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Quantify soil erosion and sediment export in response to land use/cover change in the Suha watershed, northwestern highlands of Ethiopia: implications for watershed management

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Abstract

Soil erosion accelerated by human activities is a critical challenge affecting soil health, agricultural productivity, food security and environmental sustainability in the highlands of Ethiopia. The aim of this study was to examine the dynamics of soil loss and sediment yield potential, and identify soil erosion hotspots using RUSLE with GIS in the Suha watershed, north western highlands of Ethiopia. Digital Elevation Model, LU/LC, rainfall, soil, and conservation practice were used as input data for RUSLE model. The estimated total annual soil loss for the entire watershed increased from 1.22 million tons in 1985 to 2.43 million tons in 2019, with average annual soil loss rates of 15.2 t ha^{-1} yr^{-1} and 31.4 t ha—1 yr^{-1} respectively. Total sediment yield also increased from 317.52 to 630.85 thousand tons over the past 35 years. In addition, the area of soil erosion hotspots changed from 15.2% (12,708 ha) to 32% (25,660 ha) during the same periods. Sub watershed 1, 2, 15, 17, 18, and 23 are severely degraded parts of the watershed. Expansion of agriculture and bare land as the expenses of other land use types over the past 35 years could be the major causes of extensive soil erosion risk in the watershed. Besides its temporal variability, soil loss and sediment export also showed variation between land use/cover classes. The estimated results of soil loss and sediment yield as well as soil erosion hotspots revealed that the soil erosion risk is progressively increasing during the study periods. Unless action is taken and the current condition is reversed, it will critically threat the livelihoods of the community in the watershed. Generally, the results underscore urgent demand for integrated and effective watershed management strategies.

Keywords: LULC change, GIS, RUSLE, Soil erosion, SY, Suha watershed

Introduction

Land degradation in the form of soil erosion is a major challenge worldwide, having negative impacts on social, economic, and environmental development (Arabameri et al. 2020; Marques 2021; Ganasri and Ramesh 2016). According to research reports, soil erosion accounts for about 84% of global land degradation, with annual soil loss ranging from 25 to 400 billion tons per year (Montanarella 2015; Opeyemi et al. 2019). Land degradation in Sub-Saharan Africa is the worst in the world. On the other hand, the livelihoods of most populations in these countries are highly dependent on their natural resource base (Nkonya et al. 2015). In these regions, the extent of severely degraded soils is approximately about 350 million hectares (25% of the total area) (Vlek et al. 2008).

The highlands of Ethiopia are among the most degraded areas in sub-Saharan Africa (SSA) (Fenta et al.

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2020). The study conducted by Fenta et al. (2021) in the main river basins of Ethiopia revealed that annual soil loss was estimated to be 1.9 billion tons/yr and sediment yield was 410 million t yr^{-1}. From the same study, it was also confirmed that the highest annual soil loss (573 million t yr^{-1}) was from Blue Nile (Abay) basin followed by Tekeze basin (270.6 million t yr^{-1}). This severe soil erosion in these two basins might be due to topographic features of the basins, high population pressure, and poor land use systems (Kebede et al. 2021; Yesuph and Dagnew 2019). Sonneveld et al. (2011) also reported the national mean annual soil loss ranged from 0 t ha−1 yr^{-1} in eastern and southeastern Ethiopia to 100 t ha−1 yr^{-1} in the northwestern highlands of Ethiopia. Similarly, the study of Erkossa et al. (2015) showed 1493 million tons annual soil loss from the Upper Blue Nile Basin. Another study result from the same basin was 131 million t yr^{-1} (Betrie et al. 2011). Berihun et al. (2020) and Lemma et al. (2019) also inferred that catchments found in the upper part of Blue Nile Basin are heavily affected by soil erosion. The above findings confirmed that the severity of soil erosion and sediment export significantly vary across regions due to the difference in environmental, climatic and anthropogenic factors (García-Ruiz et al. 2015).

Soil erosion is the major cause for several economic and environmental problems. Globally, it costs the international community about $400 billion (Montanarella 2015; Opeyemi et al. 2019). In particular, the effects of land degradation on soil fertility and food security has been widely reported (Teng et al. 2018; Marques 2021). In Sub-Saharan Africa (SSA), soil erosion is the major factor for the degradation of more than 65% of agricultural land and subsequent loss of agricultural yield (Tully et al. 2015; Vlek et al. 2008). Productivity loss, food security and human wellbeing are basic problems in these regions (Sonneveld and Keyzer 2003; Nakhumwa 2004). Economic loss due to soil degradation was estimated to be US$68 billion per year and the reduction of annual agricultural GDP was 3% (Sanchez et al. 2002). The removal of fertile soil and reduction of agricultural productivity is the most severe in the highlands of Ethiopia as compared to Sub-Saharan Africa (SSA) due to excessive soil erosion (Dibaba et al. 2021; Hurni et al. 2015). Hurni (1993) reported that the productivity of soil in the highlands of Ethiopian is reducing at a rate of 2–3% annually due to soil erosion. Yesuf and Bluffstone (2007) also estimated soil erosion cost in terms of annual GDP of Ethiopia and reported that GDP is reduced from 2 to 6.75% annually.

Among an off-site impacts of soil erosion, loss of hydrological regulation that results in the contamination of water bodies and silting up of dams in the downstream areas affecting millions of rural and urban communities (Borrelli et al. 2020; Fenta et al. 2021). The storage capacity and life expectancy of reservoirs and lakes in Ethiopia has progressively reduced due to continuous sediment load (Lemma et al. 2018; Haregeweyn et al. 2017). For instance, the study of Zemadim et al. (2014) showed that 3.5 million m^3 of sediment has been accumulated in Koka dam in 23 years. Yitaferu (2007) also estimated siltation in Lake Tana and showed that the sediment loading rate was 14.84 million tons per year. Total loss of Haramaya Lake (Eshetu et al. 2014) and Cheleleka wetland in the Central Rift Valley of Ethiopia (Degife et al. 2019) were the results of excessive soil erosion and subsequent siltation. The problems of siltation and nutrient enrichment in Gilgel Gibe-I hydro-power dam were also reported by Devi et al. (2008).

Suha watershed, which is part of the head waters of the Upper Blue Nile in the north-western highlands of Ethiopia, is highly threatened by soil erosion and nutrient depletion. Causal factors are many and diverse including the rugged terrain with steep slopes, loss of vegetation cover due to deforestation and over grazing, inappropriate land use practices including complete removal of crop residues from crop fields and lack of appropriate conservation measures. In the research area, frequent and significant land use and land cover changes, which had detrimental consequences on soil and water resources are occurred. Soil fertility problems due to soil erosion are not yet resolved and are expected to continue in the future (Simane et al. 2013).The Suha River is one of the tributaries of the Blue Nile River that carries sediment and potentially causing siltation in the Grand Ethiopia Renaissance Dam (GERD). The selection and application of soil and water conservation technologies is site specific due to the variation in physiographic, socioeconomic and climatic factors among regions or catchments (FAO 2017). Assessment and quantification of land degradation is the first essential step to persuade government and local communities to take action before it is too late. Identification of the hotspots of soil erosion in the sub-watersheds provides crucial information to guide soil conservation intervention.

However, the volume of soil loss by runoff water and its spatial distribution and sediment yield of the watershed has not yet quantified. Even though, it is expected that soil erosion is severe in this watershed, soil and water conservation strategies are not applied in erosion prone areas as it is evidenced from field survey work. Besides to this, the perception of farmers about soil erosion and their willingness to conserve their farm lands is not yet investigated. Generally, information on the extent and severity of soil erosion and its management strategies was lacking in this area. Hence, regular monitoring of soil erosion, identification of hotspot areas of the watershed and knowing its environmental implications is crucially important for decision making and selection of proper technologies, design appropriate management strategies and implementation.

The findings of this study could be useful in resolving problems related to soil erosion, soil nutrient export, agricultural productivity and food security. The results could also provide new information for land managers, government offices, and development organizations to consider soil and water conservation technologies while they are designing development plans and implementing mitigation measures. Moreover, it helps to raise awareness among the local community about the importance of not further degrading the natural resources. Therefore, the aim of this study was to examine the impacts of LULC change on soil loss and sediment yield potential, and identify soil erosion hotspots for effective watershed management in the Suha watershed, north western highlands of Ethiopia.

Materials and methods

Description of the study area

This study was conducted in the Suha watershed, part of the Upper Blue Nile Basin, and has an area of 80,343 ha. Geographically, it is bounded between 37° 56′ 15″ and 38° 18′ 49″ E and 10° 06′ 46″ and 10° 41′ 56″ N. Elevation ranges from 1040 m.a.s.l at the location of the lowest point to 3986 m.a.s.l at the location of the highest point (Fig. 2). According to FAO (2006) slope classification, the topography of the watershed is categorized in to flat to very gently sloping, gently sloping, sloping, strongly sloping, moderately steep, steep and very steep (Table 1).

The study area is characterized by humid climate and has a mean annual rainfall ranged from 1213 mm at the lower part to 1396 mm in the upper part of the watershed (based on the data obtained from Bichena, Dejen, Kuy and Robgebeya stations. The mean minimum and mean maximum temperature of the area is 8.3 °C and 23.6 °C respectively (Fig. 1). It has a unimodal type of rainfall that extends from June to September. Fenta et al.(2021) classified agro-ecological zones of Ethiopia by considering elevation and mean annual rainfall. Based on this classification, the study area is categorized as Moist Kolla (elevation ranges from 500 to 1500 m), Moist Weyna Dega (1500–2300 m), Moist Dega (2300–3200 m), Moist High Dega (3200–3700 m) and Moist Wurch (> 3700 m).

