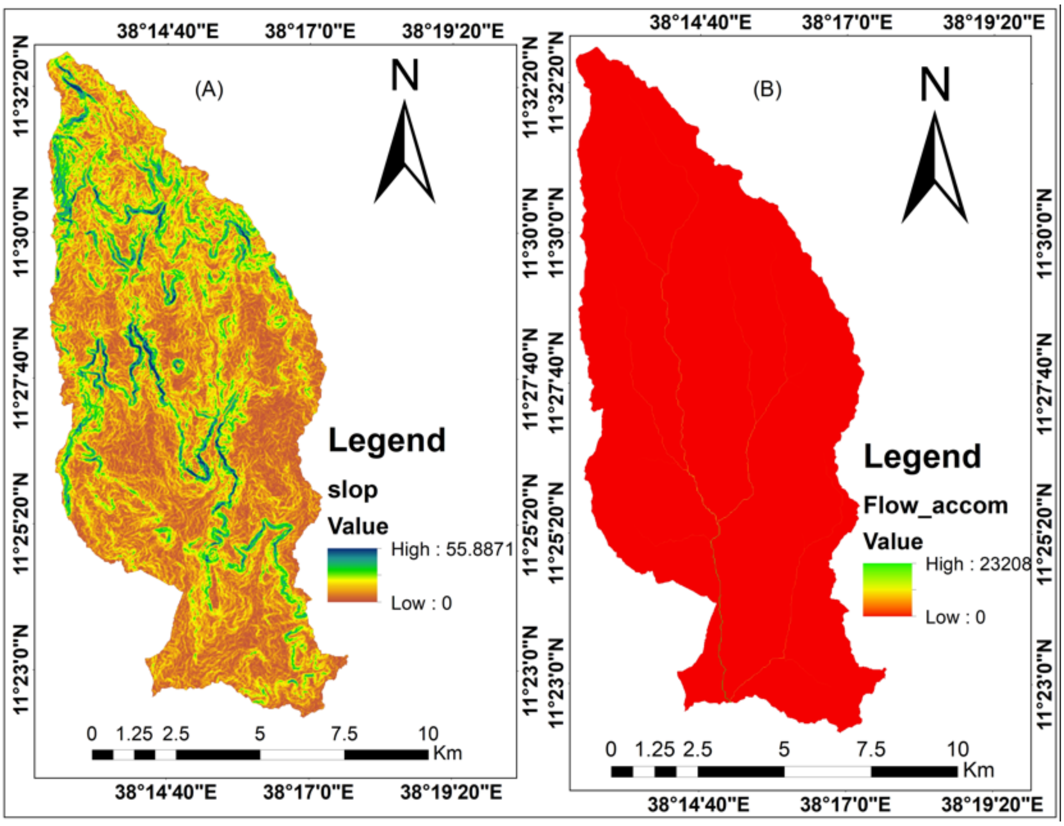


*Figure 7. Map of slop in percent (A) and Flow accumulation (B).*

For this study, the result of the Ls factor ranges from 0 (the flatter and lower part) to 36.7283 (the steeper and upper part) (Figure 7A). The majority of the study area has a comparatively lower LS-factor, which was noted to be present throughout the whole study area. In this study, around the center of the southwestern and eastern regions of the watershed of the dam were primarily found to have high LS values. This is due to the fact that the LS-factor's value increases in tandem with the slope gradient. Thus, the higher the LS-factor value, the greater the area's vulnerability to soil erosion caused by water, and vice versa.

## 3.4. The Management Practice (P)Factor

The P-factor values correspond to different conservation practices for two scenarios: one where only contouring is generally practiced, and another where both contouring and terracing are thoroughly implemented. The value of the P-factor ranges from 0.55 to 1, depending on the land management strategy currently used in the study area on various slope gradients. The maximum value is generally set to one, suggesting the absence of any soil control actions. These values are specified within a gradient range of slope expressed in percentage, as suggested by [58] in the table below.

*Table 8. Different P- factor values for slop classes.*

| Slope in Percent | P-factor Values for Contouring with Terracing | P-factor Values for Only Contouring |
|---|---|---|
| 0-7 | 0.1 | 0.55 |
| 7-11.3 | 0.12 | 0.6 |
| 11.3-17.6 | 0.16 | 0.8 |
| 17.6-26.8 | 0.18 | 0.9 |
| >26.8 | 0.2 | 1.0 |

In the study region, farming practices on steep land include the making of very bad and weak terraces that closely look like contour farming. This approach is a form of protective agriculture. On a trip to the field, it was seen that no added methods have been developed in the drainage basin. Instead, traditional protective methods, especially utilizing drainage canals, are extensively put to use in the area. that is utilized to securely drain overabundant runoff from croplands during storms. Nevertheless, the present canals were badly planned, and some have fallen short because of insufficient maintenance. Consequently, the drainage basin lacks improved and stable soil and water protection actions. Estimating P-values is tricky due to the lack of steady protective practices and disparities in the application of protective actions across various topographical positions within the drainage basin.

