Research Article

Soil erosion and sediment yield assessment using RUSLE and GIS-based approach in Anjeb watershed, Northwest Ethiopia

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Received: 4 August 2020 / Accepted: 8 April 2021

Published online: 26 April 2021

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Abstract

Soil erosion is a serious and continuous environmental problem in Ethiopia. Lack of land use planning, environmental protection, over-cultivation, and overgrazing are prominent causes of erosion and sedimentation. This study is conducted in Anjeb watershed located in the Upper Blue Nile Basin, Ethiopia. In this study, the quantity and distribution of soil erosion, sediment delivery ratio (SDR), and sediment yield of the watershed were assessed by employing remote sensing, geographic information system (GIS), and revised universal soil loss equation analysis capabilities. Important data sets of topography, soil, conservations practices, cover management, and rainfall factors were processed and superimposed in GIS analysis, and soil loss rate, SDR, and sediment yield of the watershed were derived. Based on the result found, the watershed was categorized into six classes of erosion: slight (0–5), moderate (5–10), high (10–15), very high (15–30), severe (30–50), and very severe (> 50) $\text{t ha}^{-1} \text{yr}^{-1}$. The estimated average annual soil loss was $17.3 \text{ t ha}^{-1} \text{yr}^{-1}$. The soil loss rate is higher in the steeper and topographically dissected part of the watershed. The average sediment delivery capacity was about 0.122. The result showed that the average sediment yield in the watershed was grouped into classes of low (< 2.5), moderate (2.5–7.5), high (7.5–12.5), very high (12.5–22.5), severe (22.5–40), and very severe (> 40) $\text{t ha}^{-1} \text{yr}^{-1}$. It is found that from a total of $20,125.5 \text{ t yr}^{-1}$ eroded soil over the whole watershed 2254.5 t yr^{-1} of sediment has been brought and deposited to the channels. Sediment accumulation from the watershed threatens the storage capacity and life span of Anjeb reservoir which is the source of irrigation water downstream. The study provides an insight to planners and resource managers to design and implement practices of watershed management to reduce erosion and enhance land productivity and to minimize the reservoir sediment accumulation.

Article Highlights

- The soil loss in the watershed ranges between 0 and $195 \text{ t ha}^{-1} \text{yr}^{-1}$
- The range of SDR value of the channel networks was between 0.03 and 0.214.
- From a total of eroded soil materials, 12.2% have been delivered to the channels, and 87.8% deposited before getting into the channel networks.

Keywords Anjeb · GIS · RUSLE · SDR · Sediment yield · Soil loss

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1 Introduction

Soil erosion includes the disaggregation, transport, and deposition of soil and weathered particles [1]. In the dry season, the plant cover becomes sparse and makes the surface susceptible to raindrop impacts during the beginning of the wet season [2, 3] which gives rise to high soil erosion. The continuous fragmentation of soil aggregates and the loss of topsoil due to severe rainfall erosivity disturbs the agricultural production systems [3, 4]. In many parts of the world in general and in Ethiopia in particular, soil erosion affects the stability of ecosystems [5, 6] and frequently causing irreversible land degradation. Soil erosion has shown accelerating trends in the twentieth century around the globe [7]. The global mean soil erosion is estimated between 12 and 15 t ha⁻¹ yr⁻¹ [8]. Annually, there is a loss of about 0.90–0.95 mm of soil from the land surfaces [9]. FAO reported that the global annual water-triggered soil erosion is estimated at about 20–30 gigatonnes per year [9]. The global annual water and wind-driven soil erosion is estimated at around 75 billion tons [10].

Soil erosion is operating under various interrelating processes functioning in a multifaceted hierarchy. In tropical regions, the leading cause of land degradation by water is anthropogenic activities [10]. Inhibition of erosion and sedimentation are significant since they have a direct effect on soil fertility and the quality of water [11]. Soil erosion results in low productivity of the agricultural sector, the collapse of ecosystems, and an increase in sediment accumulation [12]. Soil erosion is the cause of the deterioration of crop yields and wasting of lands which give rise to food insecurity [9, 13]. Soil erosion declines the crop yields to 17% that enhances the usage of chemical fertilizers, which through time results for land relinquishment [7]. The cycle of nutrients of soils could be significantly affected by soil erosion, transportation, and deposition of sediments [14]. Therefore, the catastrophic problem of soil erosion needs to be minimized considerably [15].

On-site and off-site problems of basins can be related to the variety of soil erosion processes. On-site effects are related to land degradation and loss of agricultural productivity, and off-site effects are mainly related to sedimentation of reservoirs and loss in water storage capacity [6, 16, 17]. Soil erosion brings the removal of fertile topsoil, degrades the water quality of downstream areas of catchments [18], and can reduce the storing capability of dams and reservoirs and hence impedes the functionality of hydraulic structures [19]. The annual loss of storage capacity of the world's reservoirs due to sediment deposition is around 0.5–1%, and reservoirs may lose the majority of their capacity in the next 25–30 years [20]. Reports have shown that the amount of sediment

yield in African reservoirs and rivers varies between 0.002 and 157 t ha⁻¹ yr⁻¹ [21]. Reference [8] indicated that 19% of the reservoirs in Africa are under the problems of siltation because of water erosion and about 4,940,000 km² of Africa land is susceptible to various kinds of degradation from which water degradation is estimated to cover about 2,270,000 km² [9]. A number of hydropower and irrigation reservoirs in Ethiopia (e.g., Legedadi, Abasamuel, Angerib, Borkena, Tekeze, and Gilgel Gibie I) have been affected by the problem of siltation. It is reported that their size is reducing and the water quality is deteriorating which impedes the intended use and the life span of these reservoirs [22]. By clogging irrigation channels, sedimentation raises water conveyances maintenance costs and creates a negative impact on downstream agriculture [23, 24]. Soil erosion and its resulting sediment concentration also strongly impact aquatic environments when the rate of sedimentation exceeds the tolerance levels of such environments [25]. The other environmental problem due to soil erosion could be landslide susceptibility of hilly areas [26] mainly because of low vegetation cover due to poor soils. Surface erosion may cause landslides that occur on gullies areas [27]. Therefore, assessing soil erosion including its spatial distribution can be considered as an input for the development of an environmental policy framework to protect soil and other resources [28].