The analyzed results of landsat images for the period 1985–2019 indicated that six land use land cover classes are present in the study watershed. The largest proportion of land use type is cultivated field that accounts 74% of the total area and cereal crops are cultivated predominantly in the watershed. On the upper part of the catchment, oats (*Avena sativa*), barely (*Hordeum vulgare*), potato (*Solanum tuberosum*), wheat (*Trticum vulgare*) and onion (*Allium cepa*) are cultivated. In the middle part, teff (*Eragrostis teff*) is predominantly cultivated and in the lower part, sorghum is the dominant crop. The other land use types include: grazing land (9.1%), forest land (1.3%), shrub land (4.9%), and bare land (8.4%) and built up area (2.0%). Currently *Eucalyptus* plantation is expanding in farm lands for different purposes.

Soils of the northern and central highland plateaus of Ethiopia are developed from basaltic basements (Elias 2016). In the study area, five major soil types are identified; Vertisol (57.4%), Leptosol (26.7%), Cambisol (9.6%), Luvisol (6.1%) and Nitosol (0.3%). The central part of the watershed is predominantly covered by Vertisol. Cambisol and Luvisol are present in the upper part of the watershed whereas Leptosol covers the largest proportion of the lower part (Fig. 2).

Soil erosion modeling

Soil loss and sediment yield were estimated using various data sources; which are described in (Fig. 10 and Table 2). Slope map of the watershed and LS_factor values were generated from Digital Elevation Model (DEM) of the study area derived from ASTER (Advanced Space borne Thermal Emission and Reflection Radiometer) with a spatial resolution of 30 m *

Table 1 Slope classes and proportion of each class in the Suha watershed (this classification is based on FAO (2006))

No	Slope (%) range	Slope class	Area (ha)	Proportion (%)
1	0–2	Flat to very gently sloping	2586.7	3.2
2	2–5	Gently sloping	10,748.4	13.4
3	5–10	Sloping	19,234.7	23.9
4	10–15	Strongly sloping	12,380.7	15.4
5	15–30	Moderately steep	19,471.7	24.2
6	30–60	Steep	12,231.2	15.2
7	> 60	Very steep	3686.9	4.6
	Total		80,340.3	100

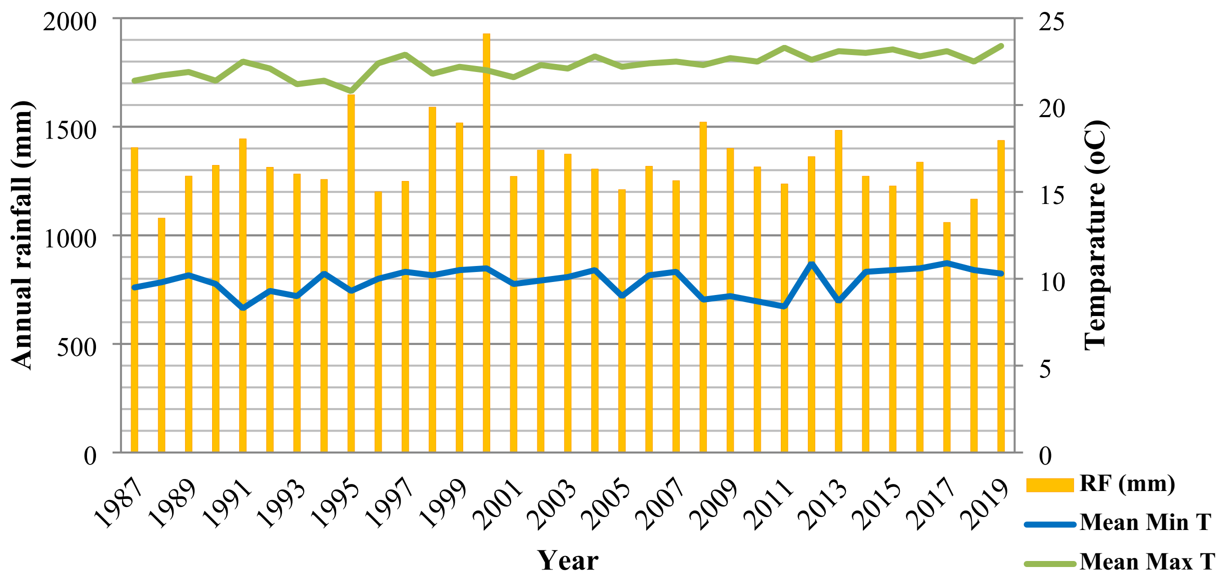


Fig. 1 Long term trend of climatic condition in the study area (1987–2019)

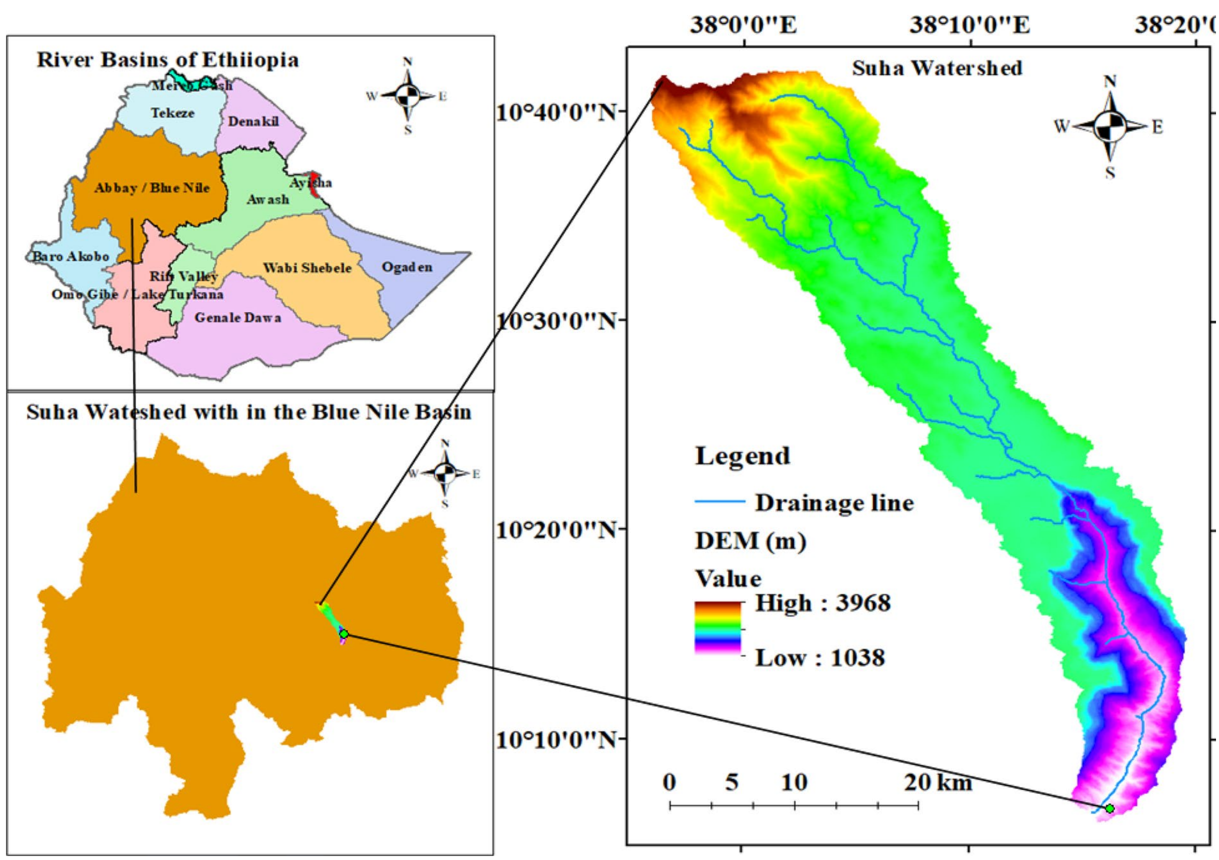


Fig. 2 Location Map of the study area

Table 2 Data sources used for RUSLE model to estimate soil loss and sediment yield

Data type	Source	References
DEM	ASTER	USGS (http://gdex.cr.usgs.gov/gdex)
Soil	Abay Basin master plan project	MoWR (1998) (Abay Basin Master Plan)
Rain fall	Data from stations (1974–2019)	National Meteorological Agency, Ethiopia
LU/LC	Landsat analyzed images (1985–2019)	USGS (https://earthexplorer.usgs.gov/)
C factor	Land use land cover classes	Own analysis
P factor	LU/LC class maps and slope map	Own analysis

30 m. Land cover factor (C_factor) and management/conservation practice (P_factor) were generated from land use/cover raster maps. Rainfall data was obtained from National Meteorological Agency, Ethiopia and soil data from Abay Basin Master Plan (MoWR 1998). These data inputs were integrated in RUSLE model using ArcGIS 10.5 software.

Estimating RUSLE-factors

The processes of soil erosion are influenced by two major factors, geomorphology (physical features) and hydrology of the catchment (Aga et al. 2019; Marttila and Kløve 2010). Depending on their data requirements and applicability, different methods (models) were developed to estimate soil erosion risk in different parts of the world. In this study, RUSLE with GIS was employed to analyze annual soil loss (Auerswald et al. 1992). RUSLE is one of the empirical models and widely applied in regions where data sources are scarce (Hurni and Meyer 2002; Bewket and Teferi 2009). The effectiveness of this model has been confirmed by previous studies (Markose and Jayappa 2016; Rozos et al. 2013). However, this method only estimates soil loss from sheet and rill erosion, not considering gully and stream bank erosion. In addition, it is incapable of estimating SDR and SY. Because of this, additional algorithm was applied to estimate SDR. Soil loss estimation using RUSLE in GIS environment involves integration of five different parameters (R, K, LS, C and P) as shown in Eq. (1) below (Renard et al. 1997; Sheikh et al. 2011).

$$A = R * K * LS * C * P \tag{1}$$

where, A is the annual soil loss (metric tons/ ha/year); R is the rainfall erosivity factor (MJ mm/h/ha/year); K is soil erodibility factor (metric tons/ ha/MJ /mm); LS = slope length factor (dimensionless); C is land cover and management factor (dimensionless); and P is conservation practice factor (dimensionless).