The results indicate that the entire other portion of the research area has lower P-factor values, while the western and centeral eastern portion of the study region has greater P-factor values. The study area's slope map (Figure 8A) illustrates that the southern, western, and eastern regions of the study area have very flat and gently slopes from 0 to 17 percent., whereas the top northern portion of the study area has steeper slopes that are greater than 17 percent. Due to the fact that slope steepness conditions have a significant impact on P-factor values, the upper portion of the research area was found to have a greater P-factor value. In this instance as well, the entire regions of the watershed area out of some top regions of the study area's had a concentration of lower P-factor, as the P-factor values are displayed in (Figure 9A). As a result, given the greater LS-factor values at the top and the middle portions of the research area, the anticipated soil erosion would be higher.

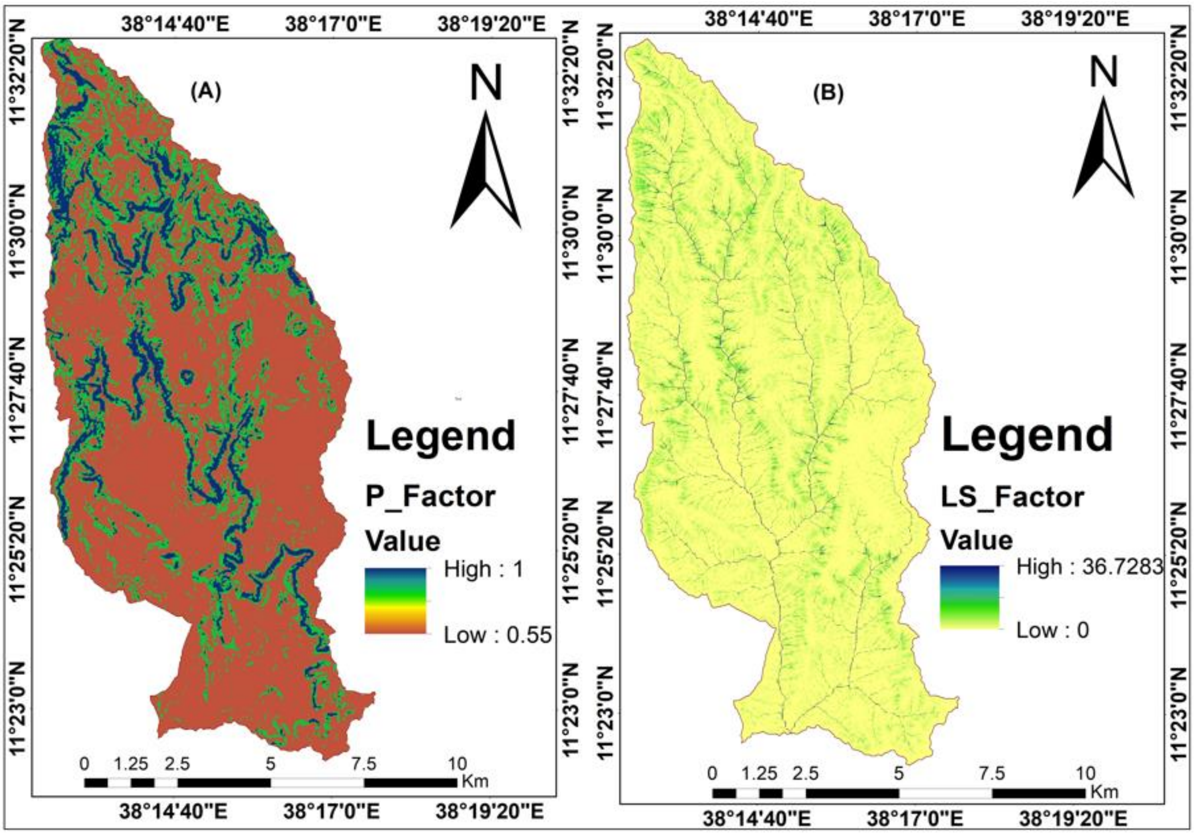


***Figure 8.*** *Management practice (P) (A) and Slop length (LS) (B) factor map.*

## 3.5. The Cover (C)Factor

The area of each LU/LC class was computed from the categorized LU/LC image and shown in Table 9. According to the computation, the area's of the watershed cover was made up of roughly 3.31% bulit area, 0.06% bare area, 1.91% shurb land, 0.60% sparse vegetated area, and 94.62% by agricultural land. These percentages corresponded to C-factor values 0.5, 0.6, 0.01, 0.05, and 0.15, respectively. From the area, around 3.37% of the region is made up of bare land and built areas that have the highest C-factor value (0.5-0.6). Because the soil in this location is exposed to the initial rainfall events without protection, it was anticipated that soil erosion would be high. (Table 9) provides a summary of the LU/LC types along with their corresponding C-factor values, as suggested by Gelagay and teferi [20, 42].