The reduction of sediment volume delivered to the reservoirs can be achieved by reducing soil erosion as well as by minimizing the sediment delivery from the hillslopes to the rivers. Quantifying spatially distributed sediment yield and precise identification of sediment source and erosion vulnerable areas are significant for watershed conservation prioritization and reduction of the socio-economic and environmental cost because of sedimentation on various irrigation and hydropower reservoirs [29, 30]. Erosion and sediment yield information is, therefore, a crucial issue in detecting the source of pollution [31] comprehensive control and management of watersheds as well as in the design and maintenance of hydrostructures such as dams and reservoirs [32]. Knowledge of the quantitative and spatial distribution of erosion is required to control sediment load and has important implications for the study of off-site and on-site environmental impacts because of sediment deposition.

Soil loss can be quantified by considering the erosion processes, the methods to be followed, and the availability of data in relation to the factors of soil erosion of an area [33]. Availability of data and the methodology remain an important issue in the history of soil erosion studies. There are various methods to estimate soil erosion which range from process-based to factor-based approaches [33]. To estimate soil erosion, varieties of models (empirical, conceptual, and physical) that differ in data inputs and

complexity have been established worldwide [34]. Among these models which gained universal acceptance is the empirical RUSLE [35]. The selection of models for erosion estimation is subjected to data availability and proposed use of the model among others [34]. The RUSLE method is suitable for the analysis and estimation of soil erosion going on a long time [25] and has been implemented in various environments and climates [36, 37]. It was developed to advance the assessment of the geographical extent of potential soil erosion. It is a proven and effective method for assessing soil loss in various areas of the globe. Studies were conducted especially in highland watersheds of Africa to estimate soil erosion using the RUSLE methodology [38, 39]. The RUSLE has become a widely accepted model because of its spatial characteristics and simplicity. The development of RUSLE model improves the assessment of soil erosion of areas [40]. A physically distributed component is developed and incorporated with the RUSLE to assess soil loss from landscapes. Soil loss per grid cell of an area can be quantified by employing RUSLE [41]. The focus of USLE is on cropland inter-rill and rill erosion considering the impacts of topography and climate [15] but has limitations to estimating gully erosion [42, 43]. The USLE was improved to RUSLE by Renard et al. [35]. RUSLE has a special advantage over the USLE since it incorporates process-based and empirical characteristics [40, 44]. Sediment yield in a watershed could be predicted with RUSLE having data inputs from GIS and RS [45]. GIS allows more accurate outputs for the RUSLE in small watersheds, even though it is exposed to limited data availability [46].

The RUSLE methodology is chosen in this study because it has adequate data requirements and compatible with GIS [47]. The spatial layers of RUSLE model inputs can be overlaid and processed in GIS [48]. The spatial distribution of sediment yield along stream channels was estimated with a sediment delivery model. In previous years' significant number of erosion assessment methods used plot scale observations to extrapolate catchment or landscape erosion rates [49, 50]. Recent advances in GIS, remote sensing, and DEM have promoted the application of spatial models of erosion and sediment distribution at catchment scales [51].

As the spatial gross soil loss is measured with RUSLE, the amount of eroded and transported soil in a watershed could be estimated using observations of sediment deposits from measurement points or outlets and sediment rating curve methods. Sediment delivery in watersheds could be estimated with the SDR approach [52]. Soil particles detached from the ground by raindrop impacts are transported to the rivers that augment the sediment load and SDR of basins [53]. The SDR estimates the amount of sediment that could be transported to the stream networks from the drainage area above [54]. It is a fraction

of upslope gross erosion and is considered as an index of sediment conveyance efficiency in watersheds [55]. The SDR enables to estimate sediment transport in watersheds where there are inadequate sediment yield observations. The Anjeb watershed is among Ethiopian critical watersheds that experiences scarcity of data related to soil erosion and sediment yield. In this study, the RUSLE is applied together with SDR to estimate the sediment yield. This study is the first attempt to estimate sediment yield by integrating spatial soil loss which has been estimated with RUSLE methodology and the SDR approach in the foot of the Choke Mountain Range which is among the highest mountain ranges in Ethiopia and the potential source of water for the Blue Nile River. Estimating sediment yield by integrating soil loss with SDR is not common in Ethiopian ungagged watersheds which are vulnerable to high soil erosion and sediment yield. In most Ethiopian watersheds including the Anjeb watershed, there is a scarcity of data, especially measured data related to soil erosion and sediment yield. Because of this, there has been no attempt in estimating the soil loss and sediment yield of the watershed yet. No previous studies related to erosion and sediment processes employing any modeling framework have been conducted in the watershed. In addition, the amount of sediment accumulating in the Anjeb reservoir from the upstream of the watershed has not yet quantified which is fundamental for the proper management of the reservoir and the selection and implementation of appropriate watershed management practices in the watershed. The method we followed in the study helps to fill the knowledge and information gap to quantify soil loss and sediment yield in data-scarce ungagged Anjeb watershed and other related watersheds in the area and help local resource managers to construct suitable watershed management practices. It provides an insight to planners and decision-makers to understand the susceptibility of the watershed to erosion and to design soil and water conservation options. The Anjeb reservoir which is constructed on the river Anjeb for irrigation to the downstream areas is significantly affected by sediment deposition from the upstream of the watershed. The practices of crop cultivation in all parts of the watershed coupling with low vegetation cover increase soil erosion in the watershed and sediment silting in the reservoir. According to the report of East Gojjam District Agriculture and Natural Resource Office [56], currently, the size of the reservoir and the irrigation area downstream is decreasing which affects the life of the population who depend on irrigation. Therefore, to plan and implement watershed-level management interventions and to minimize the sediment load of the reservoir, studying soil loss and sedimentation processes of the watershed is a critical issue. The objectives of this research were: (1) estimation of the spatial pattern of soil

