



Soil loss estimation and severity mapping using the RUSLE model and GIS in Megech watershed, Ethiopia



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ABSTRACT

Soil erosion is the most serious problem that affects economic development, food security, and ecosystem services, which is the main concern in Ethiopia. This study focused on quantifying soil erosion rate and severity mapping of the Megech watershed for effective planning and decision-making processes to implement protection measures. The RUSLE model integrated with ArcGIS software was used to accomplish the objectives. The six RUSLE model parameters: erosivity, erodibility, slope length and steepness, cover management, and erosion control practices were used as input parameters to compute the average annual soil loss and identify erosion hotspots in the watershed. The RUSLE estimated a total soil loss of 1,399,210 t yr⁻¹ from the watershed with a mean annual soil loss of 32.84 t ha⁻¹ yr⁻¹. The soil erosion rate varied from 0.08 to greater than 500 t ha⁻¹ yr⁻¹. A severity map with seven severity classes was created for 27 sub-watersheds: low (below 10), moderate (10–20), high (20–30), very high (30–35), severe (35–40), very severe (40–45) and extremely severe (above 45) in which the values are in ton ha⁻¹ yr⁻¹. The area coverage was 6.5%, 11.1%, 8.7%, 22%, 30.9%, 13.4%, and 7.4% for low, moderate, high, very high, severe, very severe, and extremely severe erosion classes, respectively. About 82% of the watershed was found in more than the high-risk category which reflects the need for immediate land management action. This paper could be important for decision-makers to prioritize critical erosion hotspots for comprehensive and sustainable management of the watershed.

1. Introduction

Accelerated soil erosion creates many critical problems such as environmental, and socio-economic (Abdo and Salloum, 2017; Borrelli et al., 2017; Brady and Weil, 2003; Hurni et al., 2015), land degradation, agricultural production, and food security problems (Arekhi and Ros-tamizad, 2011; Balabathina et al., 2020; Mohammed et al., 2020), intensifying climate change, increased conflict, and mass human migration (IPBES, 2018). It has been estimated that about 80–85% of agricultural land suffers from soil erosion and six billion hectares of fertile land are being lost every year due to water erosion and other land degrading factors (Comino et al., 2015; Ganasri and Ramesh, 2016; Oldeman et al., 1990; Pimentel et al., 1976). Worldwide, the soil erosion rate from cultivated land ranges from 22 to 100 t ha⁻¹ yr⁻¹ and causes a 15–30% reduction in crop productivity (Morgan, 2005). In mountainous agricultural land, annual soil loss may reach 400 t ha⁻¹ (Pimentel et al., 1995).

Sub-Saharan Africa (SSA) countries have been highly threatened by broader land degradation problems, more specifically serious erosion and crop nutrient depletion problems that abruptly disrupt sustainable agricultural production and aggravate food insecurity (FAO, 2015; Menale et al., 2007; Taye et al., 2018; Tuo et al., 2018; Zhao et al., 2019). Ethiopia, one of the SSA countries is facing severe soil degradation problems resulting in a decline in various soil functions and is the ultimate cause of an irreversible change in poorly renewable soil resources (Addis and Klik, 2015; Chakraborty et al., 2020). In the highlands of Ethiopia, erosion is at an all-time high, with 1.5 to 3.5 billion tons of fertile soil being lost each year, 45% of which is agricultural land (FAO, 1986; Hurni, 1985, 1993; Taye, 2006). In a plot-based experiment of long-term analysis of the Soil Conservation Research Programme (SCRIP), the mean annual soil loss on cultivated lands was estimated at 40 t ha⁻¹ yr⁻¹ and it ranges from 1 t ha⁻¹ yr⁻¹ to more than 300 t ha⁻¹ yr⁻¹ (Hurni et al., 2010). Severe soil erosion on farmland, which

Abbreviations: BNRB, blue Nile river basin; DEM, digital elevation model; GIS, geographic information system; HWSD, harmonized world soil database; LULC, land use land cover; RUSLE, revised universal soil loss equation; SRTM, shuttle radar topographic mission; SW, sub-watershed; SWAT, soil and water assessment tool; USGS, United States geologic survey; USLE, universal soil loss equation.

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is about 100 t ha⁻¹yr⁻¹ was also reported by Birhanu (2014) and 42 t ha⁻¹ by FAO (1986).

The Megech watershed, part of the Ethiopian highlands and the Blue Nile River Basin (BNRB), is highly affected by soil erosion due to intensive rainfall coupled with human interventions, such as the removal of vegetation cover for agricultural practices, the improper agricultural system and wrong livestock management systems (Balabathina et al., 2020; Eisenberg and Muvundja, 2020; Halefom et al., 2018; Hurni et al., 2010; Setegn et al., 2009). This high rate of soil erosion in the watershed system can increase the downstream sedimentation problem, loss of onsite crop production, water pollution in Lake Tana, and siltation of reservoirs found in the watershed. The most important domestic and irrigation water source dams; Angereb and Megech, can be possibly affected by sedimentation problems that arise from the upstream areas of the watershed. For instance, 47% of the volume of the Angereb reservoir was filled with sediments and 18% of the dam has been at high risk (Abdo and Salloum, 2017; Halefom et al., 2018).

Intensive efforts were exerted in the Ethiopian highlands to implement and expand soil and water conservation practices to counteract the increasing impact of soil degradation (Addis et al., 2016; Hurni et al., 2010). Although such a large capital and effort was exerted, the effectiveness of the installed conservation measures is still in doubt. Before applying any protection measures, pre-assessment work on targeted watersheds such as identifying the root causes of soil erosion, quantifying the magnitude of soil loss, as well as assessing erosion hotspots is some of the key points to look for options to address the issues of soil degradation (Abdo and Salloum, 2017; Addis et al., 2020; Aneseyee et al., 2020; Birhanu, 2014; Hurni et al., 2010). Implementing conservation efforts at the watershed level is impossible at once. Watershed and sub-watershed-based spatial and temporal quantification of soil erosion and identifying erosion hotspots are the first essential phases of an integrated watershed management plan to implement sustainable land management strategies and land use planning (Addis et al., 2020; Aneseyee et al., 2020; Efthimiou et al., 2014).

The most commonly used models for the spatiotemporal prediction of soil loss and severity mapping at the basin and catchment scale are the universal soil loss equation (USLE), revised universal soil loss equation (RUSLE), modified universal soil loss equation (MUSLE), water erosion prediction project (WEPP) and erosion productivity impact calculator (EPIC) (Augustine and Hudson, 2014; Morgan, 2005). The RUSLE model has been the most widely used, flexible, very simple, and less data demanded model to predict the spatial distribution of soil erosion (Ayele et al., 2020; Desalegn et al., 2018; Getnet and Mulu, 2021; Teshome et al., 2021; Tsegaye et al., 2019; Tsegaye and Bharti, 2021). The RUSLE model is the most widely applied technique because of the ability to quantify annual soil loss and its compatibility with the ArcGIS interface and remote sensing (RS) (Ketema and Dwarakish, 2021; Srinivasan et al., 2019).

Some studies related to soil erosion assessment on a basin-scale in the Lake Tana basin included the study watershed (Balabathina et al., 2020; Lemma et al., 2019; Setegn et al., 2009). However, there was no sufficient study, and/or there is a spatiotemporal limitation regarding quantifying soil loss in the Megech watershed, and sub-watershed-based hazard evaluation is not yet identified. Therefore, to undertake feasible planning and the right decision-making processes, quantifying and assessing the spatial distribution of soil erosion and developing an erosion hazard map in the Megech watershed were very crucial.

2. Materials and methods

2.1. Description of the study area

The research was carried out in the Megech watershed, located on the north side of Lake Tana sub-basin in the Amhara region, Ethiopia (Fig. 1). The Megech catchment is one of the main river basins in the upper BNRB in which its altitude ranges from 1878 to 2978 m above mean

sea level. The basin covers an area of 427 km² and is geographically located between 12.49° and 12.76° North latitude and 37.41° to 37.63° East longitude. The watershed is found in the Wogera and Gondar-Zuria districts and is characterized by a mountainous, rugged, and steep topography that varies from 0° to 68° slopes. Megech River is one of the river basins that contributes stream flow to Lake Tana and it contains several tributaries such as Angereb, Dimaza, and Keha. Two dams are constructed in the watershed; the older dam, Angereb, which is used to supply water for Gondar town, and the Megech dam, which is being constructed in the downstream watershed, will be used for both irrigation purposes and water supply to Gondar town.

The Megech watershed falls into two agroclimatic zones so-called Dega (cool sub-humid) in mountainous areas and Weyna Dega (cool-humid) in the lowlands (Hurni, 1998). The climate of the Megech watershed, generally for upper BNRB, shows tropical monsoon climate characteristics (Conway, 1997). The rainfall distribution ranges from 1510 mm in the highlands to 710 mm in the lowlands, with an average annual rainfall of about 1090 mm. Nearly 80% of the rainfall occurs from June to September. The long-term average maximum and minimum temperatures are about 27.3 °C and 13.5 °C respectively (WWDSE, 2008). The main soils in the watershed are leptosols, nitisols, luvisols, and vertisols. Rainfed agriculture in a mixed farming system with cereals, pulses, oilseeds, spices, and livestock has been practiced in the watershed (Abdo and Salloum, 2017; WWDSE, 2008).