Rational of using RUSLE for soil erosion modeling

The Revised Universal Soil Loss Equation (RUSLE) improves most of the soil erosion factors. RUSLE modifies R_factor to account the impacts of raindrops on the detachment of sol particles in flat slopes. Improvement in slope length and steepness (LS) factor in RUSLE is a major change that accommodates complex slopes. Moreover, modifications were considered in C_factor (contribution of residue considered) and P_factor (strip cropping included). RUSLE also considers areas of net sedimentation in the converging and diverging terrain. All these improvements in soil erosion factors enable users to apply this model in the study of soil erosion risk and sediment delivery in different catchments having various spatial scales and complex topography.

Rain fall erosivity (R-factor)

it is an index that quantifies detached and transported sediment from sheet and rill erosion by rainfall/runoff (Wischmeier and Smith 1978; Woldemariam and Harka 2020).This parameter could be estimated by considering the kinetic energy of the storm and maximum 30 min intensity (Wischmeier and Smith 1978). However, meteorological stations lack long term data of 30 min intensity and because of this gap other empirical equations that correlate mean annual rainfall and R factor were developed (Manaouch et al. 2021). Rainfall data from four stations (Bichena, Dejen, Kuy and Rebugebeya) were used to calculate R-factor values of the study area (Fig. 3). Annual rainfall records from these stations covering the period of 45 years (1974–2019) were used. The mean annual rainfall was first interpolated to generate continuous rainfall data for each grid cell by "3DAnalyst Tools Raster IDW Interpolation" in Arc GIS environment (Fig. 4). Then, the erosivity (R) factor value was calculated using Eq. (2) suggested by Hurni (1985) for the Ethiopian conditions.

$$R = -8.12 + 0.562P \tag{2}$$

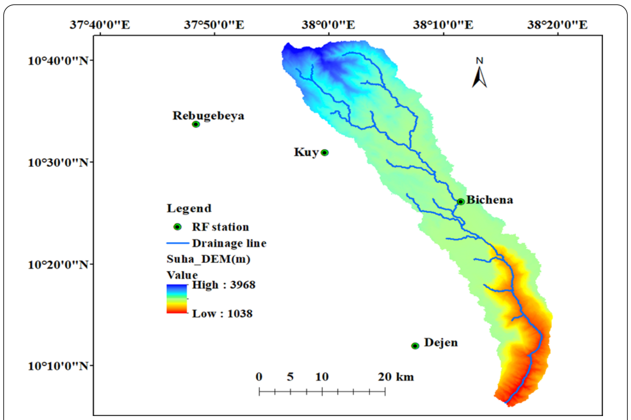


Fig. 3 Rainfall stations in and nearby the Suha watershed

where R is the rainfall erosivity factor and P is the mean annual rainfall (mm).

Soil erodibility (K) factor

Soil erodibility is the most important factor that determines soil erosion and it signifies the inherent characteristics of the soil to erosion (Manaouch et al. 2021). Severity of soil erosion and its spatially variability is due to the variation in soil texture, organic matter (OM) content, aggregate stability and permeability (Uddin et al. 2019; Panagos et al. 2014). Different methods can be applied in estimating soil erodibility depending on the availability of data. However, in data scarce regions, like Ethiopia, K-factor values are adapted from literature based on soil color (Hurni 1985; Hellden 1987). In this study, the same approach was applied to estimate K-factor values. Six major soil types were identified in the study area and K-factor values recommended for Ethiopian conditions were adopted from Hurni (1985) and Hellden (1987) for each soil type (Fig. 5 and Table 3).

Topographic (LS-factor)

LS factor is the ratio of soil loss from a given area to that of RUSLE standard plot with length (22.13 m) and steepness (9%) while maintaining other factors constant (Renard et al. 2011). Even though different algorithms were developed so far, most of them are site-specific and LS_factor values are highly variable across regions. In this study, the method proposed by Hurni (1985) for Ethiopian condition was adopted to generate LS_factor values using slope length and slope of the watershed (Fig. 6 and Table 4). Slope length was calculated using equations developed by Moore and Burch (1986) and employed by other researchers (Kidane et al. 2019; Mohammed et al. 2020; Moisa et al. 2021).

Land cover (C) factor

This factor represents the extent of land cover by different vegetation type, from dense forest to annual crop cover. The values of this parameter ranged from 0 to 1, in which the lower value represent dense forest cover and the higher value represent bare lands (Erencin et al. 2000). C_factor values can be estimated using various techniques. In this study, C_factor values were assigned for each land use/cover class by adopting from literature

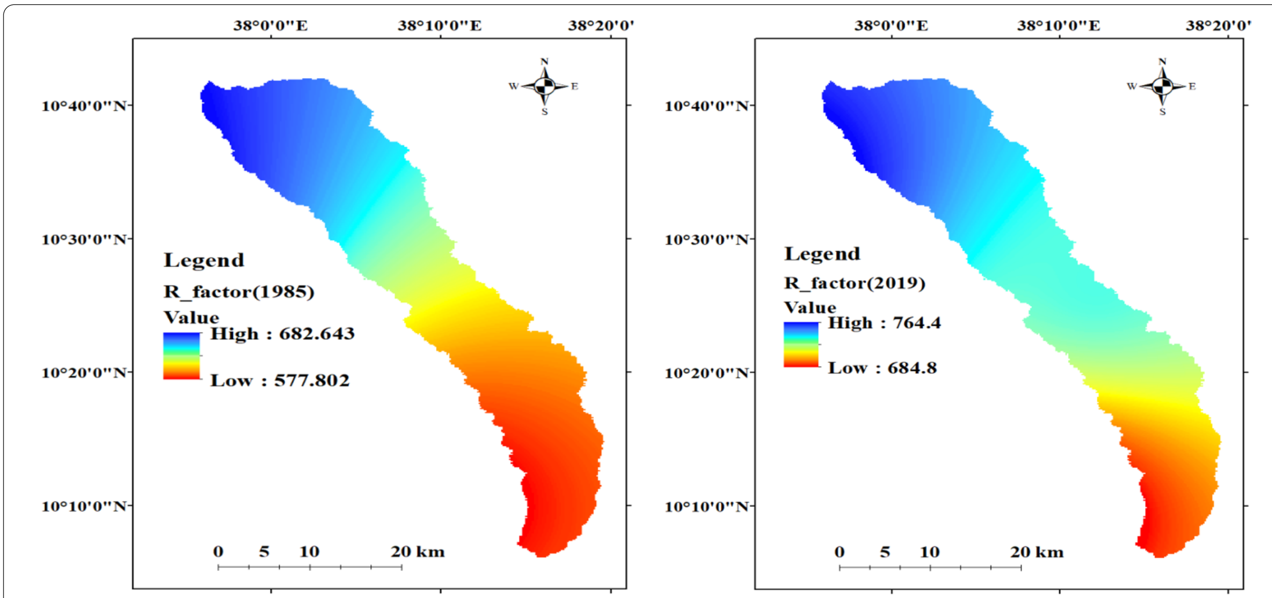


Fig. 4 R_factor map of 1985 (left) and 2019 (right)

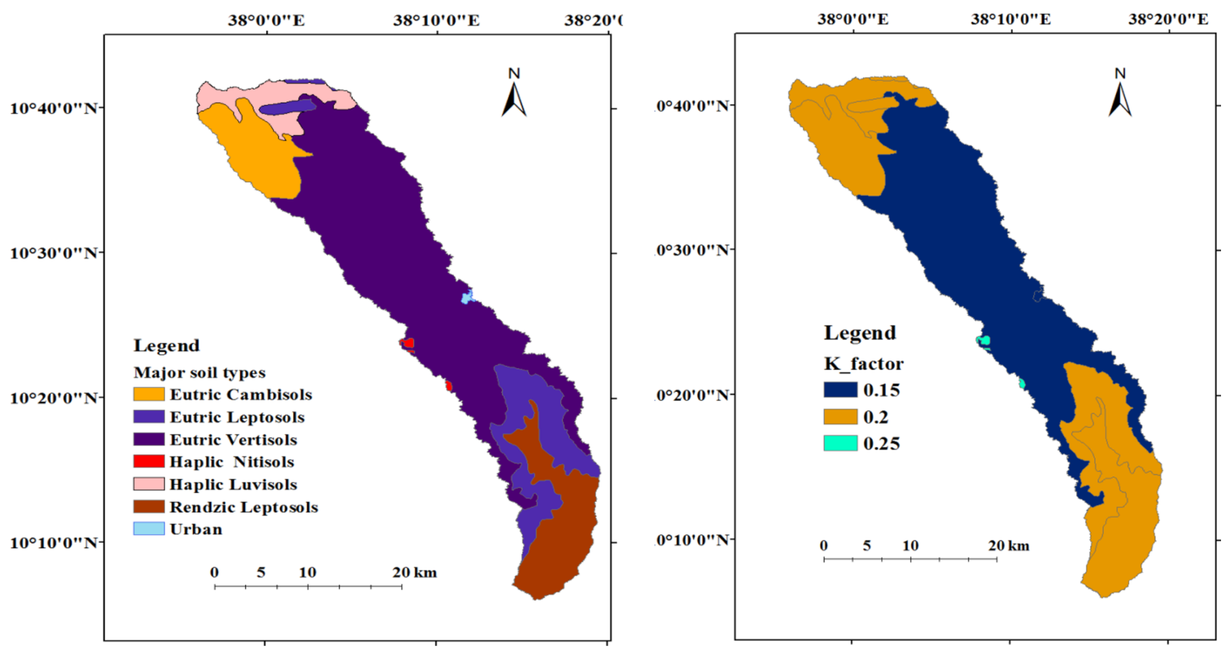


Fig. 5 Map of soil type (left) and K_factor (right)