*Table 9. LU/LC types and corresponding C-factor values.*

| Land Use Land Cover Types | Area (km²) | Percent Area Coverage | C-factor Values | Sources |
|---|---|---|---|---|
| Agricultural Land | 99.98 | 94.32 | 0.15 | (Hurni, 1985) |
| Sparse vegetated | 0.64 | 0.60 | 0.05 | HURNI (1985) |
| Shrub Land | 2.03 | 1.91 | 0.01 | (Hurni, 1985) |
| Bulit area | 3.51 | 3.31 | 0.5 | (Jain & Kothyari, 2000) |
| Bare Land | 0.07 | 0.06 | 0.6 | (Hurni, 1985) |

In this region, agricultural fields adjacent to bare soil with C-factor values of 0.6 were given a maximum C-factor value of 0.15. About 94.62% of the study area's of the region is covered in agricultural land, as shown by the map (Figure 9B), with some sporadic distribution in the study area's regions. As a result, this component has a greater impact on erosion almost in all portions of the watershed. The C-factor map (Figure 9A) for the corresponding land use and land cover class makes this very evident.

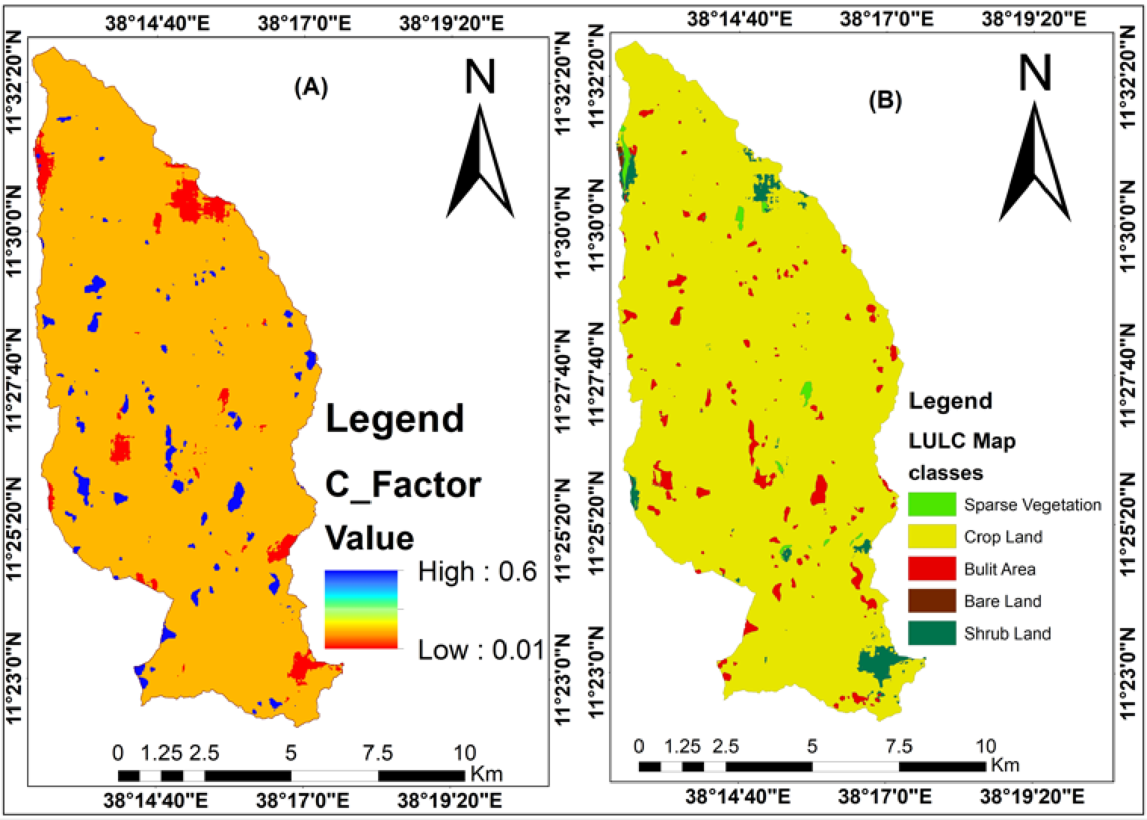


*Figure 9. C factor (A) and LULC map (B).*

## 3.6. Estimation of Annual Soil Loss of the Area by RUSLE Model

The five parameters of the RUSLE model include cover management, support practice variables, slope length and steepness, rainfall erosivity, and soil erodibility. Using the built raster calculator function tool of the ARC GIS 10.8 environment, all those parameters of the RUSLE model have been multiplied in order to estimate the average yearly soil loss in the dam's catchment. The average annual soil loss in the area is finally shown on the soil erosion map, as seen here (Figure 10). The outcome demonstrates that the Aguat Wuha Dam watershed's potential annual soil loss ranges from 0 to 431.86 t/ha/year. The watershed's soil erosion map displays areas with the greatest raster values as being highly vulnerable to soil erosion, whereas the study area with the lowest raster values is less vulnerable to soil erosion.