2.2. Data sources and collection methods

To estimate rainfall-driven soil loss and identify erosion hotspots in the watershed, various datasets from different sources were used. Daily rainfall data for the period 2000–2020 were collected from 14 in/nearby weather stations (Fig. 2), which are monitored by Ethiopian National Meteorological Agency (NMA), and then the yearly rainfall total was calculated. The K factor was derived from the Harmonized World Soil Database (HWSD), a combination of regional and national soil information systems with the soil information from the FAO-UNESCO World Digital Soil Map (DSMW), (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012). Similar grid-based soil data was also obtained from the design and inspection and the Ministry of Water Resources in Ethiopia for cross-validation. A 30 × 30 m resolution Shuttle Radar Topographic Mission Digital Elevation Model (SRTM DEM) map was downloaded from the United States Geological Survey (USGS) (<https://earthexplorer.usgs.gov/>) to drive the LS factor.

The cover management factor was computed from Landsat 08 satellite imagery which was downloaded from USGS earth explorer (<https://earthexplorer.usgs.gov/>) and the support practice (P) factor was computed using the integration of land use and slope gradient parameters. Reference points taken from Google Earth and ground observations were used as a guide for appropriate land use classification and accuracy assessment. All input parameters used for the present study are depicted in Figs. 2 and 3.

2.3. Data analysis approach: RUSLE model

The RUSLE model has been a widely used, non-data-demanding and cheap predictive model for both forest and agricultural watersheds (Renard et al., 1997). This model usually uses institutional data, such as medium to low-resolution satellite images and finite rainfall data (Prasannakumar et al., 2012). The output of the RUSLE model allows soil conservationists to determine the spatial pattern of soil loss (Sardari et al., 2019). This allows us to identify the critical areas within fields or basins that are contributing major amounts of soil loss. The RUSLE model is implemented to estimate the annual soil erosion rate and hazard evaluation through the integration of the six factors; rainfall erosivity (R), soil erodibility (K), slope length (L), slope steepness (S), cover management (C) and conservation practice (P) (Bagwan and Gavali, 2021; Gayen et al., 2020; Kabir et al., 2018). The mean annual

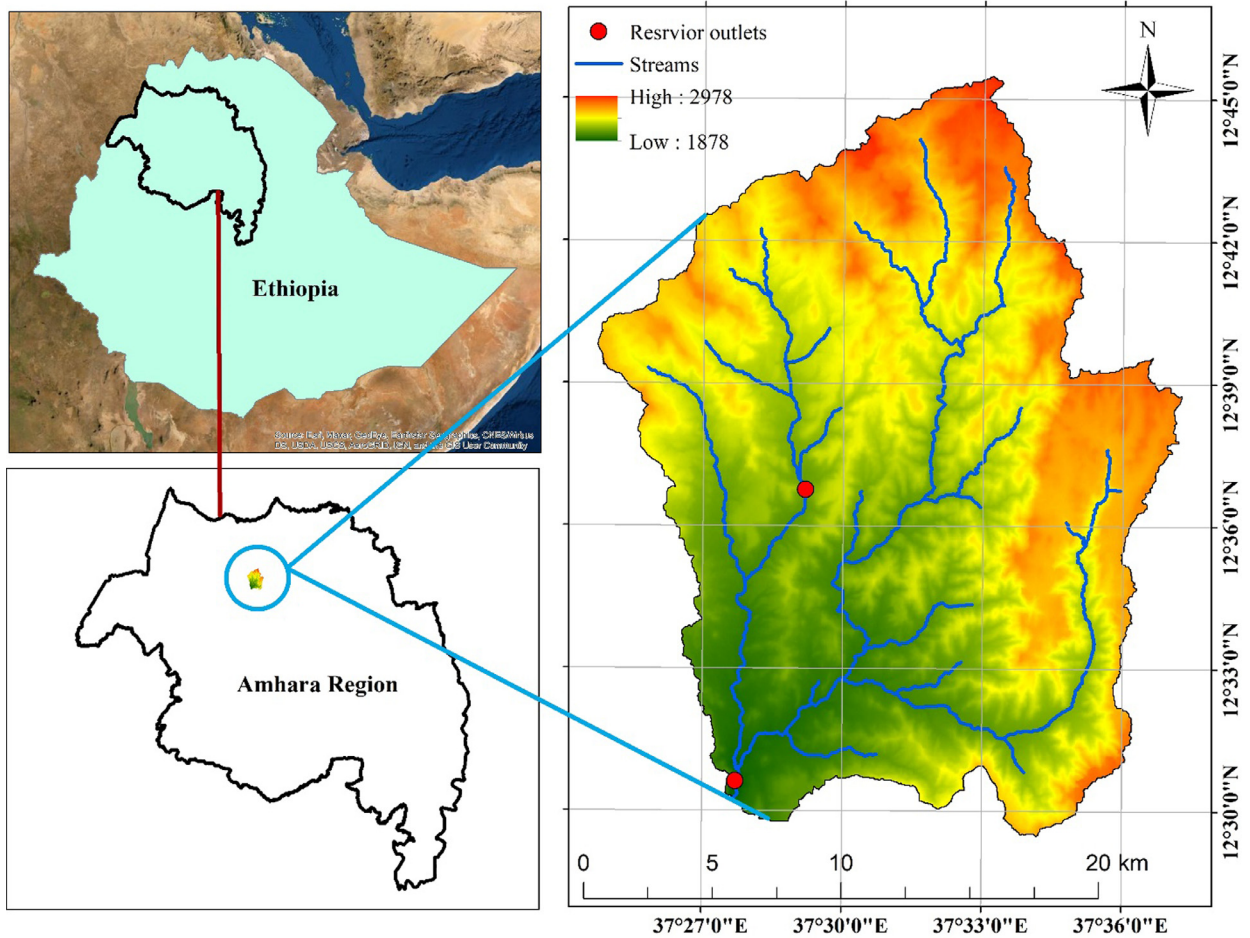


Fig. 1. Map of the Megech watershed.

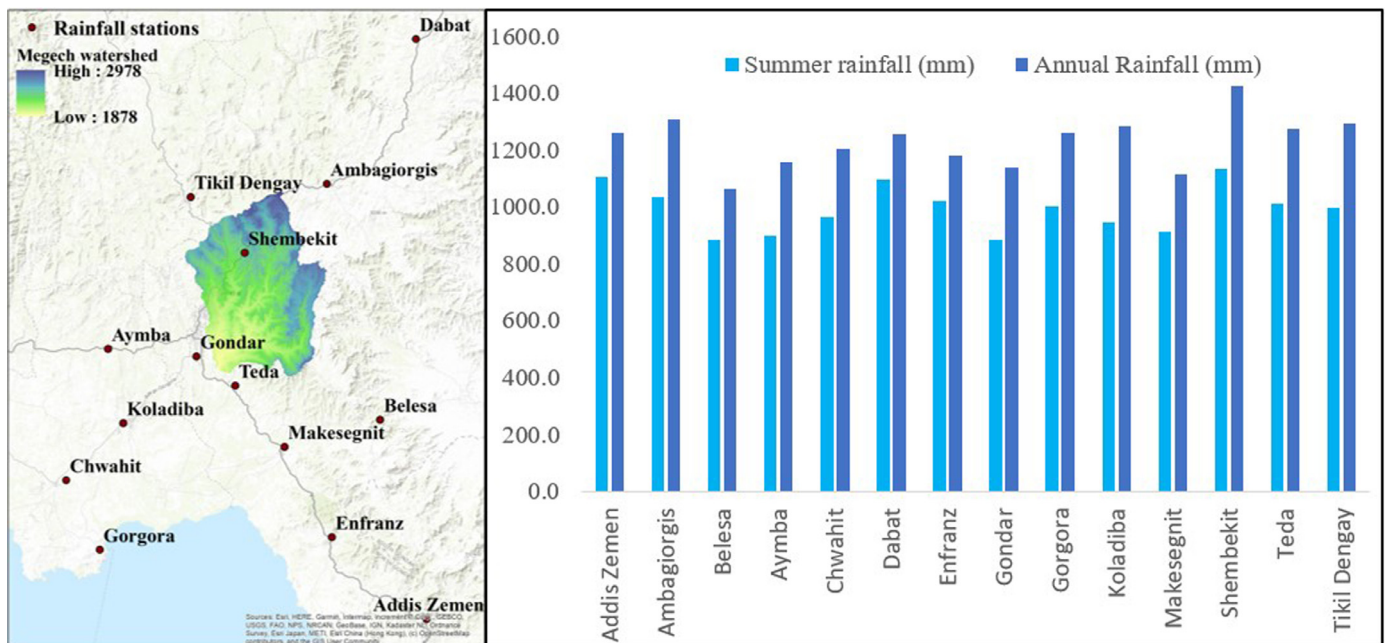


Fig. 2. Meteorological stations used to collect rainfall data.