Table 3 Soil units, soil color and adopted K-factor values in the Suha watershed

Soil unit	Soil color	K-values	References
Eutric Cambisols	Brown	0.2	Hurni (1985), Hellden (1987)
Eutric Leptosols	Brown	0.2	
Eutric Vertisols	Black	0.15	
Haplic Nitosols	Red	0.25	
Haplic Luvisols	Brown	0.2	
Rendzic Leptosols	Brown	0.2	

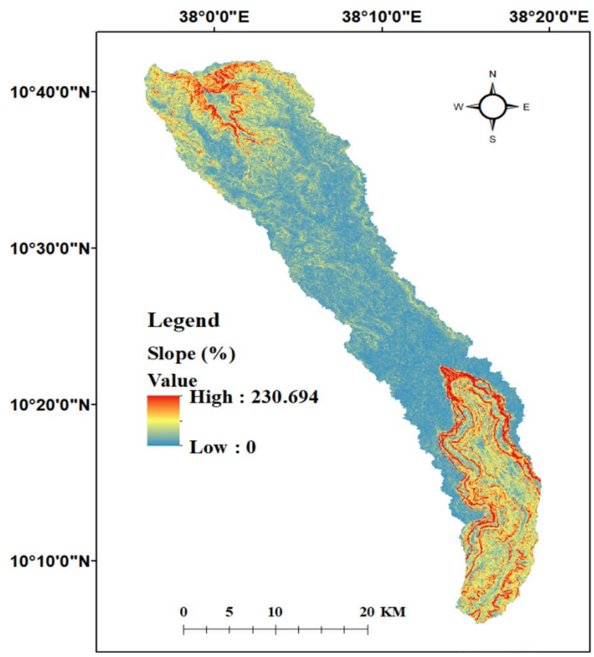
(Gashaw et al. 2017; Belayneh et al. 2019) (Fig. 7 and Table 5). Other researchers also used similar approach (Degife et al. 2021; Fenta et al. 2021; Gashaw et al. 2017; Moges and Bhat 2017). Six types of land use land cover classes were identified in the study area (Table 6). The extent and trend of land use/cover changes are described in Table 5. Land use land cover change showed significant temporal and spatial variation between 1985 and 2019 years in the study watershed. The proportion of cultivated land has increased from 55.2% (44,131.9 ha) to 74.4% (59,731.5 ha); bare land also increased from 1.8% (1417.7 ha) to 8.4 (6714.9 ha). In all study periods, agricultural land, bare land, and built-up area significantly increased, whereas grazing land and shrub land decreased considerably.

Table 4 Factor_L and Factor_S values derived from slope length and slope of the watershed

Slope length (m)	Factor_L	slope of watershed (%)	Factor_S	Reference
< 5	0.5	< 5	0.4	Hurni (1985)
5–10	0.7	5–10	1.0	
10–20	1.0	10–15	1.6	
20–40	1.4	15–20	2.2	
40–80	1.9	20–30	3.0	
80–160	2.7	30–40	3.8	
160–240	3.2	40–50	4.3	
> 240	3.8	> 50	4.8	

Conservation or management factor (P-factor)

This parameter reflects the ratio of soil loss from managed field to bare land or up and down (along the slope) cultivated fields (Morgan 1996; Wischmeier and Smith 1978).Values were ranged from 0 to 1, in which the lowest value represents well managed fields and higher value for unmanaged fields (Morgan 1996). In this study, P_factor values suggested for Ethiopia conditions (Hurni 1985) were adopted and assigned to each land use/cover class. (Fig. 8 and Table 6). Other scholars (Atoma et al. 2020; Tadesse et al. 2017; Tamene et al. 2017) also applied the same method to estimate soil erosion risk in Ethiopia.



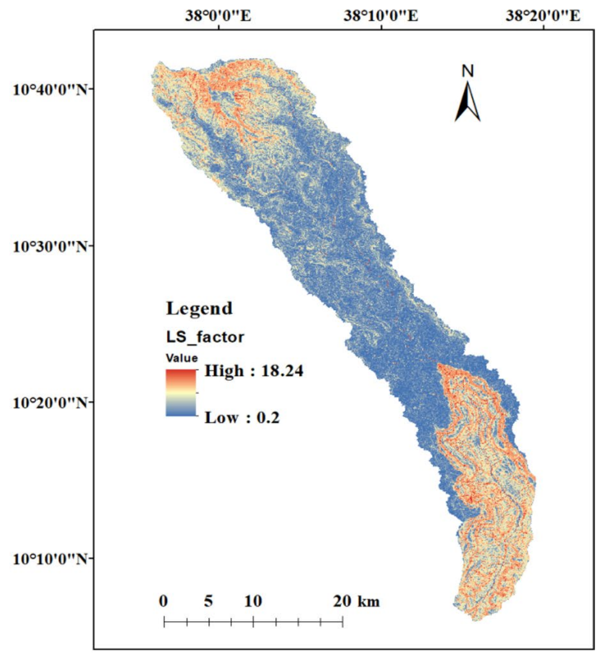


Fig. 6 Slope map (left) and LS_factor map (right) of Suha watershed

Estimating SDR and SY

Sediment delivery ratio (SDR) is the proportion of eroded sediment that reaches the outlet of the catchment to the total amount of eroded sediment (Julien and Frenette 1998). This parameter can be estimated using different algorithms depending on the availability of measured data. In data scarce regions, SDR can be analyzed using stream channel bed slope as data input in Arc GIS environment. This approach has been applied in different catchments of Ethiopia where data availability is challenging (Zerihun et al. 2018). In this study, DEM with 30 m * 30 m resolution was used as data input for this purpose. Flow direction, accumulation and stream network were analyzed from this DEM. In addition HEc GeoHMS tool in Arc GIS was applied to calculate stream channel bed slope (Zerihun et al. 2018).

$$\mathrm{SDR} = 0.627 * (\mathrm{SCS})^{0.403} \tag{3}$$

where, SDR is sediment delivery ratio and SCS is the stream channel slope (%).

Sediment yield (SY) is the amount of sediment that leaves the watershed (Sharp et al. 2018). The scarcity of measured sediment data is the main problem in the study of sediment dynamics. In this study, SY was estimated by integrating gross soil loss and SDR of the watershed (Eq. (4)) (Mutua et al. 2006).

$$\mathrm{SY} = \mathrm{E} * \mathrm{SDR} \tag{4}$$

where, SY = Sediment yield (ton/yr); SDR = the proportion of sediment reaching in the outlet of the watershed; E = Total soil loss (ton/yr) of the watershed.

Table 5 Land cover classes (adopted from Yeneneh ea al. 2022) and their corresponding C- factor values in the Suha watershed

LU/LC class	Area (ha)				C_factor value and reference	
	1985	1999	2009	2019	values	References
Agricultural land	44,313.9	51,938.9	57,523.8	59,731.5	0.15	Gashaw et al. (2017), Hurni (1985)
Grazing land	25,762.2	18,272.3	11,329.5	7193.8	0.01	Gashaw et al. (2017), Tadesse and Abebe (2014)
Forest land	668.0	543.6	883.2	1076.5	0.001	Gashaw et al. (2017), Morgan (2005)
Shrub land	7441.3	6592.5	4364.5	3897.1	0.014	Gashaw et al. (2017)
Bare land	1417.7	1967.4	4854.5	6714.9	0.6	Belayneh et al. (2019)
Built up area	725.7	1016.9	1376.4	1719.7	0.09	Gashaw et al. (2017)

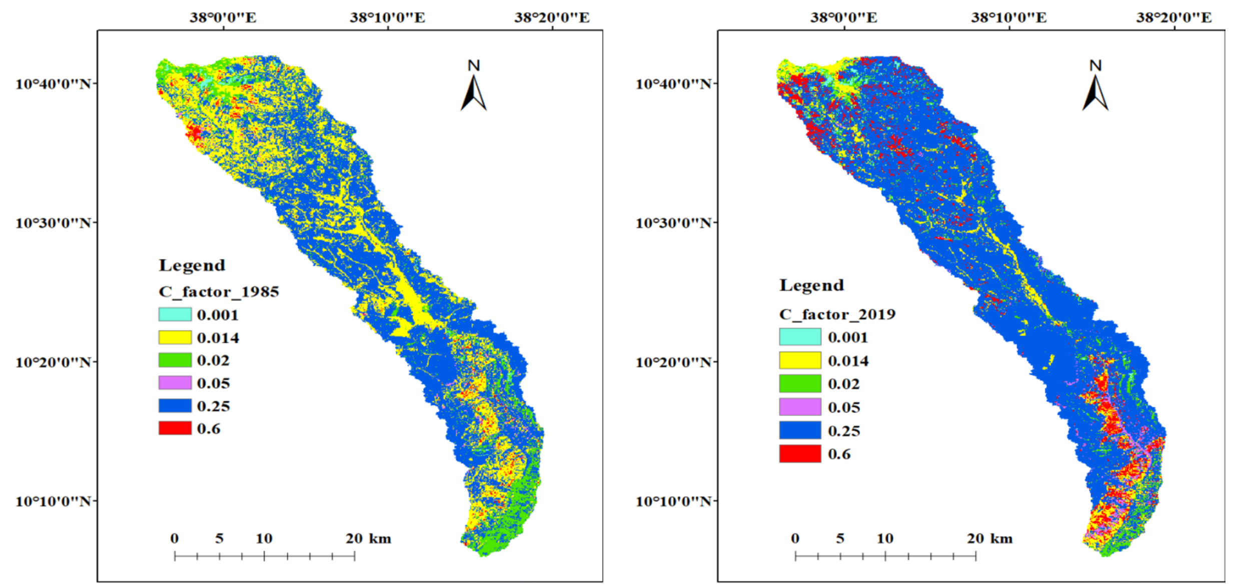


Fig. 7 C_factor map of 1985 (left) and 2019 (right) for the Suha watershed

Delineation and prioritization of sub-watersheds

This task is essential for resource use efficiency and effectiveness of watershed development. Soil and water conservation activities demand huge investment (resource and labor intensive), implying that allocation of limiting available resources for priority area is essential. Sub watersheds were delineated from a 30 * 30 m resolution of SRTM DEM using Arc Hydro Tools in ArcGIS10.5 environment. Based on the analysis result, the study watershed was classified in to 24 sub watersheds (Fig. 9). Prioritization of sub watersheds for implementation of soil conservation measures was carried out based on the magnitude of the rate of soil erosion, which was obtained by superimposing map of annual soil loss of the watershed with sub watershed maps in Arc GIS. The application of zonal analysis based on the hydrological response unit (HRU) by grouping of identical hydrological responsive areas, is also becoming a useful approach to delineate