Renard define soil loss tolerance as the greatest amount of soil loss that can be removed from a certain plot of land without causing the soil to deteriorate [46]; this amount is estimated to be 5- 11 t ha-1 yr-1. Accordingly, the study area's center regions, which accounted for roughly 70.56% of the entire area, may be categorized as low-risk areas for soil erosion. This is due to the fact that the maximum allowable erosion limit of 11 t ha-1yr-1 was determined to be the outcome of the soil erosion rate in this location. In decreasing order, the LS-factor, R-factor, and K-factor all significantly impact the erosion process. Consequently, the lower soil loss vulnerability values were caused by the study area's centeral eastern and southeastren regions, which are known for their relatively flat and gentle slope, lower rainfall erosivity values of around 567.77 MJ ha-1hr-1yr-1, and lower K-factor values [26].

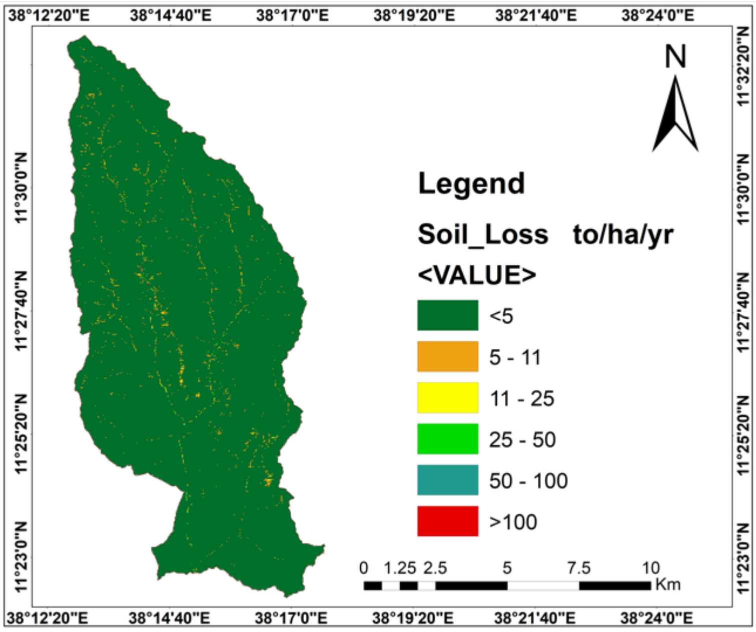


***Figure 10.*** *Annual soil loss map.*

## 3.7. Identification and Prioritization of Soil Erosion Hotspot Areas for Treatment

Based on the results, it was determined that soil erosion moderately to severely affected 39.49% (> 4203.38 ha) of the research region. According to (Table 10), there are three levels of soil erosion severity: high (11-25 t ha-1 yr-1), very high (25-50 t ha-1 yr-1), and severe (50-100 t ha-1 yr-1). Roughly 162.57 ha, or 1.53% of the entire area, were under risk of extremely severe soil erosion (>100 t ha-1yr-1). This portion of the region is primarily located in the catchment's central portion. This is because farming on steep slope lands results in greater LS-factor values of 10 to 36.72, which in turn leads to higher rainfall intensity around the designated region and a larger erosive power of rainfall (Figure 9A and 9B). For the current state of the research region, (Table 10) presents the area coverage and relative percentage of each class of soil erosion severity.

The soil erosion map of the research watershed has been used to calculate the area coverage and relative percent of each class. Finding hotspot locations for soil erosion is made easier with the use of the annual erosion map. The primary elements influencing a location's propensity for soil erosion due to rainfall are land use, land cover, slope steepness, and supportive management parameters.