erosion using RUSLE in GIS environment for conservation prioritization; (2) estimating the spatial SDR of the watershed; and (3) estimating sediment yield and mapping its spatial distribution along the channels of the watershed.

2 Materials and methods

2.1 Description of the study area

Anjeb watershed with its size of 1165 hectares is situated in Amhara Region, East Gojjam Zone, Gonchia Siso Enessie, and Enarji-Enawga districts (Fig. 1). It is almost 160 km far Southeast of the Regional capital, Bahir Dar, and is about 320 km far North of Addis Ababa, capital of Ethiopia. The watershed is part of the North Western Highlands of Ethiopia. The source of river Anjeb is the foot of Choke Mountain Range, one of the highest mountain ranges of Ethiopia with its peak of about 4000 m a.s.l. The river Anjeb is the tributary of The Blue Nile River. The Anjeb reservoir on the River Anjeb has been serving as a source of water for irrigation to the downstream areas. Agricultural practice (crop cultivation) is common in all parts of the watershed, and there is a low amount of vegetation cover that reduces the detachment and transport of sediments to the reservoir. It is intended to serve under both dry and wet seasons at dense cropping intensity. The location of the study area is shown in Fig. 1.

The watershed has a subtropical climate with a mean annual rainfall of about 1420 mm and much of it occurs in June, July, August, and September. The highest rainfall occurs in July and the lowest in February. The mean annual air temperature of the area is 16.5 °C. The main land-use and land cover (LULC) types of the watershed include cultivation of crops, grazing, plantation, and bare land.

2.2 The RUSLE parameters of soil loss estimation

Renard et al. [54] developed the RUSLE for watershed-scale applications. The fundamental parameters required for the RUSLE model to estimate mean annual soil loss

with ArcGIS. The RUSLE is expressed and represented in Eq. (1).

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

where A is annual soil loss ($\text{t ha}^{-1} \text{ yr}^{-1}$), R , rainfall-runoff erosivity factor ($\text{MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$), K , soil erodibility factor ($\text{t h MJ}^{-1} \text{ mm}^{-1}$), LS , slope length and steepness factor, C , cover management factor, and P is the support practice factor. The diagrammatic representation of the methodological flow is presented in Fig. 2.

2.3 Determining RUSLE parameter values

The data sets used to prepare the RUSLE parameters in this study were topography, aerial photograph, soil, and rainfall. The type of data, description of the data, resolution, and data source are presented in Table 1.

2.3.1 Slope length-steepness (LS) factor

The topographic effect on rill and sheet erosion in an area is accounted for the LS-factor. The LS represents the ratio of anticipated soil loss compared to the loss from the standard plot of 22.13 m and a 9 percent slope [42, 57]. The slope for LS-factor computation for the study watershed was analyzed from the SRTM-DEM of 30 m resolution obtained from the USGS website (<https://earthexplorer.usgs.gov/>) [58]. As it is shown in Table 2 and Fig. 3a, much of the watershed is found within 5–10% and 10–20% slope classes which cover 26.9% and 51.6% of the watershed area respectively. The area coverage of the slope classes and the description of slopes of the watershed are presented in Table 2.

Several studies indicated that slope length has a determining effect on soil erosion [59, 60], and others argue that the upslope contributing area is a better representation of the effect of topography for soil loss of an area [61, 62]. Studies indicated that slope length should be substituted by the upslope contributing area [56, 61, 62]. The advanced LS-factor computation method based on the upslope contributing area suggested by Desmet and Govers [61] and Simms et al. [62] was used for this study to derive the LS-factor of the watershed.

$$LS = \text{Power}([Flowaccumulation] \times cellsize/22.13)^n \times \text{Power}(\sin([slope] \times 0.01745)/0.09)^m \quad (2)$$

were the land cover (C-factor), land management practices (P-factor), rainfall erosivity (R-factor), the slope steepness (LS-factor), and the soil erodibility (K-factor). These parameters with a spatial resolution of 30 m were integrated with GIS overlay analysis for the estimation of grid-based soil loss. The RUSLE model is chosen in this study because it is spatially distributed and compatible

where LS , is slope length-steepness factor, m and n are exponents; $m = 0.6$ (a range between 0.4 and 0.6) and $n = 1.3$ (a range between 1.0 and 1.3) [61–65]. The LS-factor of the watershed ranges between 0.0 and 12.9. The slope and the LS-factor of the watershed are represented in Fig. 3a and b, respectively.