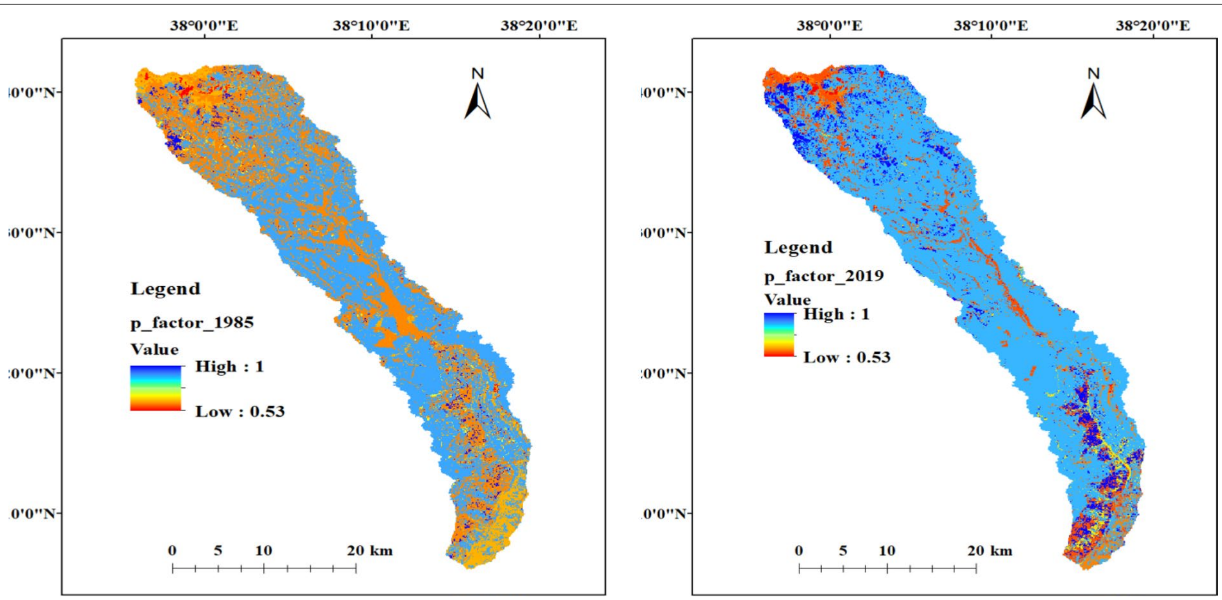


Fig. 8 P_factor map of 1985 (left) and 2019 (right) for Suha watershed

Table 6 P-factor values adopted for different land use classes in the Suha watershed

Land use land cover class	P_factor value	References
Agricultural land	0.9	Moisa et al. (2021), Atoma et al. (2020)
Grazing land	0.6	Moisa et al. (2021), Atoma et al. (2020), Tadesse et al. (2017)
Forest land	0.53	Moisa et al. (2021), Atoma et al. (2020)
Shrub land	0.63	Moisa et al. (2021)
Bare land	1	Modified from Moisa et al. (2021)
Built up area	0.7	Modified from Moisa et al. (2021

areas having similar soil erosion rates (Kumar and Mishra 2015) (Fig. 10).

Results

Extent and spatial distribution of soil loss in the Suha watershed (1985–2019)

The trend of annual soil loss and its spatial distribution in the watershed are depicted in (Fig. 11 and Table 7). Total soil loss of the catchment was 1,221,214; 1,751,477; 2,522,770 and 2,426,359 t yr^{-1} in 1985, 1999, 2009 and 2019 respectively. The total annual soil loss almost doubled (increased by 98.6%) over the past 35 years (1985–2019). The highest values of annual soil loss were observed on the upper and lower part of the watershed where there are steep slope areas and expansion of cultivation to this slope range. The mean annual soil loss rates were also showed temporal and spatial variability; 15.2, 21.8, 31.4 and 30.2 t ha^{-1} yr^{-1} for 1985, 1999, 2009 and 2019 respectively. High soil erosion rate

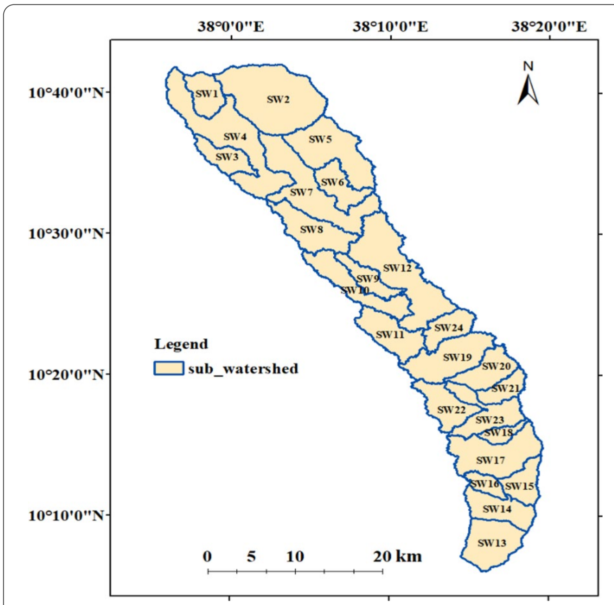


Fig. 9 Sub watersheds of the study catchment

is observed in the northern and southern parts of the watershed. In all study periods, soil loss rate is greater than the tolerable soil loss rate of 10 t ha−1 yr^{-1} estimated by Hurni (1985) for Ethiopia condition.

Estimates of sediment export and sediment deposition in the study area

The analyzed result of SDR indicated that its mean value was 0.21. Sediment export was estimated by integrating gross annual soil loss and SDR. Obtained results were 3.95, 5.66, 8.16 and 8.02 t ha^{-1} yr^{-1} for 1985, 1999, 2009 and 2019 respectively (Fig. 12, Table 7). The spatial distribution of sediment export also illustrated in (Fig. 12). This describes the extent and source of sediment from specific area.

Sediment deposition is the amount of sediment displaced from the upstream area and deposited on gentle slopes and depression areas within the catchment. The total annual sediment deposition values were 903,698; 1,296,093; 1,866,850 and 1,795,505 t yr^{-1} for the study periods (Table 8).

Severity classification is based on Degife et al. (2021), Yesuph and Dagnew (2019), Haregeweyn et al. (2017).

Impacts of LU/LC change on soil erosion in the Suha watershed

To explore the impacts of land use land cover classes on soil erosion, zonal statistics analysis was applied in Arc GIS. Significant variation was observed on the values of mean annual soil loss rate among different land use / cover classes. The highest mean value of soil loss (from 53.7 to 102.7 t ha^{-1} yr^{-1}) was observed in bare lands followed by cultivated land (from 17.3 to 29.4 t ha^{-1} yr^{-1}) and built up areas (from 16.4 to 32.4 t ha^{-1} yr^{-1}) from 1985 to 2019 years (Fig. 13). Obviously the lowest value was recorded in forest land followed by shrub land. Slope length and slope steepness play a great role in the processes of soil erosion. Significant differences were also observed on soil erosion rate in different landscape positions of the watershed. Areas