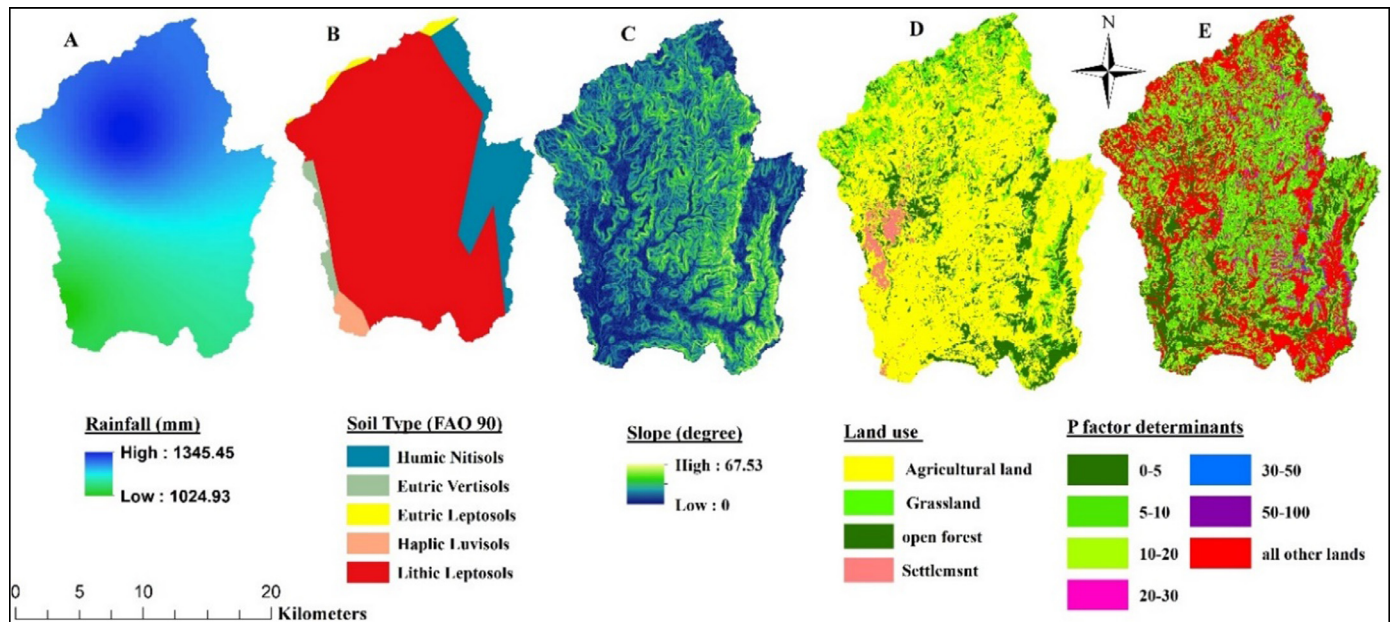


Fig. 3. The input factors for the RUSLE model: rainfall in mm (A), Soil category (B), slope in degree (C), land use land cover type (D) and support practice category (E).

soil loss in the Megech watershed was estimated based on the RUSLE general formula given in Eq. (1) (Wischmeier and Smith, 1978), and the data processing approach is shown in Fig. 4.

$$A = R * K * L * S * C * P \quad (1)$$

Where A = estimated mean annual soil loss ($\text{ton ha}^{-1} \text{yr}^{-1}$), R = erosivity factor ($\text{MJ mm ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$), K reflects soil erodibility factor ($\text{Mg h MJ}^{-1} \text{mm}^{-1}$), L , S , C and P , are slope length and gradient factors, cover management factor and erosion control practice factor respectively.

2.3.1. Rainfall-runoff erosivity factor (R)

R factor is the climatic factor that contributes to soil loss through detaching and transporting power by raindrop and runoff forces, respectively (Morgan, 2005). Rainfall intensity and duration are the main significant factors of the R factor. Raindrop/splash erosion is the dominant type of erosion on barren soil surfaces that causes the soil to detach, separate the aggregated soil particles, and initiate them to transport downstream areas (Arekhi, 2008). The R factor is computed by multiplying the maximum 30 min intensity of rainfall and kinetic energy for individual rainfall events (Wischmeier and Smith, 1978). In ungauged watershed, the R factor can be calculated using the average annual rainfall data of nearby weather stations (Renard and Freimund, 1994). As the Megech watershed is ungauged, we computed the R factor using rainfall data collected from 14 in/nearby weather stations (Fig. 2) from the period 2000 to 2020. Using monthly rainfall data from these stations, we computed the mean yearly rainfall total.

The R value for each rainfall station was calculated using Eq. (2) which was developed by Hurni (1985) for the Northwest Ethiopian highlands and used by several authors: (Amsalu and Mengaw, 2014; Aneseyee et al., 2020; Belayneh et al., 2019; Bewket and Teferi, 2009; Eniyew et al., 2021; Gashaw et al., 2018; Habtamu and Jayappa, 2022; Hellden, 1987; Kebede et al., 2021; Moges and Bhat, 2017):

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

Where R = Rainfall erosivity ($\text{MJ mm ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$) and P = mean annual precipitation (mm).

The meteorological stations used to compute the R factor were Ambagiorgis, Addis Zemen, Aymba, Belesa, Chuahit, Dabat, Enfranz,

Gondar, Gorgora, Koladiba, Maksegnit, Shembekit, Teda, and Tikil den-gay. A point map was developed using the inverse distance weight (IDW) interpolation method under the spatial analysis tool package in ArcGIS 10.3, and then an erosivity map was prepared (Fig. 5). This interpolation method is also used by Aneseyee et al. (2020), Belayneh et al. (2019) and Gashaw et al. (2019). The output layer map was then transformed into a 30 by 30 m raster grid.

2.3.2. Soil erodibility factor (K)

Erodibility indicates the capability of the soil to withstand the detaching, beating, and eroding forces. The K value assigned to a particular soil type indicates the amount of soil lost per unit of erosive energy compared to bare soil, assuming a standard USLE research plot is 22.1 m long by 1.83 m wide, and 9% slope (Ganasri and Ramesh, 2016; Renard et al., 1997; Wischmeier and Smith, 1978). The percentage of topsoil, sand, silt, clay, and organic carbon (OC) are the determinant factors in computing the K factor (Maqsoom et al., 2020; Mohammed et al., 2020; Wischmeier and Smith, 1978). Due to the lack of data in the study watershed, HWSO was used to prepare the soil map and develop the K factor map. HWSO consists of a 30'x30' raster image linked with a Microsoft access formatted attribute database that consisted of the determinant soil properties including; the percentage of topsoil of sand, silt, clay and OC (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012). The raster image contains the soil types and textural classes. This raster image was extracted using the watershed shapefile and the watershed soil map was produced (Fig. 3B). The K factor was then calculated based on Eq. (3) developed by Sharpley and Williams (1990), and utilized by the authors, Balabathina et al. (2020), Hu et al. (2019) and Mohammed et al. (2020).

$$K = A * B * C * D * 0.1317 \quad (3)$$

where each letter has its formula:

$$A = [0.2 + 0.3 \exp(-0.0256SAN(1 - (SIL100)))] \quad (3.1)$$

$$B = \left[\frac{SIL}{CLA + SIL} \right]^{0.3} \quad (3.2)$$

$$C = [1.0 - (0.25C + \exp[(3.72 - 2.95C))]] \quad (3.3)$$

$$D = [1.0 - (0.70SN1SN1 + \exp[(-5.41 + 22.9SN1))]] \quad (3.4)$$

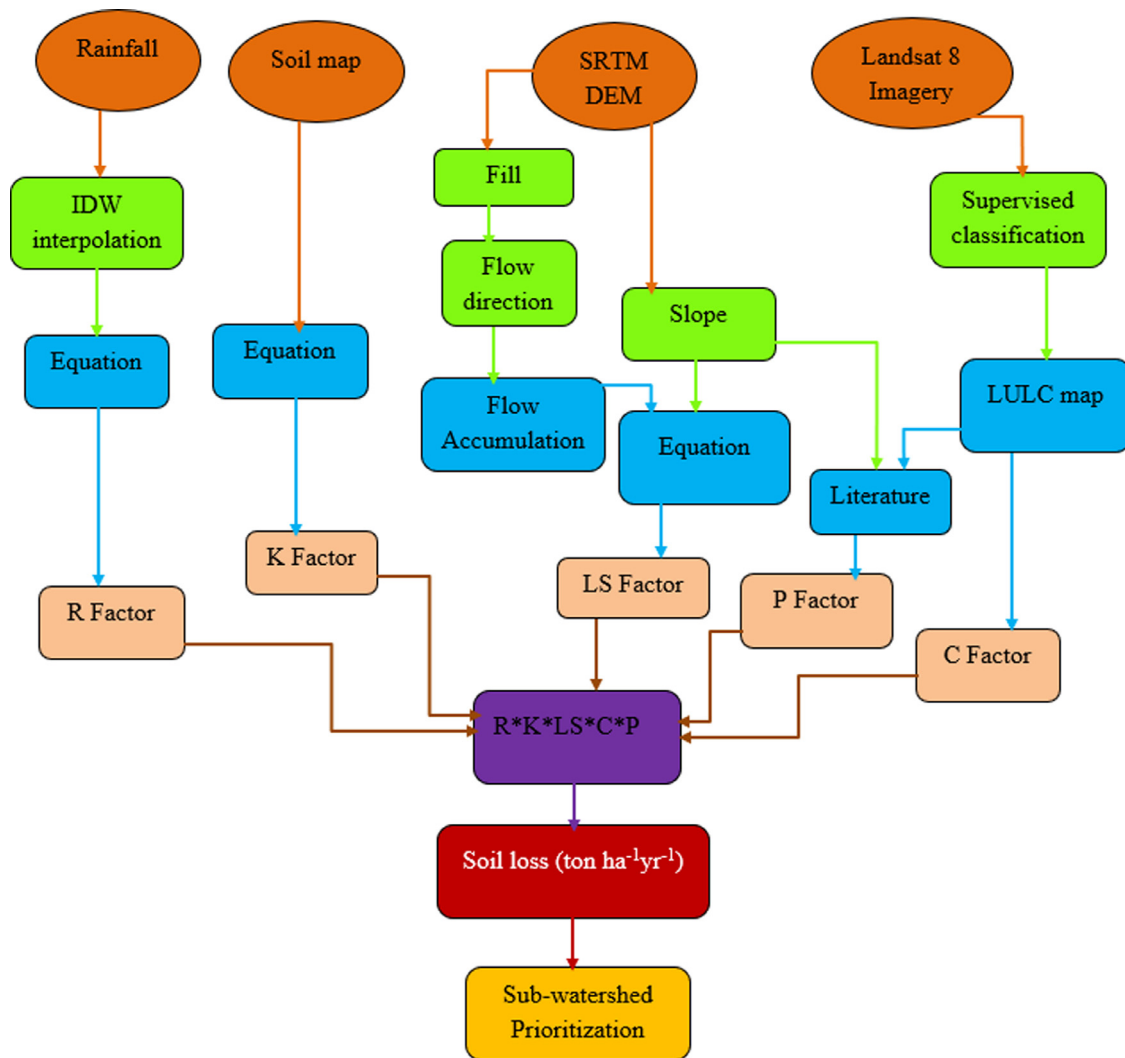


Fig. 4. Methodological approach to estimate soil loss using the RUSLE model.