Fig. 1 Location map of Anjeb watershed

2.3.2 Rainfall erosivity factor (R-factor)

The rainfall erosivity or R-factor is defined as the measured yearly total separate storm erosion index values, $E/30$, where E is the total storm kinematic energy and $/30$ is the maximum rainfall intensity in 30 min. The numerical value R in RUSLE is needed to quantify the effect of raindrop impact [54]. Because of scarcity in the record of maximum rainfall intensity in 30 min in the study area, the R-factor in this study was computed based on the method developed by Hurni [66] for Ethiopian Highlands using average yearly rainfall data (Eq. 4). The spatial rainfall layer (Fig. 3c) of the watershed was prepared using an interpolation method of inverse distance weighting (IDW) in ArcGIS from rainfall of 30 years (1986–2015) of Felege Bihran, Gunde Woyin, and Digo Tsion stations (Table 3). The IDW has been one of the most accurate methods in estimating spatial rainfall. In IDW the amount of rainfall to be estimated at station x is given by Eq. (3).

$$r_x = \frac{\sum_{i=1}^n \left(\frac{r_i}{D_i^b} \right)}{\sum_{i=1}^n \left(\frac{1}{D_i^b} \right)} \quad (3)$$

where r_x is rainfall to be estimated using the nearby station, r_i is a rainfall of the nearby stations, D is the distance between the index station and the ungauged location, and a weight b is the inverse square of the distance between the stations. IDW is a globally accepted statistical method in interpolating rainfall data of stations.

The rainfall of the watershed ranges between 1390 and 1449 mm (Fig. 3c). The R-factor was calculated in the ArcGIS raster calculator using Eq. (4).

$$R = -8.12 + (0.562 \times P) \quad (4)$$

where R is the erosivity of the rainfall and P is the average yearly rainfall (the spatial layer of rainfall derived from IDW interpolation). The R-factor of the watershed ranges between 789.7 and 822.6 MJ mm ha⁻¹ h⁻¹ yr⁻¹ (Fig. 3d).

Fig. 2 Schematic representation of methods

Table 1 Data and data sources used in the study

Data	Description	Resolution	Source
Topography	Shuttle Radar Topographic Mission Digital Elevation Model (SRTM-DEM)	30 m	USGS database (https://earthexplorer.usgs.gov/)
Aerial photograph	Aerial photograph	Resampled to 30 m	Ethiopian Mapping Agency (EMA 2015)
Rainfall	Station annual rainfall of 30 years (1986–2015)	Interpolated with 30 m resolution	National Meteorological Agency of Ethiopia (NMA)
Soil	Soil types and soil color. Samples of soil colors were collected from the field	Soil color polygons were digitized in 30 m resolution	Abay Basin Master plan project, Ethiopia (MoWR, 1998), for soil types. Field investigation for soil color

Table 2 Slope classes of the watershed based on FAO classification

Slope class (%)	Description	Area (ha)	Watershed area %
0–5	Flat	121	10.4
5–10	Gently sloping	313	26.9
10–20	Sloping	601	51.6
20–30	Strongly sloping	124	10.6
30–41.3	Steep	6	0.5

2.3.3 Soil erodability factor (k-factor)

The K-factor is the vulnerability of particles of the soil for erosion because of the impact of rainfall and runoff

[35]. The interaction among soils, hydraulic processes, and the transportability of sediments gives rise to the K-factor of an area [67]. Different approaches were followed by authors to define the K-factor of soils [35]. The availability of soil data in an area governs the choice of methods to determine the K-factor values. The soil type data of the study watershed was acquired from the Ministry of Water Resources Ethiopia [23]. The soil types of the study watershed are Eutric Nitosol, Eutric Verisil, and Haplic Alisol (Table 4). Because of limited data on soil properties, the soil colors were chosen to determine K-factor values as recommended by Hurni [66] and Helldén [68].

The soil colors were identified from soil samples taken from the field using Auger holes attached with GPS. The soil colors were differentiated using Munsell soil color chart, Munsell Color [69]. The GPS points were exported in ArcGIS, and through digitizing soil color map was prepared

Fig. 3 Slope (a), LS (b), rainfall distribution (c), and R-factor (d) maps of the watershed

(Fig. 4a). The K-factor value was assigned to each soil color, and erodibility map was prepared (Fig. 4b). The K-factor value ranges between 0.0 and 0.3 t h MJ⁻¹ mm⁻¹ (Table 4 and Fig. 4b).

2.3.4 Land use and land cover and management factor (C)

The C-factor describes the effect of LULC types on soil loss [35]. Soil erosion and transportation is affected by the land feature cover and the land use of an area. The LULC data have been prepared to determine the C-factor value. The LULC data of the watershed are prepared from a high-resolution aerial photograph (image of the area taken using aerial cameras mounted on an aircraft [70]). Currently, the availability of data from remote sensing makes it easier to produce LULC of an area that can be suited for the soil loss estimation on a watershed scale.

To prepare LULC of the study watershed, it was difficult to differentiate areas covered by crops from plantations

and extremely grazed lands and bare lands from agricultural fields which were not presently covered by crops using satellite images since they have similar spectral reflectance values. Hence, in this study 0.25-m high-resolution aerial photograph [70] was used to digitize areas covered by crops, bare lands, and grazing lands. The areas of plantations and agricultural fields which were not covered by crops were differentiated through the classification of an aerial photograph. Through the ArcGIS operation of 'merge', LULC types prepared through classification and digitizing were combined together, and the LULC raster layer was prepared. Agriculture/crop cultivation, plantation (eucalyptus), grassland (grazing land), bare land, and waterbody are the LULC types of the watershed (Table 5 and Fig. 4c). Much of the watershed was covered by agriculture/crop cultivation and eucalyptus plantation which accounted for 74.2% and 17.3% of the watershed, respectively (Table 5). The C value was assigned to each LULC according to the proposal of Hurni [66] to the Highlands

Table 3 Average annual rainfall of stations (mm)