***Table 10.*** *Severity class of annual soil loss and area coverage.*

| No | Annual Soil-loss class (t $ha^{-1}$ $yr^{-1}$) | Area (ha) | Area coverage (%) | Severity Class | rank |
|---|---|---|---|---|---|
| 1 | <5 | 6421.62 | 60.43 | Low | V I |
| 2 | 5-11 | 1076.44 | 10.13 | Moderate | V |

| No | Annual Soil-loss class (t $ha^{-1}$ $yr^{-1}$) | Area (ha) | Area coverage (%) | Severity Class | rank |
|---|---|---|---|---|---|
| 3 | 11-25 | 1162.02 | 10.93 | High | IV |
| 4 | 25-50 | 1096.62 | 10.31 | Very High | III |
| 5 | 50-100 | 699.17 | 6.58 | Sever | II |
| 6 | >100 | 162.57 | 1.53 | Very Sever | I |

The results of the RUSLE model and SDR assessment indicate that some areas of this Aguat Wuha Dam watershed, lying in the southern and southwestern parts, are highly susceptible to severe soil erosion and sediment yield due to steep slopes, high rainfall intensity, and erodible soils. The steep land and fine-textured soil areas of these zones are found to be more prone to sediment transport. Further, vast areas of farmland and areas with sparse vegetation cover are assigned high values of the C-factor, which effectively means no protection against erosion in the southwest part. Precipitation of high intensities falling on steep slope gradients, coupled with poor land cover, results in soil erosion whose sediment gathers at a focal point.

A high sediment yield in the southern and southwestern parts of the watershed would, therefore, constitute a serious threat to the functionality of the dam through siltation-reducing capacity in holding water for various uses over time. If left unattended, this may threaten the long-term sustainability of the dam and involve costly dredging operations. Such impacts can be mitigated through targeted conservation interventions such as reforestation, terracing, and contour farming, which are very crucial for soil stabilization and runoff reduction. Added to this, land management practices that are sustainable, especially in the agricultural zones, will contribute to maintaining soil health and minimizing erosion rates. Protection of vulnerable areas through proper watershed management and strategic land-use planning will be vital in preventing further land degradation and ensuring the long-term viability of the dam and its surrounding environment.

## 3.8. Validation of the Model with Previous Results

The estimated soil loss rate and the spatial patterns are generally realistic, compared to previous studies on some of Ethiopian basins, reserviors, and watersheds. The model's validation revealed that the ranges of soil loss were significantly correlated with estimates for the northwestern Ethiopian highlands, rseriviours and basins, the upper Beles watershed (0-503.04 tons/ha/year [59] gumara watershed (0-442.9 tons/ha/year; [60], and jabithena watershed (0-504.6 tons/ha/year [41] Various researchers employ different grades of soil loss severity based on the study's objectives and the study area's geographic setting. Consequently, the watershed's soil loss map's spatial distribution was classified based on severity classes [26], and the erosion risk map was ranked accordingly.

## 3.9. Sediment Delivery Ratio

In watersheds with steep slopes, small drainage areas, and field locations closer to the streams, sediment delivery ratios are higher than in watersheds with flat, wide valleys, large drainage areas, and fields far away from the stream channel. This is because on greater areas, the possibility of trapping soil particles increases and, correspondingly, the possibility of transported soil particles reaching water channels decreases. Thus, most of the eroded soil from the upper areas is brought into the channel and delivered to the watershed outlet [53].

The percentage of eroded sediment that enters the channel and adds to the sediment yield varies from 1.5% to 19.28%. 19.28 percent of the eroded soil particles reach the channel system and are supplied to the streams in the watershed of the dam in the upper, steeper, and closer portion of the dam site. As a result, this area of the watershed has a high capacity for transporting degraded material and a low capacity for trapping it.

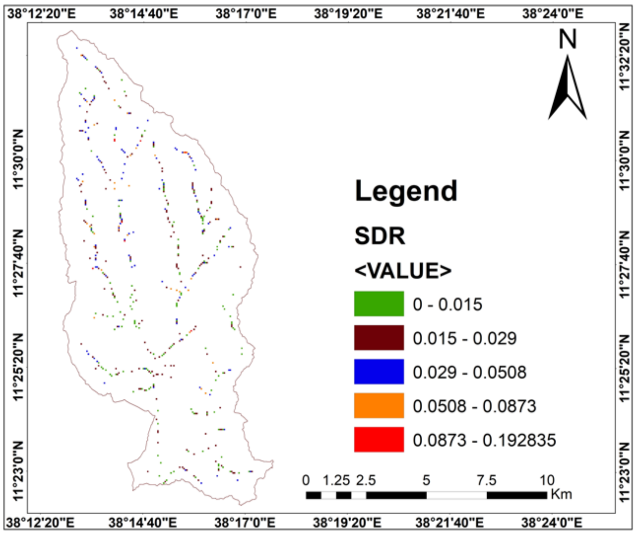


***Figure 11.*** *Sediment delivery ration map of the area.*

Since erosion happens in steeper locations, the sediment delivery ratio map (Figure 11) reflects the final nature of sediment delivery, which is that there are more options for the sediment to be delivered into the channels than to be deposited downslope. This makes the map acceptable. When the main channel slope-based equation is compared to the known watershed facts, it estimates relevant values.