Where SAN indicates the percent of sand; SIL indicates the percent of silt, CLA indicates the percent clay; C indicates the percent organic carbon content (OC%) and SN1 indicates sand percentage subtracted from one and divided by 100.

Using ArcGIS format, the calculated K value was then assigned to the corresponding soil category on the attribute table of the masked watershed and developed the K factor raster map (Fig. 5) by clicking the symbology option in the properties and then converting it to a 30 by 30 m raster grid using the K value added in the attribute data.

2.3.3. Slope length and steepness (LS) factors

The LS factor measures the effect of slope length and steepness on soil erosion. The L value is computed by dividing the actual horizontal slope length by the experimentally measured slope length of 22.1 m, and the S factor is calculated as a ratio of the actual slope to an experimental slope (9%) (Arekhi, 2008; Renard et al., 1997; Wischmeier and Smith, 1978). The length of the slope affects the speed of runoff and limits the number of particles eroded (Andualem et al., 2020). LS factor was computed from a 3 arcsec SRTM DEM with 30 m resolution which was downloaded from USGS earth explorer (<https://earthexplorer.usgs.gov/>). The DEM was extracted using the study watershed shapefile and subjected to raster calculation to obtain L and S factors. The computation of LS factors requires preprocessing of flow accumulation and slope angle. The preprocessing procedures employed were filling sinks, flow direction, and flow accumulation. The DEM was used as input data

to process flow accumulation and slope angle in ArcGIS Spatial analyst plus arc hydro tools extension. The L factor was calculated based on the improved RUSLE equations described in the following using Eq. (4) (Wischmeier and Smith, 1978):

$$L = \left(\frac{\lambda}{22.13} \right)^m \tag{4}$$

Where L reflects the slope length factor; λ is the horizontal field slope length in meters and “m” is the variable slope length exponent.

In the original USLE, the “m” value for a slope level greater than 5% is 0.5, which is the same value for all slopes greater than 5%. However, RUSLE uses Eqs. (4.1) and (4.2) to improve the value of the slope exponent (Renard et al., 1997; Oliveira et al., 2013). Therefore, the slope exponent value increase as slope inclination gets higher. The value of β is computed based on the slope angle for soils sensitive to sheet and rill erosion (Foster et al., 1977; McCool et al., 1987). In this study, the extracted DEM of the Megech watershed was subjected to Eqs. (4.1) and (4.2) and then computed using Eq. (4) to develop the L factor.

$$m = \frac{\beta}{(1 + \beta)} \tag{4.1}$$

$$\beta = \frac{\left(\frac{\sin\theta}{0.0896} \right)}{[3(\sin\theta)^{0.8} + 0.56]} \tag{4.2}$$

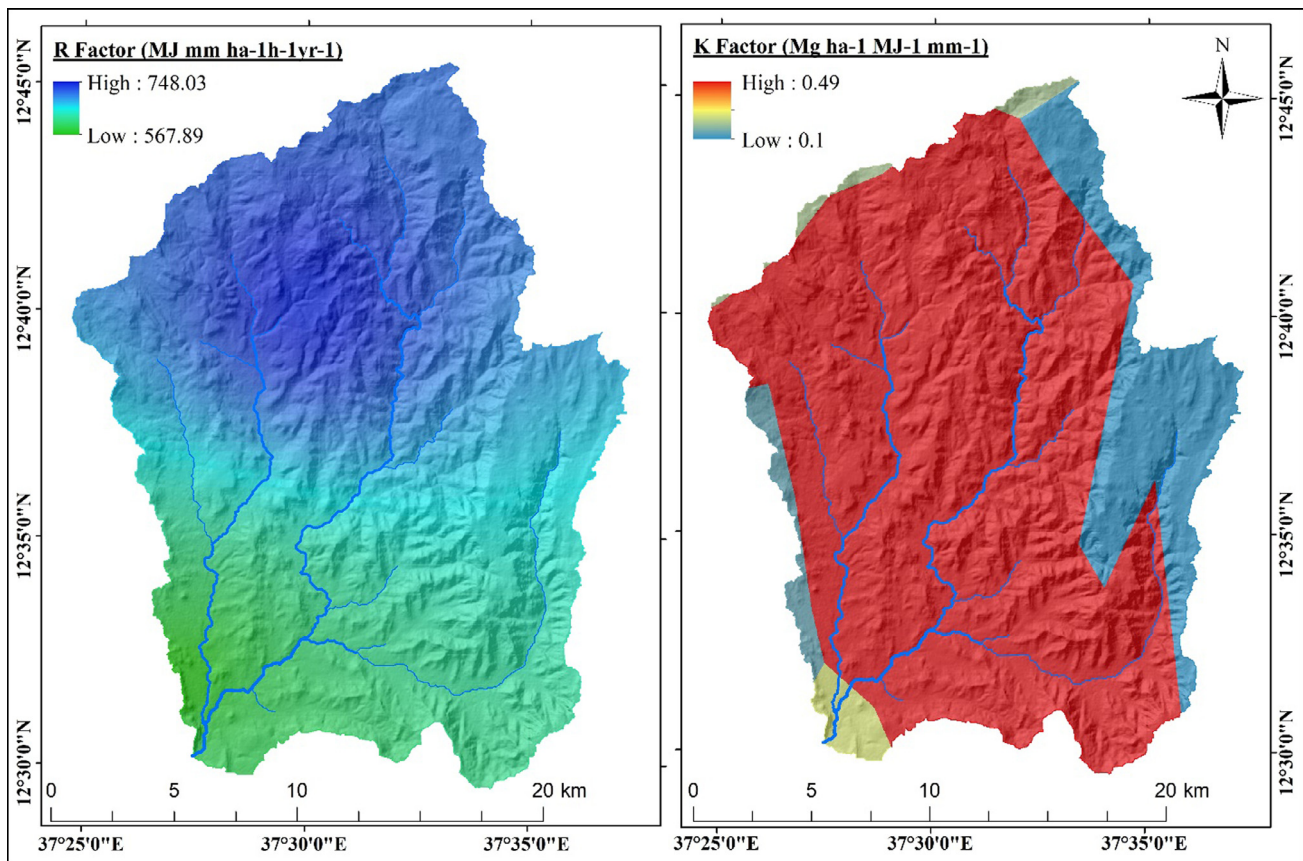


Fig. 5. Rainfall erosivity and soil erodibility map of the Megech watershed.

Where β is the relative proportion of rill to inter-rill erosion; and θ is the slope gradient angle.

The S factor was computed based on Eqs. (5) and (6) as described in RUSLE handbook 703 (McCool et al., 1987; Renard et al., 1997).

$$S = 10.8\sin\theta + 0.03, \text{ for } \theta < 9\% \quad (5)$$

$$S = 16.8\sin\theta - 0.50, \text{ for } \theta \geq 9\% \quad (6)$$

where S indicates the slope gradient factor; and θ indicates the slope angle.

The topographic factor in the RUSLE model was then obtained by multiplying the factors L and S ($LS = L \times S$). This method to estimate the LS factor is also used by Belayneh et al. (2019) and Saha et al. (2022).

2.3.4. Cover management (C) factor

C factor is the ratio of soil loss from particular cropland to the corresponding soil loss from clean-tilled, continuous fallow lands, and generally, the value ranges from 0.001 for dense forests to 1.0 for bare land (Arekhi, 2008; Ganasri and Ramesh, 2016; Wischmeier and Smith, 1978). It explains the level of soil protection under specified land cover management. Farming practices, surface roughness, vegetation cover, root biomass, and crop rotation are critical considerations in cover and management practices (Mohammed et al., 2020). Landsat 08 satellite imagery acquired on 30 January 2019, with 30×30 m resolution, was downloaded from USGS earth explorer (<https://earthexplorer.usgs.gov/>) to compute the C factor. Of the 11 bands, only 6 (bands 2–7) were selected and combined as a composite band in the ArcGIS environment. Because these bands have a better resolution to classify the targeted land use land cover (LULC). By changing and selecting the appropriate band combinations, the LULC types were classified in the Megech watershed using a maximum likelihood

supervised classification system. 160 control points were selected using a simple random sampling method to estimate the accuracy assessment of the classified image. A confusion matrix was carried out in the ArcGIS environment using a pivot table toolbox in the data management tool. Overall accuracy was computed by dividing the total number of correctly classified pixels by the total number of sampled/reference pixels (Anderson et al., 1976). After careful classification, each LULC type was assigned by its unique value based on the literature indicated by Hellden (1987) and Hurni (1985), and used by Belayneh et al. (2019), Gessesse et al. (2015), Moges and Bhat (2017) and Zerihun et al. (2018).