Year	Stations and rainfall		
	Felege Bihran	Gunde Woyin	Digo Tsion
1986	1704.2	1293.2	1864.7
1987	1120.3	1141.3	1574
1988	1325.0	1531.8	1407
1989	1739.3	1604.5	1178
1990	1874.1	1259.8	1464
1991	1425.4	1490.2	1276
1992	1825.4	1225.8	1724.3
1993	1560.9	1798.5	1686
1994	1466.1	1548.0	1741.6
1995	1360.1	1357.7	1485.7
1996	1305.4	1706.6	1633.3
1997	1309.9	1581.0	1295.4
1998	1483.0	1673.2	1504.8
1999	1184.7	1586.3	1233
2000	1358.4	1623.9	1509.5
2001	1396.4	1557.6	1702
2002	1090.2	1401.5	1800.2
2003	1211.1	1715.68	1766.6
2004	1227.8	1397.6	1535.1
2005	1089.2	1549.6	1455
2006	1446.8	1690.0	1719.4
2007	1446.7	1675.9	1654.6
2008	1187.7	1594.7	1561.8
2009	1123.3	1592.7	1264.4
2010	1488.4	1322.7	1455.8
2011	1433.4	1903.6	982.2
2012	1193.1	1120.6	703.5
2013	1417.4	1713.2	764.6
2014	1204.7	1639.3	1213.6
2015	1195.2	1458.5	1662.6
Average	1373.1	1525.2	1460.6

of Ethiopia (Table 5 and Fig. 4d). The value of waterbody is assigned based on the recommendation of Ban et al. [71].

2.3.5 Support practice factor (P)

The P-factor is the ratio of soil loss with a particular support practice to the corresponding loss with up and down slope cultivation [42]. This factor considers local erosion management control practices which reduce the eroding power of rainfall and runoff by their impact on drainage patterns [72]. In a shortage of data on management practice, the P-factor was determined from combinations of slope and land use data and is widely accepted and applicable for areas with varying slopes [42, 73]. Hence, to assign the value of P-factor the watershed was grouped into cultivated land, waterbody, and other land

Table 4 Soil types, colors, and K-factor values

Soil type	Soil color	Area (ha)	K value
Eutric Nitosol	Yellow	14.0	0.3
Eutric Nitosol	Red	31.5	0.25
Haplic Alisol	Brown	32.8	0.2
Eutric Verisol	Brown	685.9	0.2
Haplic Alisol	Yellow	199.2	0.3
Eutric Verisol	Yellow	110.5	0.3
Eutric Vertisol	Black	68.8	0.15
Haplic Alisol	Black	10.3	0.15
Water	Water	12.0	0

use. Further, the cultivated lands were categorized according to slope classes, since management practices are depending on slopes. The LULC and slope raster layers of the watershed were overlaid in ArcGIS to create a layer of agricultural fields with varying slope classes, and P-factor was allocated for the corresponding slope class [42, 73, 74] (Table 6, Fig. 5a). The p value of the waterbody is assigned to 0 since there is no erosion on waterbody. A value of 1 is assigned for other land uses.

2.4 Sediment delivery ratio (SDR)

There are a few methods to calculate the amount of eroded soil, namely, sediment rating curve, measurement of sediment deposit, and other empirical methods. During a rainfall event, only some of the eroded soil is routed to the basin channels and the outlet. The ratio between the basin sediment yields at the basin outlet to the total soil erosion over the basin is described as SDR [75]. Sediment yield models are often based on an empirical lumped approach, and a typical lumped concept is the SDR [52]. It is a measure of sediment transport efficiency which accounts for the amount of sediment actually transported from the eroding sources to the catchment channels and outlet compared to the total amount of soil detached and eroded above the channels or the outlet point.

Topographic characteristics affect the SDR of basins. Landscapes with short and steep slopes supply more sediment than long and flat slopes. In this study, SDR was determined from stream channel slopes of the watershed using Eq. (5).

$$SDR = 0.627 SLP^{0.403} \quad (5)$$

where SLP is the slope of stream channels in percent. The estimation of SDR using stream channel slopes provides a realistic result in watersheds having inadequate sediment data [76, 77]. The slope of stream channels was prepared from DEM using an ArcGIS

Fig. 4 Soil color (a), K-factor (b), LULC (c), C-factor (d) maps of the watershed

Table 5 LULC and C-factor value of the watershed

LULC	Description	Area (ha)	Coverage (%)	C value
Plantation	Area mainly covered with eucalyptus trees	201.5	17.3	0.001
Cultivation land	Land used for crop production mainly of cereals	864	74.2	0.15
Bare land	Exposed soil consisting of sparse vegetation	16	1.4	0.05
Grassland	Area mainly covered by grasses and used for grazing purpose	71.1	6.1	0.05
Waterbody	Area covered by water	12.4	1.1	0

interface HEC-Geo-HMS tool. After terrain and basin processing on DEM, the average slope of each cell along the flow path of streams was calculated using HEC-Geo-HMS (Fig. 5b). In calculating SDR, each cell in the flow path is considered as the outlet of its upstream catchment. The channel slope values of the watershed vary between 0.009 and 0.09 as it is represented in Fig. 5b.

2.5 Sediment yield (SY)

The SY is the sediment load at last point of the slope length, in the channels, at the outlet or sediment basins. It is the sediment load normalized for the drainage area and is the net result of erosion and deposition processes within a watershed. Sediment yield is typically unavailable as a direct measurement in a watershed lacking adequately recorded sediment data. The accurate

estimation of SDR coupling with spatial soil loss is an important and effective approach in predicting sediment yield [78]. In this study, sediment yield is computed by superimposing the soil loss and SDR layers of the watershed using Eq. (6).

$$SY = \sum_{i=1}^n SDR * E \quad (6)$$

where *SDR* is the fraction of soil erosion that has delivered to the *i*th grid cell of the nearby channel or outlet, *SY* is the sediment yield, and *E* is the soil erosion of the *i*th grid cell, and *n* is the total grid cells.