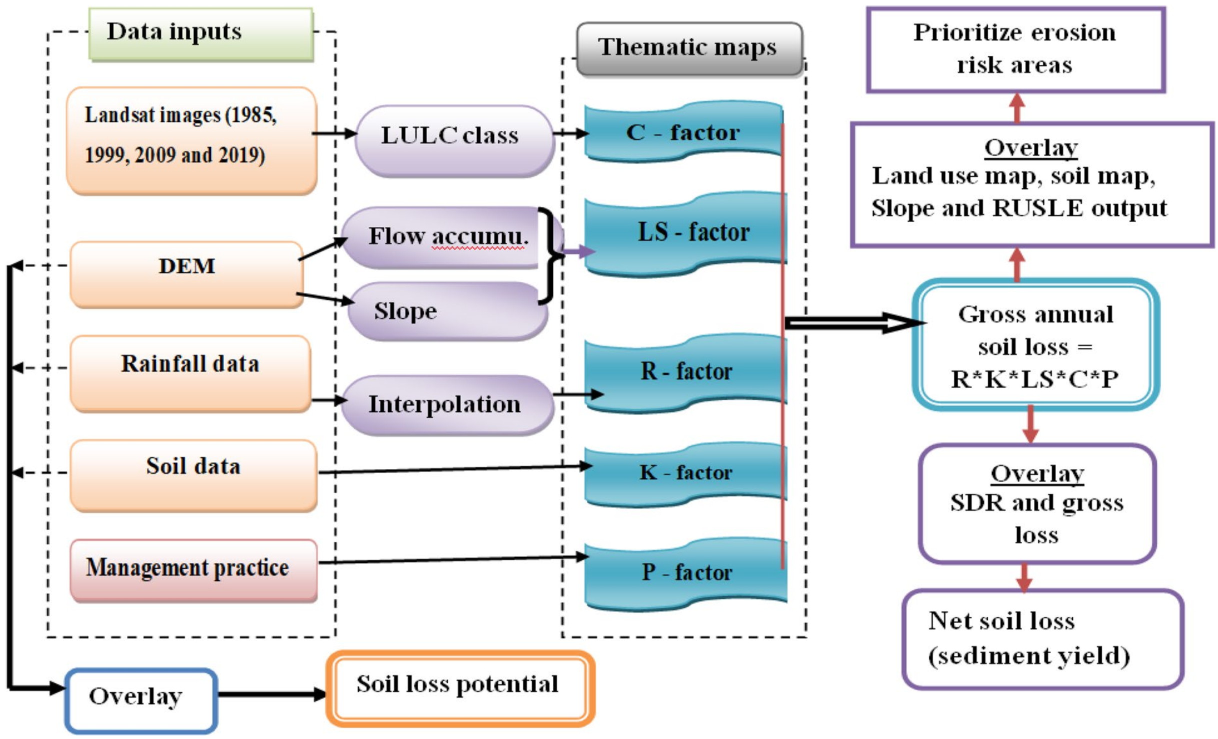


Fig. 10 Methodological framework used to estimate soil loss potential, soil erosion risk and sediment yield in the Suha watershed

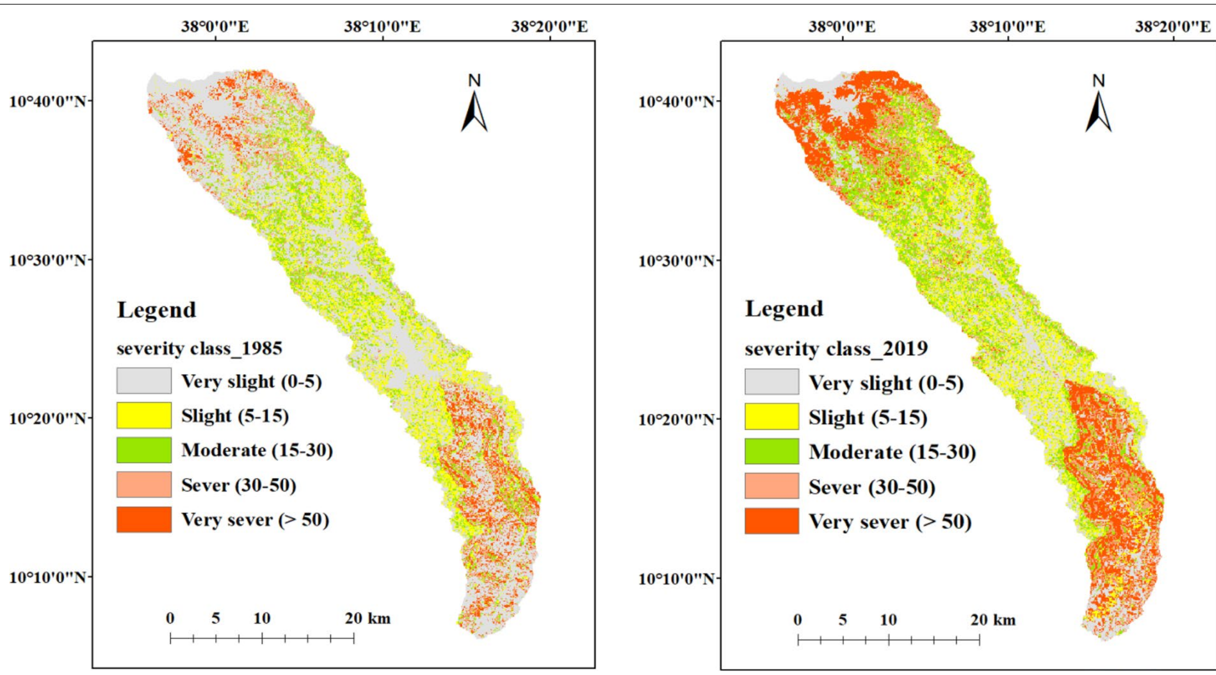


Fig. 11 Spatial distribution and severity class maps of soil erosion for 1985 (left) and 2019 (right) in the Suha Watershed

Table 7 Soil loss and sediment export trends of the Suha watershed in the last 35 years

Year	Mean soil loss rate (t ha^{-1} yr^{-1})	Total annual soil loss (t yr^{-1})	Mean sediment export (t ha^{-1} yr^{-1})	Total sediment export (t yr^{-1})	Sediment deposition (t yr^{-1})
1985	15.2	1,221,214	3.95	317,515.5	903,698
1999	21.8	1,751,477	5.66	455,384.1	1,296,093
2009	31.4	2,522,770	8.16	655,920.3	1,866,850
2019	30.2	2,426,359	8.02	630,853.2	1,795,505

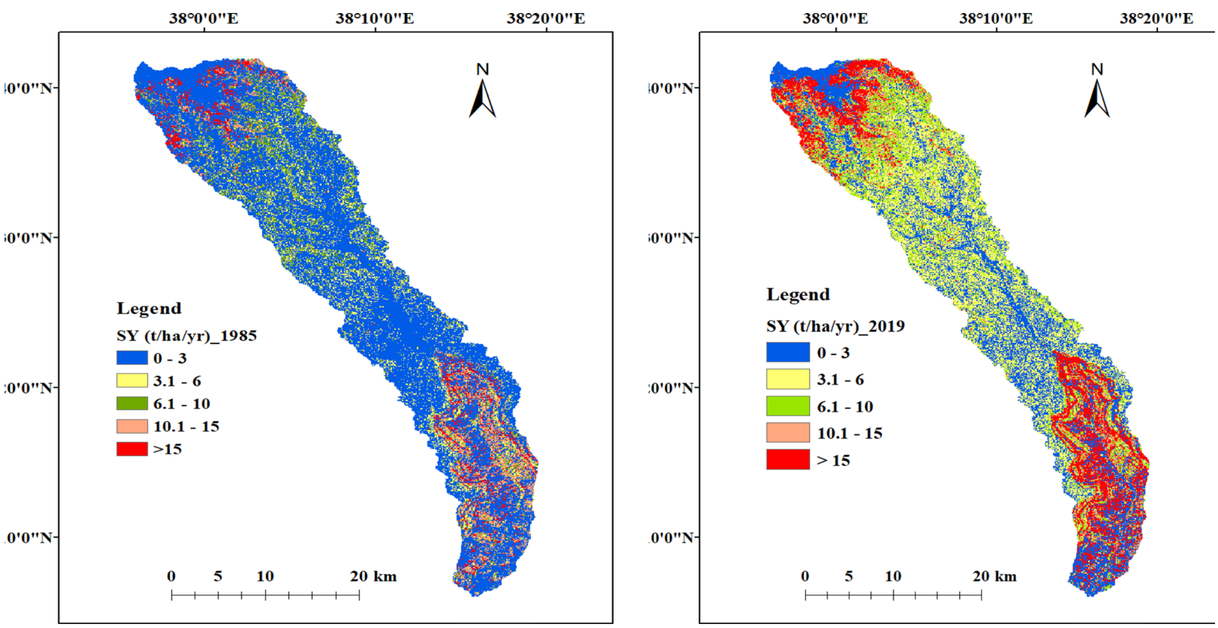


Fig. 12 Spatial distribution maps of sediment export for 1985 (left) and 2019 (right) for Suha watershed

Table 8 Soil erosion severity classes and area coverage in the Suha watershed (1985–2019)

Soil loss rate (t ha^{-1} yr^{-1})	Severity class	1985		1999		2009		2019	
		Area (ha)	(%)	Area (ha)	(%)	Area (ha)	(%)	Area (ha)	(%)
0–5	Very slight	42,957	53.5	32,624	40.6	16,223.9	20.2	22,252	27.7
5–15	Slight	13,826	17.2	14,930	18.6	24,881.6	31.0	16,788	20.9
15–30	Moderate	10,852	13.5	13,350	16.6	12,211.7	15.2	15,643	19.5
30–50	Severe	6126	7.6	8020	10.0	8572.9	10.7	9138	11.4
> 50	Very severe	6582	8.2	11,419	14.2	18,452.9	23.0	16,522	20.6
	Total	80,343	100	80,343	100	80,343	100	80,343	100

with slope gradient greater than 30% showed a mean soil loss rate from 26.6 to 60.9 t ha^{-1} yr^{-1} (Table 9).