2.3.5. Support practice (P) factor

The factor of support practices (P) is the relative proportion of soil loss with certain erosion control practices to the corresponding soil loss if the cultivation system is up and down the slope (Wischmeier and Smith, 1978). The P value is 1 for soils without support practices and close to zero when proper erosion control measures are implemented (Ganasri and Ramesh, 2016). Several erosion control practices include contour stripping, contour tillage, terracing, and grassed waterways, all of which act as a barrier to runoff velocity and at the same time reduce soil erosion and tend to reduce the P factor (Alemayehu et al., 2020; Arekhi et al., 2010; Bewket and Teferi, 2009; Srinivasan et al., 2019). A detailed assessment of erosion protection measures is necessary to obtain a precise result of the P factor (Bewket and Teferi, 2009). After a rigorous assessment of the study watershed, some soil and water conservation practices such as stone-faced graded soil bund and agroforestry plantations were found. However, these conservation measures are inconsistent, and even the bund ditches were filled with sediment; which means that it could not act as a barrier to runoff velocity if proper maintenance is not undertaken. Based on this fact, we used an alternative method using a combination of LULC and slope gradient as input parameters to calculate and derive the P factor map as

Table 1
The P factor of the Megech watershed.

Land Use	Slope (%)	P value
Agricultural Land	0–5	0.1
	5–15	0.12
	15–30	0.14
	30–50	0.19
	50–75	0.25
	>75	0.33
Non-agricultural land		1

proposed by Wischmeier and Smith (1978) (Table 1). This method was also indicated by several research findings (Amsalu and Mengaw, 2014; Bewket and Teferi, 2009; Gashaw et al., 2018; Moges and Bhat, 2017). As indicated in previous works of literature, Kebede et al. (2021) and Teshome et al. (2021), the watershed was classified as agricultural and nonagricultural land.

2.4. Soil loss estimation and severity mapping

After computing and developing a 30×30 m raster layer for the six parameters, the final soil loss estimation was made by multiplying these parameters using the raster calculator under the spatial analysis tool package of ArcGIS environment using Eq. (1). Finally, the erosion severity map was generated by subdividing the main watershed into 27 sub-watersheds. The 27 sub-watersheds were generated during the delineation of the main watershed using the SWAT model extension in ArcGIS. The main reason for using the SWAT model extension is that we can set a minimum area threshold level. The sub-watersheds were delineated using the initial area of 500 ha which is recommended for the objective of land development and soil conservation plan (Desta et al., 2005). The sub-watersheds were then classified into seven categories based on erosion severity using the average annual soil loss estimated in each sub-watershed. The severity categories were low (VII), moderate (VI), high (V), very high (IV), severe (III), very severe (II) and extremely severe (I). Sub-watersheds with extremely severe soil erosion were assigned to the class I category and low severity class sub-watersheds were categorized in class VII.

3. Results and discussions

The spatial distribution of soil erosion was assessed and quantified by a cell-by-cell raster calculation using the six RUSLE model parameter layers: rainfall erosivity, soil erodibility, topographic (LS) factor, cover management, and erosion control practice factors in ArcGIS software. The soil erosion severity map was also developed that could be provided as a guide for farmers, development agents, and land managers for an appropriate conservation intervention plan.

3.1. Rainfall erosivity (R)

Rainfall intensity and duration are the main significant factors in this parameter. The annual rainfall distribution in the study watershed ranged from 1024.93 to 1345.45 mm (Fig. 3A). Greater rainfall was observed in the northern part of the watershed and decreased in the southern part near the outlet. More than 80% of the rainfall was observed from June to September (Fig. 2). The R factor ranged from 567.89 to 748.03 $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$ with an average value of 672.5 $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{yr}^{-1}$ (Fig. 5). Thus, the factor R has a great weight on total annual soil loss. The spatial distribution of the R factor was higher from the northern to the mid-part of the watershed. However, the R factor decreased when we moved from the northern to the southern (outlet) part of the watershed. Protection activities used to minimize the impact of rainfall, runoff, and sedimentation can be adopted based on the erosivity values.

Table 2
Main soil types at the Megech watershed and the corresponding K factor.

Soil type (FAO 90)	Texture (USDA)	K Factor	Area (ha)	Area (%)
Eutric Leptosols (Lpe)	loam	0.21	460.88	1.1
Lithic Leptosols (LPq)	clay loam	0.49	34,423.88	80.6
Haplic Luvisols (LVh)	Sandy clay loam	0.26	776.7	1.8
Humic Nitisols (NTu)	clay	0.1	6244.55	14.6
Eutric Vertisols (Vre)	light clay	0.14	800.52	1.9

Where K value is in $\text{Mg ha}^{-1} \text{MJ}^{-1} \text{mm}^{-1}$.

3.2. Soil erodibility (K)

Based on the extraction from HWSD, the Megech watershed has about five soil types: Humic Nitisols, Eutric Vertisols, Eutric Leptosols, Haplic Luvisols, and Lithic Leptosols with its corresponding textural classes of heavy clay, light clay, loam, sandy clay loam, and clay loam (Fig. 3B and Table 2). Lithic Leptosols were found in the dominant soil type which accounts for 80.6% of the total study area. The K values for the study watershed were 0.1, 0.14, 0.21, 0.26, and 0.49 $\text{Mg ha}^{-1} \text{MJ}^{-1} \text{mm}^{-1}$ for Humic nitisols, Eutric vertisols, Eutric Leptosols, Haplic Luvisols, and Lithic Leptosols respectively (Table 2). The K factor equation used in this study allows the variability of K values from 0.1 to 0.5 which coincides with the K value documented in the US Department of Agriculture Technical Bulletin No.1768 (Sharpley and Williams, 1990). The K value normally varied from near zero to about 0.6 and is very low for soils with high water retention capacities, such as well-drained sandy soils or friable tropical clays with high hydrous oxides of iron and aluminium or kaolinite (Brady and Weil, 2003). The K factor computed in this study was therefore realistic. Soil erodibility depends mainly on the content of organic matter in the soil and the texture of the soil (Stone and Hilborn, 2000). Generally, soils with high water infiltration capacity and moderate soil structural stability have a K factor of 0.2 to 0.3, while the most easily eroded soils with low infiltration capacity will have 0.3 or higher (Brady and Weil, 2003).

80.6% of the watershed had a K value of 0.49 $\text{Mg ha}^{-1} \text{MJ}^{-1} \text{mm}^{-1}$, which could have a greater contribution to soil erosion. Humic Nitisols in the eastern part of the watershed, had the least (0.1) K-value. Lithic Leptosols followed by Haplic Luvisols are more sensitive to erosion. However, Humic Nitisols and Eutric Vertisols are less susceptible to rainfall-driven erosion. Soil with higher levels of OM is usually less sensitive to erosion because it coagulates soil colloids and creates a more stable and aggregated soil structure. Fine to medium-textured soils and soils with low organic matter content have low infiltration capacity and are more sensitive to water erosion (Lal and Stewart, 1990; Pimentel, 2006).

3.3. Slope length and steepness (LS)

The LS factor is the most significant factor in soil erosion in mountainous areas, which is the characteristic of the Megech watershed. The average slope of the Megech watershed was 14° (26.2%) and ranged from 0 to 68° (Fig. 3C), characterized by higher topographic features. More than 70% of the research area was found in slope classes greater than strong to extremely strong ($>8^\circ$) slope classes, which means it aggravates rainfall-driven rill and inter-rill soil erosion. As depicted in Fig. 6, soil loss was increased as the slope class increased. About 32.8% of the watershed was classified in the slope class of $8\text{--}16^\circ$ and had an average erosion rate of $18.6 \text{ t ha}^{-1} \text{yr}^{-1}$.

The L factor was higher in valleys and depressions due to the high flow accumulation rate (Fig. 7). Whereas, the S factor was higher in the southeastern to the central part of the watershed where a higher slope gradient was observed (Figs. 3C and 7). The average LS factor value was 4.62 and generally, the LS factor ranged from 0.03 to 183.32 (Fig. 7). The LS factor increases with increasing slope steepness and flow accumulation. When slope length gets higher, the oppor-

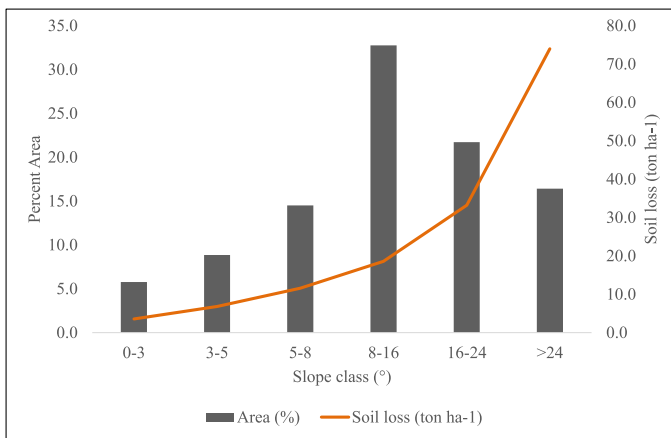


Fig. 6. The effect of slope gradient on soil loss.

tunity for accumulation and concentration of runoff water is also increased; slope steepness also accelerates the runoff velocity (Brady and Weil, 2003; Ganasri and Ramesh, 2016; Ghosal and Bhattacharya, 2020; Wischmeier and Smith, 1978). Slope steepness has a greater influence on soil erosion than slope length (Ghosal and Bhattacharya, 2020).