### 3.10. Annual Sediment Yield of the Watershed

The SDR model based on channel slope was utilized to calculate the sediment yield. It was described as the amount of yearly soil erosion that is transported to a specific location within the watershed system from the catchments of the dam, as determined by RUSLE. The section above estimates the yearly soil loss in the Aguat Wuha Dam watershed, which was found to range from 0 to 431.86 metric tons per hectare annually. The main stream channel slope was used as the primary criterion to determine the sediment delivery ratio, and the Aguat Wuha watershed was found to have an average sediment delivery rate of 9.42 percent. Ultimately, a regionally dispersed map of sediment yield was created in the Arc GIS 10.8 environment by multiplying the raster layers. By multiplying the soil loss map (Figure 11) and the sediment delivery ratio map (Figure 12), the yearly sediment yield of the watershed was calculated.

The sediment yield (SY) of the watershed of the study dam, as shown in Figure 12, varies from 0 to 104.94 tons/ha/year, and its spatial pattern is comparable to that of the soil loss and sediment delivery ratio map.

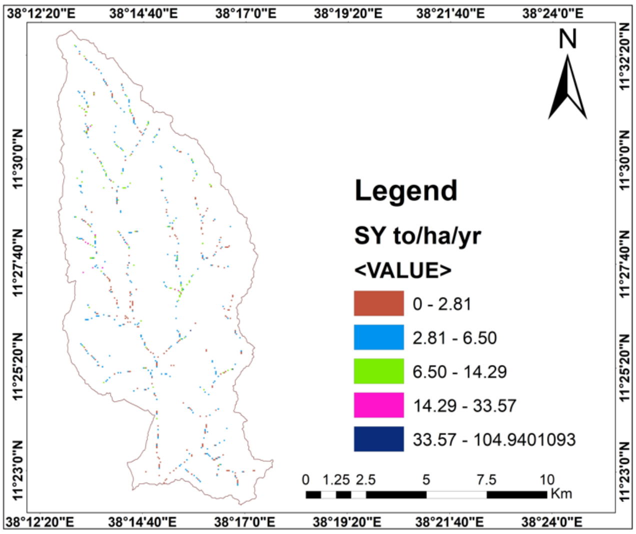


*Figure 12. Annual sediment yield of the watershed.*

#### 3.10.1. Reservoir Sedimentation Management Methods

The next section outlines the alternatives available to manage reservoir sedimentation in a sustainable way after the primary sources of sediment and the amount of sediment yield are established. In order to extend the reservoir's life, it is necessary to ascertain what management measures are viable for the research area. One of the main effects of soil erosion on outside watersheds is reservoir sedimentation, which is another indirect measure of soil erosion [61].

#### 3.10.2. Sediment Routing

It is a method of managing sediment and describes how sediment moves through or around the reservoir. Sluicing is one technique for moving sediment loads through a reservoir. All sizes of reservoirs can benefit from sluicing, although the length of the process depends on the size of the watershed and the frequency of flow floods. A somewhat large bottom outlet at the dam and the availability of surplus water are necessary for successful sluicing. The fact that considerable amounts of water must be discharged during floods in order to move sediments is a key drawback of sediment routing. It is an operational strategy that lowers the reservoir's trap efficiency by allowing a significant amount of the incoming sediment load to travel through the reservoir and dam before the sediment particles have a chance to settle [53].

To maintain enough sediment transport capacity (turbulent and colloidal) through the reservoir during the flood season, this is typically achieved by running the reservoir at a lower level. Operating the reservoir at these lower levels produces greater flow velocities and larger capacity for the transfer of silt in the water passing through the reservoir. The amount of sediment deposited is lessened by the reservoir's enhanced ability to transfer sediment by water. In order to store reasonably clear water, the reservoir's pool level is raised after the flood season. Sluicing operations' effectiveness is mostly dependent on the availability of extra runoff, sediment grain size, and reservoir morphology. Sluicing and flushing are frequently employed in tandem one with the other [62].

Another technique for managing sediment is the bypass tunnel. When sediment-laden flows are diverted before the carried sediment load is deposited inside the reservoir storage, it is referred to as a sediment by-pass for instream reservoirs. In order to implement a sediment by-pass, a weir must be built to divert flood flows, and an open channel or by-pass tunnel must be built along with the required inlet and outlet portals to allow the diverted flows to be discharged to the intended location, which is typically downstream of the reservoir [63].

Since this technique requires a huge amount s of water for effective sluicing, it needs large amount of outlet for the discharge of the water and suitable for areas of frequently characterized with flooding and depends on the shape, location and topography of the dam reservoir site, results for this method of sediment management technique are less favored and it is not well selective for this case of Aguat wuha dam reservoir.