3 Results

3.1 Soil loss

The RUSLE soil loss parameters were superimposed in ArcGIS 10.2, and the soil loss rate of each grid cell (30 m

resolution) was computed with Eq. (1). The annual soil loss of the watershed ranges from 0 to 195 t ha⁻¹ yr⁻¹, and the average annual rate of soil loss of the watershed was 17.3 t ha⁻¹ yr⁻¹. Based on the result found, the watershed has been categorized into six classes of erosion: slight (0–5), moderate (5–10), high (10–15), very high (15–30), severe (30–50), and very severe (> 50) t ha⁻¹ yr⁻¹ (Table 7 and Fig. 6). The average soil loss of the severe and very severe classes accounted for 40 t ha⁻¹ yr⁻¹ and 132.5 t ha⁻¹ yr⁻¹ and covered 5.8% and 7.1% of the watershed area, respectively. The severe erosion condition is manifested by the formation of a large and deep gully as shown in Fig. 7 which is acquired from a location presented in Fig. 6. Part of the watershed under the severe soil loss condition is located in the stepper slopes and much of it is in the upper part of the watershed where the main river originates. The average loss in the high and very high erosion classes was 12.5 and 22.5 t ha⁻¹ yr⁻¹ sequentially. The proportion of the watershed found in the high erosion class (both very high and high) is about 17.6%. A significant part of the watershed, 11.3%, has been within the moderate classes of erosion which has an average loss of 7.5 t ha⁻¹ yr⁻¹. Greater than 50% of the watershed was under the slight (average loss of 2.5 t ha⁻¹ yr⁻¹) erosion classes, and it covers from gentle to flat slopes of the watershed (Table 7). The total annual soil loss was estimated as 20,125.5 t yr⁻¹. The result indicated that a large amount of soil loss (54.6%) has come from a small section of the watershed (very severe class) which constitutes only 7.1% of the watershed area. The categories of erosion classes help to prioritize areas for conservation measures according to their level of risk.

Table 6 Land use, slopes, and *P*-factor values

Land use type	Slope (%)	(<i>P</i>) factor	Area (ha)	Coverage (%)
Agricultural land	0–5	0.11	74	6.4
	5–10	0.12	229	19.7
	10–20	0.14	466	40.0
	20–30	0.22	92	7.9
	30–41.3	0.31	3	0.3
Waterbody		0.0	12.4	1.1
Other land	All	1.0	288.6	24.8

Fig. 5 *P*-factor (a) and channel slope (b) maps of the watershed

3.2 Sediment delivery ratio (SDR)

The SDR value of a raster grid cell measures its upstream sediment delivery capability. A spatial grid of SDR was generated for channels in the watershed employing Eq. (5). The result showed that the SDR value ranges between 0.03 and 0.214. Higher SDR values (> 0.2) were observed along the higher channel slopes between 0.06 and 0.09. An intermediate amount of SDR values (0.15–0.2) was observed within the channel slope classes between 0.03 and 0.06, and SDR values (0.03–0.15) were found mainly along the main channel with slopes between 0.009 and 0.03 (Fig. 8). As it is observed from Table 8 on average SDR values of 0.19 and 0.125 cover more area of the channels (43.9%, 20.5%), respectively. The lowest SDR value (0.07) constitutes 8% of the lowest channel area in the watershed (Table 8). On average, the

sediment delivery capacity is about 0.122. This indicates that a mean of 12.2% of the eroded soil materials could be delivered to the channels and 87.8% of the eroded materials are trapped and deposit before getting into the channel networks.

3.3 Estimating sediment yield (SY)

The sediment delivered in the channel grid cells and the outlet was estimated with superimposing the soil loss and SDR raster layers as represented in Eq. (6). In order to uncover the severity of sediment yield, it is categorized into six classes, namely, low (0–5), moderate (5–10), high (10–15), very high (15–30), severe (30–50), and very severe (> 50) $\text{t ha}^{-1} \text{yr}^{-1}$ (Table 9). The very severe sediment class which covered 17% of the area of the channels has a mean sediment yield of $157 \text{ t ha}^{-1} \text{yr}^{-1}$, and

Table 7 Soil loss and erosion-risk classes of the watershed

Soil loss $\text{t ha}^{-1} \text{yr}^{-1}$	Average soil loss $\text{t ha}^{-1} \text{yr}^{-1}$	Erosion risk class	Area (ha)	Area %	Total soil loss t yr^{-1}	Soil loss %
0–5	2.5	Slight	678	58.2	1695	8.4
5–10	7.5	Moderate	132	11.3	990	4.9
10–15	12.5	High	85	7.3	1062.5	5.3
15–30	22.5	V. high	120	10.3	2700	13.4
30–50	40	Severe	67	5.8	2680	13.3
> 50	132.5	V. severe	83	7.1	10,997.5	54.6
Total			1165	100	20,125.5	100

Fig. 6 Map of soil loss distribution and sites of gully, suspended sediment, and sediment deposition

a total of 1727 tons of sediment in the watershed was from this channel section. Severe and very high sediment classes each covered 9.4% of the channels (total 18.8%), and their mean sediment yield was about $40 \text{ t ha}^{-1} \text{ yr}^{-1}$ and $22.5 \text{ t ha}^{-1} \text{ yr}^{-1}$, respectively. A low amount of sediment was from the low category of sediment classes that covers over 50% of the channels (Table 9).