3.4. Cover management (C)

The main LULC types in the Megech watershed identified using supervised classification were open forest (16.31%), grasslands (11.4%), agricultural land (70%), and settlement (2.3%). Based on the land use

classes, the C factor values were assigned to each land use type and the C factor map was generated (Fig. 8). The C factor values for these LULC types were 0.014, 0.02, 0.05, and 0.15 for vegetation cover, settlement, grassland, and agricultural land, respectively. This C factor classification was based on Hurni and Hellden classification which for well-protected land was assigned as 0 and for bare land was assigned as 1 (Hellden, 1987; Hurni, 1985). Near-surface features such as well-grassed slopes, stem leaves, litter, and biological soil crusts have a greater contribution to reducing detachment, overland flow as well as soil erosion rate (Ma et al., 2021) As LULC type varies so does the C factor. Because the C factor is computed after the determination of the LULC type of specified area. Accuracy assessment provides the means to assess the confidence with which the classified image was accurate or not. The overall accuracy assessment of classified images in this study was 94.2%, which is greater than the acceptable level. The acceptable level of overall accuracy assessment is taken as 85% (Anderson et al., 1976).

Because of the suitability of the area for human settlement, vegetation removal for the expansion of cultivated lands is a common practice experienced in the watershed. Removing vegetation cover and intensive agricultural practices aggravates soil erosion, washing away the fertile topsoil that contains essential nutrients; leaving infertile and shallow soils with poor water retention capacity (Alemayehu et al., 2020; Hurni, 1988; Hurni et al., 2010; Saha et al., 2022). Cropland is more sensitive to erosion as it is frequently tilled, vegetation is removed before planting the crop and the land is bare between the two planting seasons (Pimentel, 2006). Hence 70% of the Megech watershed is covered by agricultural land, the soil is intensively cultivated and manipulated; the watershed could be affected by rill and inter-rill erosion.

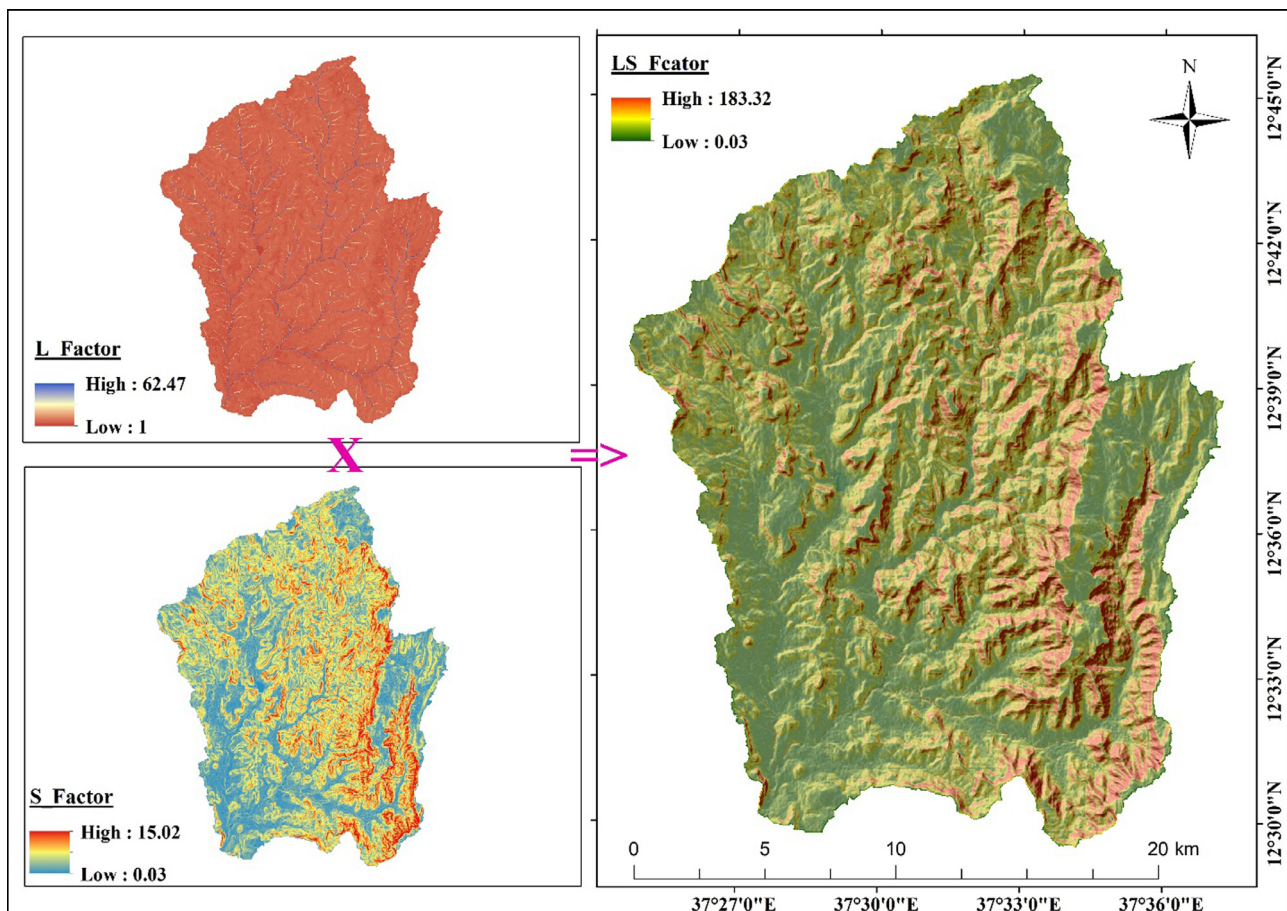


Fig. 7. The LS Factor of Megech Watershed.

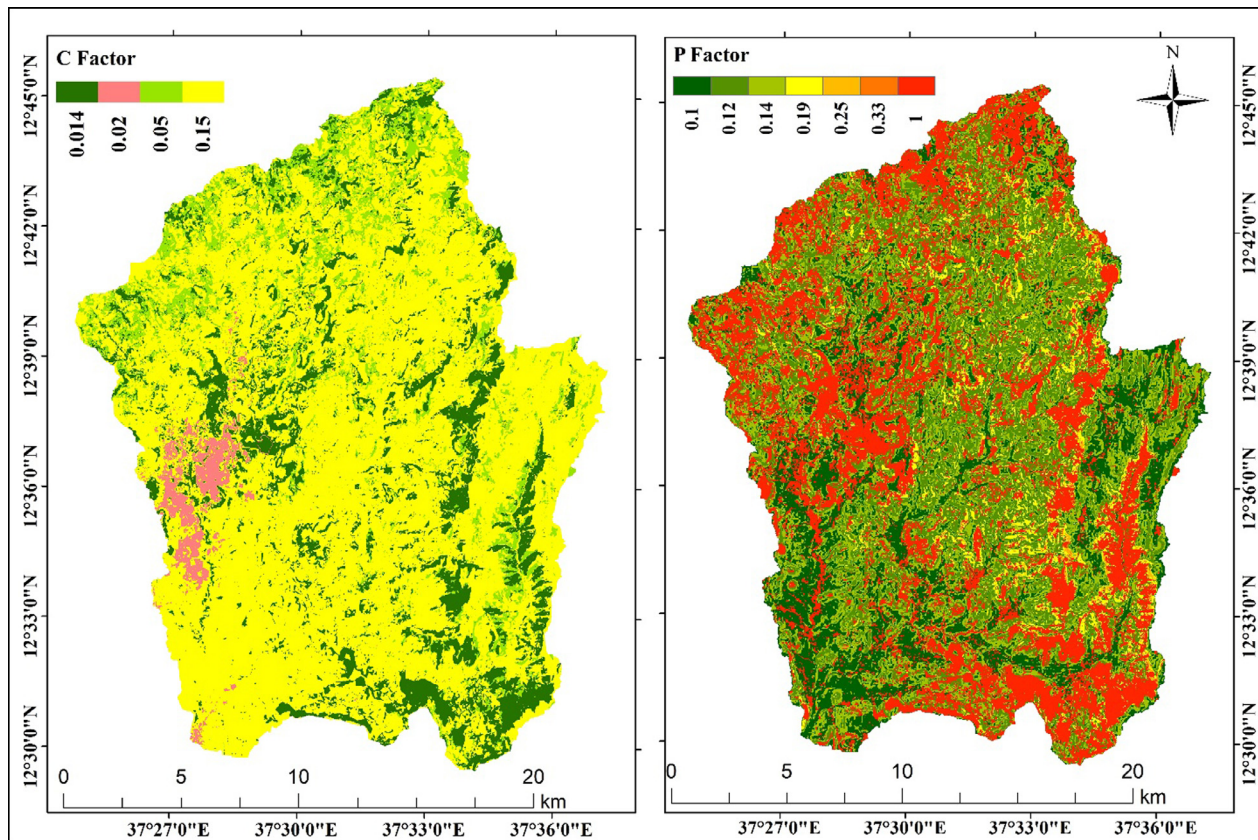


Fig. 8. C Factor and P Factor Map for the Megech Watershed.