#### 3.10.3. Sediment Deposition Removal

Second, there are mechanical methods for removing sediment deposits from reservoirs, such as hydraulic dredging or dry excavation and hydro-suction. [10]. The location of dredging may need to be frequently relocated across the reservoir, depending on the rate of silt removal. Furthermore, variations in reservoir levels can necessitate drilling in several sites. For small to medium-sized reservoirs, dredging can be done at predetermined intervals. It may also be a continuous process for certain sizable reservoirs. It doesn't offer a long-term solution to the sedimentation issue in the reservoir; rather, it is a temporary corrective remedy. Because it can remove bank deposits that flushing cannot, this approach can return storage to its maximum capacity.

In situations were raising or replacing the dam is not an option and alternative techniques (such flushing, bypass construction, and drawdown flushing) are not practical or successful, dredging is employed. Therefore, dredging to remove silt to restore lost storage capacity should only be considered a last resort because it is very costly, necessitates equipment appropriate to the site, and causes additional environmental and social issues when disposed of. Because mechanical excavation requires double handling and significant transportation costs, it is typically far more expensive than dredging. The optimal method for creating a reservoir intended to control flooding is mechanical excavation. This approach needs total depletion. Furthermore, excavation is strictly prohibited and extremely risky for hydraulic structures such as the Aguat wuha embankment dam. There are two factors to consider while using mechanical removal techniques. The first thing to keep in mind is that the disposal area's length from the reservoir should not exceed three kilometers [53]. In the event that this need is met, looking for environmental and social component is crucial. From the perspective of the river's downstream use and sediment contamination, environmental and social factors are considered. For the, Aguat wuha dam removal by mechanical excavation and dredging is not practical because of these limitations.

Kondolf Carried out that, while encouraging the use of the sediment for the reclamation of the surrounding area, the extraction of the silt using either machinery or manual labor might be a workable alternative [10]. By taking such method, the reservoir's lifespan would be extended and the restoration of devastated farmlands would be encouraged. Unfortunately, the enormous expense, technical difficulty, and environmental effects make this technology unfeasible. In contrast to mechanical excavation and dredging, a large-capacity conduit or tunnel can be built to avoid the sediment-laden flow around the reservoir, or a portion of it, when topography circumstances are favorable. If not, the economic benefit of reserving the reservoir's storage capacity would have outweighed the cost of tunnel construction by a large margin. Consequently, bypassing sediment is likewise not feasible for this case.

### 3.10.4. Sediment Deposition Control

Watershed management operations must be implemented inside the basins in order to improve land productivity and reduce water body siltation. It is not feasible to apply soil conservation measures throughout the entire basin at once due to resource constraints. It is crucial to prioritize hotspot locations according to the intensity and risks of soil erosion.
Implementing stone bunds to lessen sheet and rill erosion on hill slopes and arable land, check dams in gullies to minimize overgrazing, and livestock enclosures on steep slopes are all part of watershed management [57]. the most crucial step in reducing erosion is the establishment of initiatives for soil and water conservation. It is frequently interesting to learn how a project has been affecting the rate of sedimentation and/or movement of sediment in a reservoir if it is proposed in the watershed that contributes to the reservoir. Reducing erosion and the amount of silt entering the stream system is the goal of watershed management and soil conservation strategies. The distribution of erosion throughout the watershed and the region supplying the reservoir with an excessive amount of sediment are identified in this study. Therefore, it is necessary to apply conservation measures to these areas in order to significantly reduce the amount of silt input to the reservoir. The techniques include terracing and contour farming; no-till farming; creating trapping structures; creating grassed drainage channels; controlling gully erosion; and stabilizing important regions by reverting them to woods or grasslands.

The implementation of such conservation measures could take longer than a year. These measures also include the relative costs of different interventions to farmers and the requirement that farmers alter their typical farming practices significantly. When paired with other strategies, a small catchment can benefit from a soil and water conservation program. The watershed's susceptibility to erosion was rated according to its degree. Consequently, When the soil water conservation program is implemented with vegetation covers upstream of the reservoir, it is possible to reduce the amount of sediment flow into the reservoir in areas of the extremely severe class.