Soil erosion severity classes based on sub watersheds

Exploring the spatial variability and identifying soil erosion risk areas is crucially important for technology selection; proper planning, resource allocation and application of soil and water conservation strategies on the bases of severity class. Soil erosion severity classes were analyzed by reclassifying soil loss map and adopting class ranges of Haregeweyn et al. (2017). Soil loss rate ranged from 0 to 5 t ha^{-1} yr^{-1} rated as very slight; from 5 to 15 t ha^{-1} yr^{-1}rated as slight; moderate (15–30 t ha^{-1} yr^{-1}); severe (30–50 t ha^{-1} yr^{-1}) and

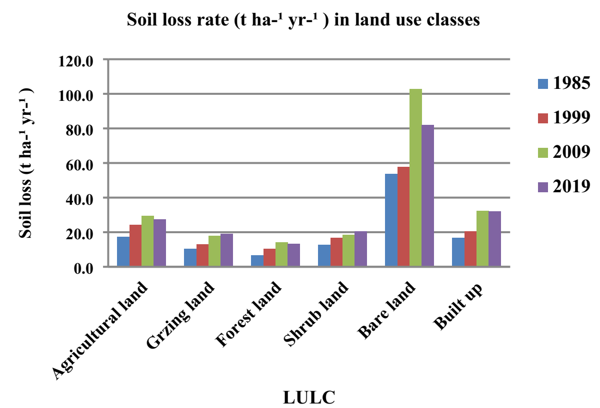


Fig. 13 Variation in mean soil loss in d/t land use classes and seasons

Table 9 Mean annual soil loss Rate (t/ha/yr) in different slope classes in Suha watershed

Slope class (%)	Mean soil loss Rate (t ha^{-1} yr^{-1})			
	1985	1999	2009	2019
0–5	6.4	8.3	10.2	10.1
5–10	8.6	11.7	14.7	14.6
10–20	14.1	20.9	28.6	28.8
20–30	22.4	32.3	50.1	49.4
30–50	27.8	38.0	60.9	58.6
> 50	26.6	41.5	60.6	57.9
Over all mean (t/ha/yr)	15.2	21.8	31.4	30.2

very severe (> 50 t ha^{-1} yr^{-1}). The analyzed results were ranged from very slight to very sever severity class (Table 10). In the entire watershed, significant variation was observed among sub watersheds in terms of their spatial distribution of soil erosion risk. Fourteen sub watersheds are classified under sever and very sever soil erosion severity class and these sub watersheds are found in the slope gradient greater than 30%. SW15, SW 17 and SW18 were classified under very sever soil erosion severity class (soil loss rate > 50 t ha^{-1} yr^{-1}) and found on the lower part of the watershed. These watersheds cover 7611.5 ha from the total area of the watershed and present on the steep slope areas. They are the first priority areas that demand urgent soil and water conservation measures. Sub watersheds under sever soil erosion severity class (soil loss rate ranged from 30 to 50 t ha^{-1} yr^{-1}) include, SW1, SW2,SW3, SW4, SW13, SW14, SW16, SW20, SW21, SW22 and SW23 and cover 35,375.2 hectare from the total watershed area. These sub watersheds are the second priority areas to undertake management actions. The other sub watersheds which cover 37,356.3 hectare of the watershed area are the last priorities for soil conservation activities as evidenced from the results of soil loss rates from these areas (Table 11). The results also showed that from the total area of the watershed 55.5% experienced > 30 t ha^{-1} yr^{-1} mean annual soil loss rate.

Model validation

Validation of model results is required to see the fitness of the RUSLE model and to compare the modeled results with measured values. However, in the study watershed measured sediment yield data are very fragmented and even in some years, data is totally missed for consecutive years. This is the basic problem for model validation. Due to this reason, analyzed results were compared with the findings of previous studies conducted in the north-western highlands of Ethiopia. Moreover, field survey was conducted and related information was gathered from development agents and households to cross check our result with the field data. Similar approaches were used by Bekele and Gemi (2021), Fenta et al.(2021), Haregeweyn et al. (2017) due to lack of measured data for validation.

Discussion

Extent and spatial distribution of soil erosion in the Suha watershed

Soil erosion causes critical socio-economic and environmental problems, particularly in developing countries. To design and implement successful management strategies, it is necessary to understand the mechanisms, extent, and severity of soil erosion, as well as the causes that drive it. Monitoring the spatiotemporal variability of soil erosion risk and sediment export is required for two fundamental practical reasons. The first one is, for proper resource allocation and effective watershed management activities. Soil and water conservation activities are labor intensive and demand huge investment. Therefore, available limited resources should be allocated to those landscapes which are vulnerable to soil erosion. The second reason is, for selection of effective soil and water conservation technologies. Different soil and water conservation technologies could be recommended for specific location depending on the agro ecology, topography and land use systems.

The results of this study revealed that the magnitude of mean annual soil loss rate significantly increased from 15.2 to 30.2 t ha^{-1} yr^{-1} over the past 35 years (1985–2019). Besides to this, the annual gross soil loss from the entire catchment similarly increased from 1.222 million tons per year to 2.426 million tons per year. This could be attributed to an expansion of cultivated land and bare land as the expense of other land

Table 10 Mean soil loss and SY of sub watersheds

No	Sub watershed	Area (ha)	Rate of soil loss(t ha^{-1} yr^{-1})				Mean SY (t ha^{-1} yr^{-1})			
			1985	1999	2009	2019	1985	1999	2009	2019
1	Sw1	1901.1	16.3	28.1	46.8	46.3	4.2	7.3	12.2	12.0
2	Sw2	8017.6	19.0	32.9	48.2	43.2	4.9	8.5	12.5	11.2
3	Sw3	1803.6	19.8	38.1	39.8	43.0	5.1	9.9	10.4	11.2
4	Sw4	7049.5	15.1	26.9	37.1	39.3	3.9	7.0	9.7	10.2
5	Sw5	4942.9	10.7	16.2	20.3	20.1	2.8	4.2	5.3	5.2
6	Sw6	2112.9	9.2	11.4	14.4	14.3	2.4	3.0	3.7	3.7
7	Sw7	6033.9	10.1	16.6	21.1	21.5	2.6	4.3	5.5	5.6
8	Sw8	3366.4	11.0	13.3	16.3	17.1	2.9	3.4	4.2	4.4
9	Sw9	1617.4	9.3	11.2	13.2	13.1	2.4	2.9	3.4	3.4
10	Sw10	3217.2	8.5	11.0	13.6	14.3	2.2	2.9	3.5	3.7
11	Sw11	2912.6	6.3	9.3	12.3	12.6	1.6	2.4	3.2	3.3
12	Sw12	7195.7	8.1	11.1	13.2	12.7	2.1	2.9	3.4	3.3
13	Sw13	3436.7	17.4	19.9	41.7	38.0	4.5	5.2	10.8	9.9
14	Sw14	2568.3	22.1	26.3	44.4	47.3	5.7	6.8	11.5	12.3
15	Sw15	1810.9	20.1	18.5	51.6	56.4	5.2	4.8	13.4	14.7
16	Sw16	956.3	21.6	33.1	45.4	45.9	5.6	8.6	11.8	11.9
17	Sw17	4643.1	26.6	32.7	51.8	47.0	6.9	8.5	13.5	12.2
18	Sw18	827.5	27.4	33.8	69.5	64.6	7.1	8.8	18.1	16.8
19	Sw19	4075.4	15.2	21.8	26.2	25.5	3.9	5.7	6.8	6.6
20	Sw20	2374.6	23.8	33.0	40.2	41.8	6.2	8.6	10.5	10.9
21	Sw21	1402.2	18.9	23.9	40.6	40.6	4.9	6.2	10.6	10.6
22	Sw22	2523.8	18.5	22.6	32.6	30.0	4.8	5.9	8.5	7.8
23	Sw23	2953.7	25.6	33.2	46.6	46.7	6.7	8.6	12.1	12.2
24	Sw24	1882.1	6.6	8.9	11.1	11.0	1.7	2.3	2.9	2.9

SY sediment yield

Table 11 Soil erosion severity class and priority levels of sub watersheds

Soil loss rate (t ha^{-1} yr^{-1})	Severity class	Priority level	Sub watershed	Area (ha)
0–5	Very slight		–	–
5–15	Slight	IV	SW6, SW9, SW10, SW11, SW12 and SW24	18,937.8
15–30	Moderate	III	SW5, SW7, SW8, SW19	18,418.5
30–50	Sever	II	SW1, SW2,SW3, SW4, SW13, SW14, SW16, SW20, SW21, SW22 and SW23	35,375.2
> 50	Very sever	I	SW15, W17 and SW18	7611.5

use types during the study period. The presence of steep slope landscapes, poor land management systems and absence of soil and water conservation strategies are also contributing factors for soil loss. Moreover, the variation of the amount of rainfall is one major cause for higher soil loss and sediment yield in the watershed.

Soil formation rate and soil loss tolerant limit for Ethiopian condition were suggested by Hurni (1986), which is within the range of 2–22 t ha^{-1} yr^{-1} and 2–18 t ha^{-1} yr^{-1} respectively. However, the values of this study are greater than these limits. In addition, the mean annual soil loss rate greater than 10 t ha^{-1} yr^{-1} could not be reversed in 50 years (Kouli et al. 2009). The results of this study are greater than this limit that confirmed the risk of soil erosion in the Suha watershed.

The trend and spatial distribution of soil erosion risk is highly impacted by human- induced activities. The highest amount of soil loss and sediment yield was observed from steep slope area (dominated by bare lands), cultivated fields on sloppy areas and open shrub lands. On the other hand, the lowest values were found in gentle slope areas and forest land use systems. Soil erosion risk is extremely high in 2009 as compared to other study periods due to the variation in mean annual rain fall and its erosivity power. Average annual rainfall has the highest value (1443.7 mm) in 2009 compared to other periods; in 1985, the average annual rainfall is 1186 mm; in 1999 (1324.3 mm), and in 2019 (1317.6 mm). Haregeweyn et al. (2015) conducted a review work on soil erosion and conservation in Ethiopia and inferred that 35% of the spatial and temporal variability of soil erosion is because of the variation in rainfall. Besides to this, land use/cover dynamic is a major factor for the change in soil loss rate and sediment yield. This continuous severe soil loss and sediment yield obviously causes both onsite and off-site effect of soil erosion. Transport of soil nutrient elements with sediment which intern impacts agricultural productivity and food security is an onsite effect of soil erosion. In addition, sediment deposition and eutrophication on water bodies, particularly on lakes is an off-site effect.