3.5. Erosion control practices (*P*)

This factor measures the effect of erosion control measures on the surface runoff velocity and its corresponding impact on the total soil erosion rate (Wischmeier and Smith, 1978). Because of the unavailability of full data on different conservation measures in the study area, the combined effects of land use and slope gradient were used as input parameters to calculate and drive the *P* factor map. Based on the RUSLE analysis, the *P* factor for agricultural land ranges from 0.1 to 0.33, while other land uses were assigned as the *P* value of 1 (Fig. 8 and Table 1). Greater *p* value was observed in northwestern and southeastern parts of the watershed, while the southwestern and some eastern parts had lower *P* values.

3.6. Soil loss estimation

The estimated total soil loss from the whole watershed was about 1399,210 t yr⁻¹ with a mean soil erosion rate of 32.84 t ha⁻¹yr⁻¹. The spatial distribution of soil loss ranged from 0.03 t ha⁻¹yr⁻¹ in the eastern, outlet, and plain areas to more than 500 t ha⁻¹yr⁻¹ in the gorged, valley, and steep slope lands of the watershed (Fig. 9). This finding is much higher than the level of soil loss threshold (5–12 t ha⁻¹yr⁻¹) (Hurni, 1988). Based on the spatial location of soil erosion, the present study found that the potential soil loss is usually greater in steep slope lands, stream banks, and hilly cultivated lands. The northwest part of the Wogera District includes Chira Anbezo, Wolleka, Kereker Bale Egziabher, Kosoye ambaras, Dabir, Ayba Kidane-mihret and Dergay Administrative kebeles were affected by severe soil erosion. The southeast part of the watershed in the Gondar Zuria district (Ambober wuzaba, Dewa Damot, Ayba Eyesus kebeles) was also highly affected by severe soil erosion. The other part of the watershed in the middle part and near Gondar also experienced moderate to high soil erosion. The eastern part (Nora

Tsadikan and Ayba Kidist Selassie Kebeles) and some plain areas near the outlet appeared to be less prone to soil erosion.

The northern, northwestern and southeastern parts of the watershed have been severely affected by soil erosion. This could be happened due to the cultivation of hill slopes, clearance of vegetation cover, poor land management practices, open grazing, and the slope steepness factor experienced in the watershed (Habtamu and Jayappa, 2022). Although there are many factors, topography and vegetation cover are the main influencing factor that determines spatial soil erosion rate (USDA-SCS, 1972; Wolka et al., 2018; Wu and Wang, 2011). Flow depth decreases and runoff velocity increases as the slope gradient gets higher (Wang et al., 2021). The largest part of the watershed is dominated by the clay loam soil textural class which could be easily eroded by sheet/inter-rill erosion. Research conducted in China found that clay loam soil textural class has been highly affected by sheet/inter-rill erosion (Sun et al., 2021). Intensive rainfall also appeared in the northern part of the watershed, which could be the cause of severe erosion in the same area.

3.7. Identification and mapping of erosion hotspots

Uniform soil loss and severity could not occur in the watershed. This is due to the variation of input parameters such as land use, topography, soil type, and different soil and water management activities (Bekele et al., 2021). Developing an erosion severity map is important to identify critical erosion hotspots and make prioritization between sub-watersheds to allocate the limited human and financial resources and install suitable protection measures at the appropriate place and time (Abdo and Salloum, 2017; Fayas et al., 2019; Gashaw et al., 2018; Osman and Sauerborn, 2001). Based on the spatial distribution of estimated soil loss, most of the Megech watershed needed attention to counteract the serious erosion problem. However, as described by

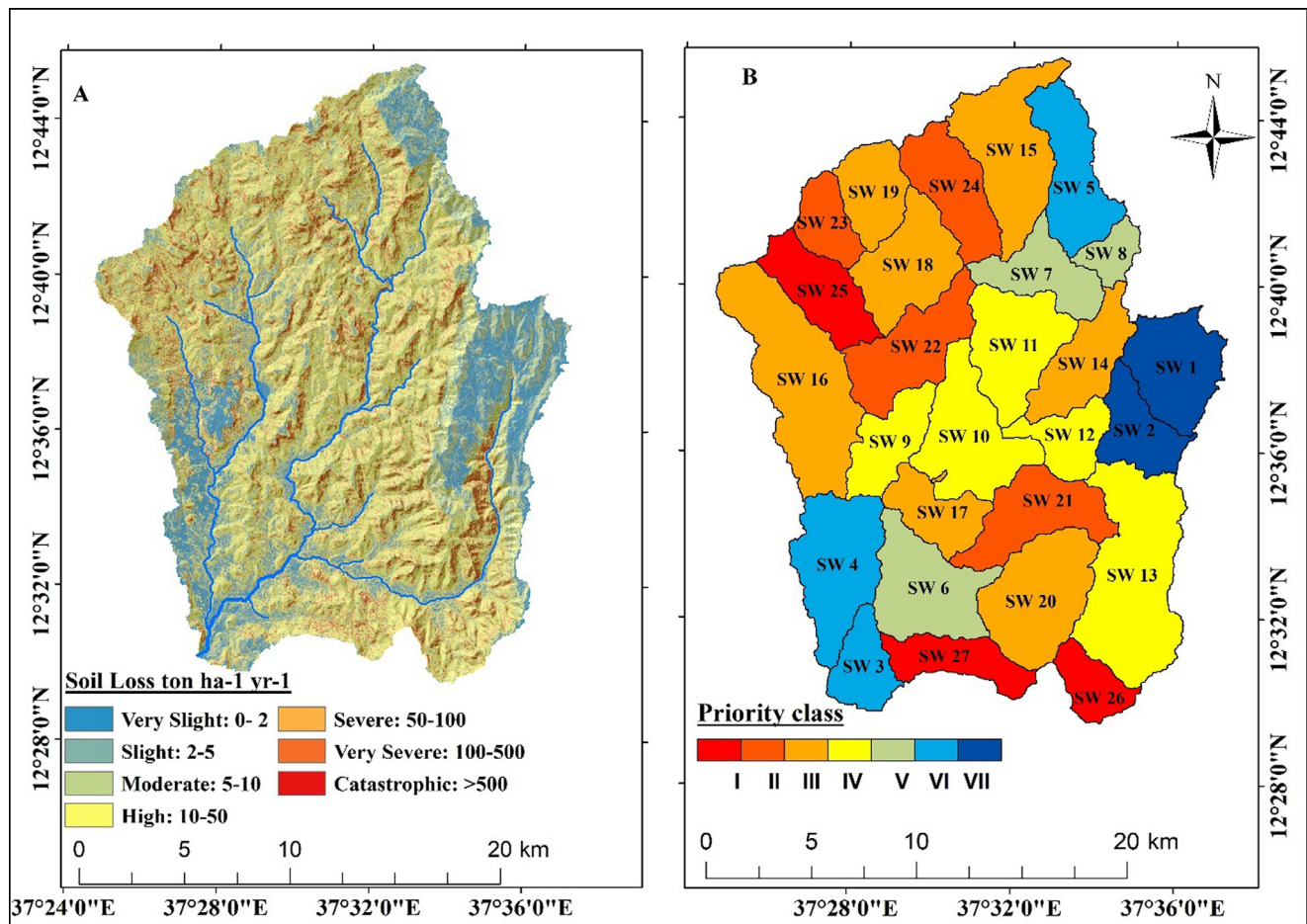


Fig. 9. Annual soil loss and severity class map of Megech watershed.

Mohammed et al. (2020), implementing protection measures throughout the watershed may not be possible at once. Selection and prioritization of the risky areas are crucial to applying appropriate conservation measures (Bewket and Teferi, 2009; Gashaw et al., 2018; Woldemariam et al., 2018). Based on this fact, the Megech watershed was classified into 27 sub-watersheds and the erosion hotspots were identified based on comparing the mean annual soil loss quantified in each sub-watershed (Fig. 9 and Table 3).

The highest soil erosion was found in Sub-watershed 27 ($48.8 \text{ t ha}^{-1}\text{yr}^{-1}$) and decreased to $2.64 \text{ t ha}^{-1}\text{yr}^{-1}$ in sub-watershed 1. The sub-watersheds were then classified into seven erosion severity classes. The severity classes were low (0–10), moderate (10–20), high (20–30), very high (30–35), severe (35–40), very severe (40–45), and extremely severe (above 45) in which the values in brackets are mean annual soil loss in $\text{t ha}^{-1}\text{yr}^{-1}$. The seven severity classes ranging from low erosion (VII) to extremely severe erosion class (I) was created to generate the severity map for the 27 sub-watersheds (Fig. 9). The corresponding area coverages from low erosion risk to extremely severe erosion risks in ha (%) were 2794 (6.5), 4721 (11.1), 3702 (8.7), 9405 (22), 13,181 (30.9), 5732 (13.4) and 3171 (7.4), respectively.

The study revealed that there was spatial variability of soil erosion in both grid and sub-watershed-based assessments. Five sub-watersheds (SW_9 to SW_13) appeared as a very high class (IV), seven sub-watersheds (SW_14 to SW_20) were classified as severe (III), four sub-watersheds (SW_21 to SW_24) were classified as very severe (II) class and finally, three sub-watersheds (SW_25 to SW_27) classified as extremely severe (I) class (Table 3). The sub-watersheds fallen in the extremely severe erosion category have been given as the priority class for a conservation plan.