From a total of $20,125.5 \text{ t yr}^{-1}$ of eroded soil over the whole watershed 2254.5 t yr^{-1} of sediment load has been brought and deposited along the channels which cover 64 hectares or 5.5% of the area of the watershed. Figure 7 shows suspended sediment and sediment deposition along the lower reaches of the channels of the watershed, and their locations are displayed in Fig. 6. Almost 12.2% of the total soil loss has been transported and deposited to the channels. The map of sediment yield is presented in Fig. 9. The sediment yield at the outlet grid cell is a product of total soil loss from the entire watershed and the SDR value of the grid cell. The sediment yield at the point of the outlet was estimated 2012.5 t yr^{-1} . From the gross soil loss of the watershed ($20,125.5 \text{ t yr}^{-1}$), 2012.5 t yr^{-1} of soil has been delivered at the outlet point.

4 Discussion

Soil erosion is governed by human and natural causes. Understanding and estimating the level and factors of erosion is a critical issue to design preventive measures. A number of models were developed worldwide to quantify the level of soil erosion in various spatial scales. RUSLE is an effective and worldwide accepted method because of its reliability in calculating soil loss studies [40, 79]. The model has strength in estimating soil erosion with limited data, mainly in developing regions where there is a scarcity of data [80, 81]. Ethiopia is susceptible to soil erosion hazards due to torrential rains, steep slopes, improper land support practices, and lack of soil covers [6, 66]. From the main parameters of estimating soil loss in the RUSLE model, rainfall erosivity, soil erodibility, and slope-steepness factors contribute to soil erosion [82, 83] and the cover-management and the controlling practice factors play a preventive function [84]. For this study, the spatial data sets of RUSLE factors were prepared separately and used for the estimation of the soil loss. Characterized by

Fig. 7 Figures of deep gully, suspended sediment, and sediment deposition in the watershed

Fig. 8 Map of sediment delivery ratio (SDR) **Table 8** Channel SDR value and the area coverage

SDR value	Average SDR	Area (ha)	Area %
0.03–0.1	0.065	5.2	8.1
0.1–0.15	0.125	13.1	20.5
0.15–0.17	0.16	8.5	13.3
0.17–0.2	0.185	28.1	43.9
> 0.2	0.21	9.1	14.2

a subtropical climate, mountainous and adulating topography in its upper part and flat terrain in its lower part in an average altitude of 2679.5 m a.s.l, the Anjeb watershed acquires a mean yearly rainfall of 1420 mm. Its slope varies from 0 to 41.3% (Fig. 3a) which provides LS-factor from 0 to 12.9 (Fig. 3b). Higher LS-factor values occupy the upper and steeper slopes of the watershed. The geologic formation is dominated by fine-grained basalts and some boulders in the elevated areas and weathered and fractured basalts along the gully sections, river courses, and flat areas and dominantly covered by Eutric Verisol and Haplic Alisol. The K-factor was assigned using the soil colors of the watershed, and soils with yellow color have higher K-factor values, and waterbody has lower values. The K-factor value ranges from 0 to $0.3 \text{ t h MJ}^{-1} \text{ mm}^{-1}$ (Fig. 4b), and the R-factor values are between 790 and $823 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ (Fig. 3d). The upper parts of the watershed receive a little lower amount of rainfall and have lower R-factor values than its lower parts. The C-factor values vary between

Table 9 Sediment delivered to the channels

Range of SY $\text{t ha}^{-1} \text{ yr}^{-1}$	Average SY $\text{t ha}^{-1} \text{ yr}^{-1}$	SY classes	Area (ha)	Area %	Annual SY tone
0–5	2.5	Low	34	53.1	85
5–10	7.5	Moderate	4	6.3	30
10–15	12.5	High	3	4.7	37.5
15–30	22.5	Very high	6	9.4	135
30–50	40	Severe	6	9.4	240
> 50	157	V. severe	11	17.2	1727
Total			64	100	2254.5

0 and 0.15 with the highest C-factor value is for cultivation land and the lower is for the waterbody. The highest P-factor value is for bare land (with a value of 1), and the lower value is for waterbody (a value of 0).

Most part of the watershed (> 50%) is under the slight erosion class and covers the lower slopes of the watershed. The severe and very severe erosion accounted for 13% of the watershed and is mostly associated with the higher slope length-steepness factor. When the erosion factor layers were compared with the soil loss layer, the LS-factor is consistent with the spatial distribution of the estimated soil erosion (Fig. 6) and it is an important factor for erosion in the watershed. Hence, conservation practice that can reduce slope length helps to mitigate soil erosion in the watershed. Important conservation

Fig. 9 Map of sediment yield in the channels

practices that help to reduce slope length are soil or stone bunds and terraces [85, 86].