The results of this research are within the range of the findings of previous studies conducted in the Upper Blue Nile Basin and other parts of Ethiopia. The results of the present study are comparable with the findings of Fenta et al. (2021), who reported a mean annual soil loss rate of 32.8 t ha^{-1} yr^{-1}from Abay Basin. Similarly, Degife et al. (2021) reported the soil loss rate of 37 t ha^{-1} yr^{-1} from Hawassa lake catchment, Ethiopia. Haregeweyn et al. (2017) from the Upper Blue Nile River Basin (27.5 t ha^{-1} yr^{-1}); Kinde et al. (2019) from Guder sub watershed, central highlands of Ethiopia (25–30 t ha^{-1} yr^{-1}); Atoma et al. (2020) from Huluka watershed, central Ethiopia (14.4–27 t ha^{-1} yr^{-1}), and Tadesse and Abebe (2014) from Jabi Tehinan watershed, northern Ethiopia (30.4 t ha^{-1} yr^{-1}) reported similar results.

On the contrary, the findings of some other studies from different parts of Ethiopia showed a higher soil loss rate than the current study. For example, Tamene et al. (2017) reported a mean annual soil loss rate of 48 t ha^{-1} yr^{-1} from Laygeda watershed, Ethiopia. The findings of Zerihun et al. (2018) from Dembecha district showed soil loss tare of 49 t ha^{-1} yr^{-1}. The study of Gelagay and Minale (2016) indicated the soil loss rate of 47 t ha^{-1} yr^{-1}from Koga watershed; Belayneh et al. (2019) reported a soil loss rate of 42.8 t ha^{-1} yr^{-1} from Gumara watershed. The recent study of Woldemariam and Harka (2020) showed the soil loss rate of 75.85 t ha^{-1} yr^{-1} (in 2000) and 107.07 t ha^{-1} yr^{-1} (in 2018) from Erer Sub-Basin, Wabi Shebelle Basin, Ethiopia. From the same study, it was reported that soil erosion severity class was increased by 18.28% over the past 18 years. On the other, some other studies reported small values of soil loss rate compared to this study. For instance, Bekele and Gemi (2021) reported a mean annual soil loss rate of 2.2 t ha^{-1} yr^{-1} from Dijo watershed, Rift valley Basin. Similarly, the results of Tiruneh and Ayalew (2015) from Enfranz watershed (4.8 t ha^{-1} yr^{-1}); Ayalew (2015) from Zingin watershed (9.1 t ha^{-1} yr^{-1}) and Brhane and Mekonen (2009) from Medego Watershed (9.6 t ha^{-1} yr^{-1}) are smaller than the results of the current study. The variation of mean annual soil loss rate in different watersheds could be due to the variation in topography, management (land use system), and the amount of rainfall.

Sediment delivery ratio (SDR) and sediment export

SDR was estimated using channel bed slopes and the results showed that SDR has direct proportion with channel bed slope. As the channel bed slope increases, the velocity of runoff and sediment export also increase from the catchment. From the results of the three study periods, it is clearly observed that the highest value of sediment yield (8.16 t ha^{-1} yr^{-1}) was recorded in 2009 compared to the other three periods; 3.95 t ha^{-1} yr^{-1} in (1985); 5.66 t ha^{-1} yr^{-1} (in 1999) and 8.02 t ha^{-1} yr^{-1} (in 2019). This could be due to detrimental impacts of LULC changes in which cultivated land and bare land increased as the expense of other land use types. The results of the current study are within the ranges of previous findings. For instance, Fenta et al. (2021) reported 7 t ha^{-1} yr^{-1} mean sediment yield from Abay Basin. Kidane et al. (2019) estimated sediment yield for the three periods (1973, 1995 and 2015) in Guder sub watershed, Ethiopia and their results showed that the mean sediment yields were 6.79, 8.65 and 9.44 t ha^{-1} yr^{-1}. Tamene et al. (2017) from Laygeda watershed, Ethiopia (12.3 t ha^{-1} yr^{-1}) and Haregeweyn et al. (2017) from the upper Blue Nile Basin (7.34 t ha^{-1} yr^{-1}) reported similar findings.

The effects of LULC change and landscape positions on soil erosion

Raster maps of land use and cover changes and soil loss were superimposed to identify the relationship between these two parameters. The spatiotemporal variability of soil erosion risk is highly impacted by human-induced activities. The analysis results revealed that the rate of soil loss is extremely high in bare lands followed by cultivated fields and open shrub lands. The rate of soil loss from bare land was 511.1% times greater than forest land and soil loss from cultivated field was 105.2% times greater than forest land. This is attributed to over exploitation of cultivated fields without applying any soil and water conservation strategies, which is evidenced from field survey work. Frequent cultivation for seed bed preparation disintegrates soil structure and reduces aggregate stability which hastens soil erosion, particularly in slope areas. In addition, cultivated fields and bare lands are exposed to direct rain drop impact contribute higher soil loss and sediment yield. Poor land use systems and over exploitation of resources are responsible factors for the expansion of bare lands. On the other hand, the lowest values of soil loss and sediment yield were observed in forest lands. Forest covers reduce rain drop impact on soil particles and velocity of runoff, thereby significantly reduce soil loss and sediment yield.The relationship between soil erosion risk and the slope of the watershed was detected by, first reclassifying the maps of soil erosion risk and slope of the watershed in to different classes and then overlaying the two raster maps. The highest mean annual soil loss (60.9 t ha^{-1} yr^{-1}) was found in the upper and lower parts of the watershed where the slope gradient is greater than 30%. This is due to the effect of the slope of the landscape on the velocity and volume of runoff that greatly impacts soil erosion and sediment transport.

Previous studies conducted in different catchments of Ethiopia showed the impacts of land use land cover changes on the soil erosion risk and sediment export. The results of the current study are comparable with the findings of previous studies. For instance, a recent study conducted by Aneseyee et al. (2020) in Winka watershed, Omo Gibe Basin, Ethiopia indicated that the highest rate of soil erosion is from cultivated land that increased through time from 10.02 t ha^{-1} yr^{-1} (in 1988) to 43.48 t ha^{-1} yr^{-1} (in 2018) and the total soil loss change is 176.35 thousand tons over the past 30 years. Similarly, Yesuph and Dagnew (2019) reported the highest rate of soil loss (51 t ha^{-1} yr^{-1}) from cultivated land in Beshillo Catchment, Blue Nile Basin, Ethiopia. Likewise, Woldemariam and Harka (2020) indicated an extensive soil loss from cultivated land use (37.06 t ha^{-1} yr^{-1}) and bare land (15.78 t ha^{-1} yr^{-1}) from Erer Sub-Basin, Wabi Shebelle Basin, Ethiopia. The study of Gashaw et al.(2019) from Andasa Watershed, Upper Blue Nile Basin, Ethiopia revealed the change in soil loss rate from 35.5 t ha^{-1} yr^{-1} (in 1985) to 55 t ha^{-1} yr^{-1} (in 2015) due to an expansion of cultivated land. The highest rate of soil loss from cultivated land could be due to intensive cultivation, and expansion of agricultural fields to steep slopes, and marginal lands with poor management systems (Aneseyee et al. 2020; Yesuph and Dagnew 2019). On the other hand, Nyssen et al. (2009) reported higher value of soil loss rate from grazing land than cultivated fields in Tigray region, Ethiopia.

Implications of soil erosion and sediment export to watershed management

Soil erosion and sediment export due to human-induced activities is a major problem in the Suha watershed, affecting soil nutrient availability, agricultural productivity, and sediment deposition in downstream reservoirs (Diwediga et al. 2018). The extent and spatial distribution of soil loss and sediment export in response to land-use change and topography vary widely. The results of this study clearly show that the soil erosion severity class has increased by 32% (25,660 ha) over 35 years, and soil and water conservation measures are urgently needed to reverse this condition. The results will help decision makers, planners, and development agencies to prioritize sub watersheds based on soil erosion severity and select effective soil conservation technologies. Areas with very severe and severe soil erosion classes are recognized as the priority areas for the application of soil and water conservation measures. It also helps in allocating limited resources based on soil erosion risk levels. As soil and water conservation measures require huge investments, limited resources should be allocated to erosion hotspot areas to significantly reduce soil erosion and sediment discharge.

Conclusion and recommendation

The Suha watershed, found in the Upper Blue Nile Basin, Ethiopia, is heavily affected by human-induced soil erosion and sediment export. In this study, RUSLE with GIS was applied to estimate soil loss and sediment export, and to identify soil erosion hotspot areas for effective watershed management. The results showed that soil erosion risk and sediment yield, as well as hotspot areas were progressively increasing during the study period. In the past 35 years, the soil loss increased by 1.205 million tons and sediment yield by 313.335 thousand tons. In addition, Soil erosion hotspot areas also increased from 12,708 ha to 25,660 ha in the same period. Significant expansion of agriculture and bare land during this period are the major causes of extensive soil erosion rate in the watershed. These results underscore urgent need for selection and implementation of effective soil and water conservation technologies. Therefore, management strategies primarily focus on soil and water conservation techniques and afforestation programs are suggested as remedial action to reverse the negative impacts of soil erosion and to ensure environmental sustainability.

Soil loss due to gully erosion, stream bank erosion, and landslides were not considered in this study since RUSLE is incapable of analyzing soil loss from these soil erosion processes. Therefore, additional approaches should be integrated to better understand the risk of soil erosion in this region. Furthermore, to get comprehensive knowledge and to design sustainable watershed management strategies, impacts of soil erosion on soil nutrient export and related replacement costs, agricultural productivity and food security should be investigated.

Abbreviations
MAP: Mean annual precipitation; GIS: Geographic information system; RUSLE: Revised universal soil loss equation; SDR: Sediment delivery ratio; SY: Sediment yield.

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Author contributions
NY: conceptualization, designed methodology, data collection and analysis, writing—original draft, EE: conceptualization, designed methodology, supervision, validation, editing the manuscript. GLF: conceptualization, designed methodology, supervision, validation, editing the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used in the current study will be available from the corresponding author on request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All authors agreed and approved the manuscript for publication in Environmental Systems Research Journal.

Competing interests
The authors declare that they have no known competing financial interests or personal relationships.

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