About 82% of the watershed was found in more than the high-risk category, which means it needs attention and immediate conservation action should be implemented. It does not mean that the lower-ranked sub-watersheds do not need any conservation measures. However, conservation measures should be considered after implementing the top-prioritized sub-watersheds. The top prior sub-watersheds were identified in the Wogera district: Chira Anbezo, Kerker Endibina, Kerker Bale Egziabher, Wolleka, Kosoye-ambaras, and Werengib and in the Gondar-Zuria district: Macha, Degola-chinchaye, Dewa Damot, and Amboberwuzamba administrative kebeles. The authors recommended using the developed severity map as a guide to introduce targeted conservation measures such as stone-faced graded soil bund, check dams, terracing trenches, and expanding biological measures in these severely affected areas.

3.8. Comparison of soil loss estimates with previous findings

Due to the difficulty of getting data for validation, previous research findings were used as a confirmation for the present study. A similar method was used by Habtamu and Jayappa (2022) and Kebede et al. (2021). The result found in this study was realistic, as confirmed by previous research studies mentioned below: the estimated average annual soil loss of the current study was found in the range of estimated soil loss in the region which is about $16\text{--}50 \text{ t ha}^{-1}\text{yr}^{-1}$ (Lakew et al., 2000). Another report also found about $27.5 \text{ t ha}^{-1}\text{yr}^{-1}$ in the Abbay River basin using the RUSLE model (Haregeweyn et al., 2017), $30.6 \text{ t ha}^{-1}\text{yr}^{-1}$ using the RUSLE model (Amsalu and Mengaw, 2014). $10\text{--}35 \text{ t ha}^{-1}\text{yr}^{-1}$ in the Koga catchment using the AnnAGNPS model (Yeshaneh et al., 2017), $27.5 \text{ t ha}^{-1}\text{yr}^{-1}$ in the Koga

Table 3
Severity class of sub-watersheds for conservation prioritizations.

Watershed	Area (ha)	Soil loss per watershed (tons)	Soil loss (ton ha ⁻¹)	Priority Class	Severity	Area coverage based on Severity (ha)
SW_1	1697	4481.14	2.64	VII	Low	2794
SW_2	1097	7708.82	7.03			
SW_3	913	12,249.51	13.42			
SW_4	2127	31,223.92	14.68	VI	Moderate	4721
SW_5	1681	30,323.98	18.04			
SW_6	1960	43,863.23	22.38			
SW_7	1240	33,931.96	27.37	V	High	3702
SW_8	503	13,770.05	27.39			
SW_9	1139	35,481.10	31.15			
SW_10	2080	66,731.85	32.08	IV	Very high	9405
SW_11	1869	63,581.34	34.02			
SW_12	920	31,981.82	34.75			
SW_13	3396	118,189.15	34.8	III	Severe	13,181
SW_14	1385	49,627.18	35.82			
SW_15	2326	88,316.70	37.97			
SW_16	3355	128,017.26	38.16	II	Very Severe	5732
SW_17	1057	40,929.20	38.74			
SW_18	1732	67,321.11	38.88			
SW_19	1107	43,044.23	38.89	I	Extremely Severe	3171
SW_20	2220	86,687.54	39.04			
SW_21	1658	67,772.68	40.87			
SW_22	1765	77,708.55	44.03	I	Extremely Severe	3171
SW_23	808	36,013.39	44.56			
SW_24	1501	67,015.46	44.66			
SW_25	1355	64,635.41	47.7	I	Extremely Severe	3171
SW_26	753	36,704.58	48.76			
SW_27	1064	51,900.26	48.8			

Where low = <10, moderate = 10–20, high = 20–30, very high = 30–35, severe = 35–40, very severe = 45 and Extremely Severe = >45 t ha⁻¹ yr⁻¹; SW stands for Sub-Watershed.

catchment using the RUSLE-InVEST model (Gashaw et al., 2021), 37.5 t ha⁻¹yr⁻¹ in the Beshillo catchment in the Blue Nile River basin using the RUSLE model (Yesuph and Dagnew, 2019), 42.67 t ha⁻¹yr⁻¹ in Gumara watershed using the same model (Belayneh et al., 2019), 23.4 t ha⁻¹yr⁻¹ in central Ethiopia using the RUSLE model (Gessesse et al., 2015) and 21.08 t ha⁻¹ in neighboring Gumara-Maksegnit watershed using SWAT model (Addis et al., 2016). A basin-scale study in the Lake Tana sub-basin using the SWAT model showed that the Megech watershed was found from the number one erosion-sensitive sub-basins which accounted for an average annual sedimentation rate of 30–65 t ha⁻¹yr⁻¹ (Setegn et al., 2009). In the same basin, using the USLE model, an average annual soil loss of 37.89 t ha⁻¹yr⁻¹ was found (Balabathina et al., 2020). The result found in the current study was in between the above-mentioned previous findings.

Our research result is lower than the result of the studies conducted and reported using the same model in a similar geographical area of northwestern Ethiopia and other parts of Ethiopia. For instance, 72 t ha⁻¹yr⁻¹ (Hurni, 1985), greater than 80 t ha⁻¹yr⁻¹ (Bewket and Teferi, 2009), 50 t ha⁻¹yr⁻¹ in degraded mountain areas (Kebede et al., 2021), 70.5 t ha⁻¹yr⁻¹ (Woldemariam and Harka, 2020), and at the watershed level also reported 107 t ha⁻¹yr⁻¹ (Woldemariam and Harka, 2020). There are also published researches in Ethiopia and other countries with findings of much higher soil loss: 223 t ha⁻¹yr⁻¹ in Dengora watershed and 256 t ha⁻¹yr⁻¹ in Meno watershed (Munye, 2020), 4735 t ha⁻¹yr⁻¹ (Teshome et al., 2021), 243 t ha⁻¹yr⁻¹ (Zelege, 2000), 576 t ha⁻¹yr⁻¹ (Eniyew et al., 2021) and in Syria, the research found an average soil loss of 137.4 t ha⁻¹ yr⁻¹ (Mohammed et al., 2020). Our research finding also gets higher than some previous research findings such as 10 t ha⁻¹yr⁻¹ (Tadesse and Tefera, 2021) and 23.7 t ha⁻¹yr⁻¹ (Gashaw et al., 2018). All the mentioned findings revealed that there is a spatial variation of soil erosion across Ethiopian watersheds because of variation in topography, rainfall, land use management, agricultural activities, deforestation, livestock grazing, and other anthropogenic practices (Andualem et al., 2020; Bekele et al., 2021; Eniyew et al., 2021; Gelagay and Minale, 2016; Kebede et al., 2011; Woldemariam and Harka, 2020).

4. Conclusion

A quantitative soil erosion assessment had been conducted in the Megech watershed using the RUSLE model in a GIS interface to quantify the mean annual soil loss and to identify erosion hotspots. The RUSLE model estimated the mean annual soil loss of the watershed as about 32.84 t ha⁻¹yr⁻¹ and total soil loss from the watershed was about 1399,210 t yr⁻¹. A specific severity map was also created for the sub-watersheds as low erosion severity (<10 t ha⁻¹yr⁻¹), moderate erosion (10–20 t ha⁻¹yr⁻¹), high erosion category (20–30 t ha⁻¹yr⁻¹), very high (30–35 t ha⁻¹yr⁻¹), severe (35–40 t ha⁻¹yr⁻¹), very severe soil erosion (40–45 t ha⁻¹yr⁻¹) and extremely severe (greater than 45 t ha⁻¹yr⁻¹). Based on this classification system, about 2794 ha were considered as low erosion, 4721 ha were in the category of moderate erosion, 3702 ha were in the category of high erosion on five sub-watersheds, 9405 ha were in the category of very high erosion in eight sub-watersheds, 13,181 ha in the category of severe erosion, 5732 ha under very severe erosion class and 3171 ha fall under extremely severe soil erosion category.

About 82% of the Megech watershed was found in more than high-risk categories of erosion. The spatial distribution of soil erosion was more serious in the northern, northwestern, and southeastern parts of the watershed due to the up and down topography, poor conservation measures, free grazing, rapid change in land use, intensive rainfall and uncontrolled human activities. Thus, the above-mentioned geographic locations of the watershed need attention for immediate conservation action. The study recommends using the developed severity map as a guide to introduce targeted conservation measures such as stone-faced graded soil bund, check dams, terracing trenches, and expanding biological measures depending on the provided priority classes. This study also bears witness that the RUSLE model integrated with the ArcGIS is a relevant and practical technique to check out spatial variability of soil erosion for appropriate management interventions.

The limitation of the present study was that the quantitative estimation of soil loss was not confirmed by field measurements due to a shortage of funding to undertake field measurements. The main problem in the study area is the scarcity of data to assess soil erosion. The

RUSLE model bears uncertainties because of the availability and meaningfulness of input data. Soil data are not available in the study watershed and some rainfall stations started recently, which obliges us to use only 20-year rainfall data. This may affect the model output and produce a coarse result. However, the estimated soil loss in the present study coincided with the previous findings conducted in the northwestern Ethiopian highlands. Based on this fact, the authors suggested that this research should be improved by the long-term observational data to understand the process of soil erosion at catchment and sub-catchment scales. Further detailed research is needed to estimate the observed sediment load in the Megech and Angereb dam reservoirs. It can also be important to predict future soil erosion trends for a better pre-mitigation option.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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