*__Table 12__. Ranks of soil erosion conservation practices.*

| Method | Cost | Technical Difficulty | Required Time | Environmental & Social Acceptance | Total Score | Acceptability Rank |
|---|---|---|---|---|---|---|
| Sediment Removal | High (1) | Medium (2) | Medium (2) | High (3) | 8 | 2 |
| Sediment Routing | Medium (2) | High (1) | Low (3) | Low (1) | 7 | 3 |

| Method | Cost | Technical Difficulty | Required Time | Environmental & Social Acceptance | Total Score | Acceptability Rank |
|---|---|---|---|---|---|---|
| Watershed Management | Low (3) | Low (3) | High (1) | High (3) | 10 | 1 |

Comparing the various sediment management techniques is necessary to address this excessive intake of sediment, which is a major practical management challenge. Costs, technical difficulties, implementation time, environmental effects, and social acceptance could be the main practical obstacles. The research indicates that, given the local conditions and the behavior of the constructed dam, the remedial approach or both mechanical sediment removal and sediment route are the least suitable options. Moreover, drying out sources is not a definitive answer to problems. In addition to being costly, sediment removal calls for a high level of expertise. Similar to this, embankment dams, modest outlet discharge capacities, and low inflow to reservoir capacity ratios restrict the usefulness of sediment routing. Furthermore, technology and skill are crucial. However, the most common corrective action to achieve approval was the preventative approach or watershed management. Afforestation, terrace construction, enclosing agriculturally degraded hillside areas, applying contemporary cropping patterns, and other relevant land management techniques are all included. Furthermore, the approach is appropriate when considering the environmental and social aspects. Without, it is not technically challenging; nonetheless, social awareness is needed. In order to maintain the storage capacity and to enhance the productivity of this nearly completed water dam of the Aguat Wuha Dam reservoir, it is thought that the soil and water conservation program for the area upstream of the reservoir, such as using trapping structures, contour plowing or farming, treading, trracing, and no till farming that is prioritized and has vegetation, is a better mitigation.

## 4. Conclusion

The Aguat Wuha watershed's annual soil loss ranges from 0 to 431.86 to/ha/year, according to the RUSLE model's results. It was discovered that the mean annual soil loss value was 19 tons/ha/year. Areas of the study watershed classified as low, moderate, high, very high, severe, and very severe soil loss classes are 6421.62 ha, 1076.44 ha, 1162.02 ha, 1096.62 ha, 699.17 ha, and 162.57 ha, respectively. Therefore, in order to maintain the sustainability of the Aguat Wuha watershed, areas with high erosion severity require immediate, high-priority soil and water intervention measures to increase the life span of the constructed dam. When compared to the information that is currently available in the watershed, the watershed map of soil erosion risk created by this study offers plausible estimates of the yearly soil loss.

Based on the main stream channel slope, the research area's sediment delivery ratio has been calculated, and it ranges from 1.5% to 19.28%. The watershed's annual range of the sediment yield from the watershed and flow into the reservoir is 0 to 153,365.3 tons. This estimate shows the extent to which the reservoir is seriously threatened by sediment yield. Reservoir sedimentation studies are necessary due to information about storage capacity reduction and the amount of time sediment would impede the reservoir's ability to function. Therefore, given the conditions of the reservoirs, applying watershed management techniques was the most effective way to lower the yield of silt. In general, effective watershed management will result in a sustained positive impact by lowering soil erosion, sediment yield, and sedimentation risk.

In general this study highlights key findings for effective dam management and erosion control, emphasizing the impact of sediment accumulation on reservoir capacity and dam efficiency, necessitating regular monitoring and controlled flushing. High erosion rates in upstream catchments contribute significantly to sediment load, requiring targeted soil conservation measures such as afforestation and terracing. Seasonal variations in river discharge influence sediment transport, making adaptive water release strategies essential for managing siltation. Structural mitigation measures, including sediment traps and check dams, can further reduce sediment inflow and protect reservoir capacity. An integrated management approach combining engineering solutions with watershed conservation is crucial for ensuring long-term sustainability and minimizing environmental impacts.

## Abbreviations

| | |
|---|---|
| AVE | Average |
| CHIRPS | Climate Hazards Group InfraRed Precipitation with Station Data |
| C | Cover Factor |
| DEM | Digital Elevation Model |
| GIS | Geographical Information System |
| GPS | Global Positioning System |
| K | Erosivity Factor |
| LS | Slop Length and Gradient Factor |
| LULC | Land use and Land Cover |
| MWIE | Minister of Water, Irrigation and Energy |
| NASA | National Aeronautics and Space Administration |
| NDVI | Normalized Difference Vegetation Index |
| NMA | National Metrological Agency |

| | |
|---|---|
| P | Management Practice Factor |
| R | Rain Fall Factor |
| RUSLE | Revised Universal Soil Loss Equation |
| SE | Gross Soil Erosion |
| USDA | United States Department of Agriculture |
| USGS | United States Geological Survey |
| WALRIS | Water and Land Resources Information System |

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**Adna Ashebir:** Conceptualization, Data curation, Formal Analysis, Methodology, Validation, Writing – original draft

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**Likinaw Mengstie:** Conceptualization, Data curation, Methodology, Software, Writing – review & editing

## Conflicts of Interest

The authors declare no conflicts of interest.

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