The soil loss of this study lies in between other studies conducted in the adjacent areas and other countries that have similar topography and rainfall conditions because topography and rainfall are the main triggering factors of erosion of a specific area or region. The estimated annual soil loss of this study ($17.3 \text{ t ha}^{-1} \text{ yr}^{-1}$) is lower than studies conducted in the adjacent areas of the North-western Highlands of the country such as $49 \text{ t ha}^{-1} \text{ yr}^{-1}$ in Dembecha District [87]; $47 \text{ t ha}^{-1} \text{ yr}^{-1}$ in Koga watershed [88]; $42.7 \text{ t ha}^{-1} \text{ yr}^{-1}$ in Gumara watershed [89]; $41.5 \text{ t ha}^{-1} \text{ yr}^{-1}$ in Megech watershed [90]; $32.8 \text{ t ha}^{-1} \text{ yr}^{-1}$ in Gilgel Abay watershed [91]; $30.6 \text{ t ha}^{-1} \text{ yr}^{-1}$ in Jabi-Tehinan District [92], and $23.7 \text{ t ha}^{-1} \text{ yr}^{-1}$ in Gelda watershed [93] (Table 10). The higher soil losses attributed to these watersheds were related to either the higher R-factor or LS-factor or both values compared to the Anjeb watershed. The R-factor and LS-factor consecutively range between 754 and $1022.6 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ and 0.27–205 in Denbecha district; $715\text{--}945 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ and 0–70 in Koga watershed; $1013.5\text{--}1157.8 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ and 0.03–62.5 in Gumara watershed, $515\text{--}1300 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ and 0–90 in Megech watershed; $734\text{--}1383 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ and 0–180 in Gilgel Abbay; $441.5\text{--}1164.4 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ and 0.0021–11.9 in Jabi-Tehinan district, and $799\text{--}980 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ and 0–28.9 in Gelda watershed. Denbecha district, Gumara watershed, and Gilgel Abbay watershed have higher R-factor and LS-factor

values so that they have higher soil loss than the study watershed. Even though Megech and Anjeb watersheds have comparable R-factor values, Megech has a higher LS-factor which results in its higher soil loss. The R-factor and LS-factor of Jabi-Tehinan district did not show a significant difference to Anjeb watershed, but Jabi-Tehinan has a larger area coverage that contributes to its little higher soil loss. The lower vegetation cover also played a significant role in the higher soil erosion of these watersheds. Forest, bush, and wetland covered 10.3% and 14.8% of Koga and Gilgel Abbay watersheds, respectively, which are lower than the cover of Anjeb watershed. Even though the vegetation cover of Gumara (26%) was higher than Anjeb watershed (17.3% plantation, Table 5), its soil loss is considerably higher since it has a higher R-factor value. There was a little lower vegetation cover in Megech watershed (13.1%) compared to Anjeb, but it had a higher soil loss because of its higher LS-factor. The low cover of forest and shrub in Gelda watershed (3.76%) together with its higher R-factor and LS-factor values provides higher soil loss than the Anjeb watershed. The very low plant cover (5.5%) in Jabi-Tehinan district might be one factor of its higher soil erosion.

On the other hand, the soil loss of this study is higher than other studies in the adjacent areas such as $4.8 \text{ t ha}^{-1} \text{ yr}^{-1}$ in Enfranz watershed [94]; $9.1 \text{ t ha}^{-1} \text{ yr}^{-1}$ in Zingin watershed [95]; $9.6 \text{ t ha}^{-1} \text{ yr}^{-1}$ in Medego Watershed [96], and $2.2 \text{ t ha}^{-1} \text{ yr}^{-1}$ in Dijo watershed [97] (Table 10). Anjeb watershed has a higher soil loss rate

than Enfranz watershed since it has higher R-factor and K-factor values. Enfranz watershed has an average R-factor of $750.6 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ and K-factor between 0.15 and $0.2 \text{ t h MJ}^{-1} \text{ mm}^{-1}$. Zingin watershed has a relatively higher R-factor ($915.9\text{--}1055.9 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$) but a far lower LS-factor (0.01–0.15) value than Anjeb. The very low LS-factor value of Zingin watershed contributes to its lower soil loss. The area size of Anjeb (1165 ha) and Medego (1091.5 ha) is comparable, but Medego has lower amount of soil loss. This is due to the fact that Medego has a lower R-factor value (average $357 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$) than Anjeb. The reason Dijo watershed has lower soil loss than Anjeb watershed is that it has a lower R-factor ($376\text{--}465 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$) and LS-factor (0–5) values which have influential factors for soil erosion in the area. The higher vegetation covers of Enfranz watershed (31.8%), Zingin watershed (34.5%), and Diji watershed (49.2%) compared to 17.3% in Anjeb watershed contribute to their reduced soil losses. Another study in the Ethiopian Highlands [66] reported that the average soil loss is $18 \text{ t ha}^{-1} \text{ yr}^{-1}$ which is very comparable with the finding of the Anjeb watershed.

The soil loss of the watershed is also in between studies of other countries. Anjeb has a lower soil loss than Kirindi Oya catchment ($33 \text{ t ha}^{-1} \text{ yr}^{-1}$) [11] in Sri Lanka which has an annual average rainfall between 1075 and 1984 mm and characterized with hills, undulating, and flat topography. The higher slopes (0–260%) of the Kirindi Oya catchment provide a higher LS-factor (0–725) which results in a higher soil loss than the Anjeb watershed. The soil loss of Anjeb watershed is higher than Nzoia basin in Mountain Elgon ($0.51 \text{ t ha}^{-1} \text{ yr}^{-1}$) [82] of Kenya which has a mountainous and hilly topography in its upper part and flat plains in its lower part with a mean elevation of 2300 m a.s.l and an average annual rainfall of 1375 mm. Nzoia basin has a lower R-factor ($339.4\text{--}855 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$)

and a very low LS-factor (0–0.299) than Anjeb that contributed to its lower values of soil loss. The soil loss of Anjeb is a little higher than Harare Metropolitan Province ($13.2 \text{ t ha}^{-1} \text{ yr}^{-1}$) [98] in Zimbabwe which is characterized by undulating and rolling topography with an elevation between 1455 and 1556 m a.s.l and annual precipitation between 470 and 1350 mm. Anjeb watershed has relatively a higher R-factor and K-factor values than the Harare Metropolitan Province (R-factor $320\text{--}323 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$) and (K-factor 0.06–0.09) which results to its higher soil loss.

A soil loss study conducted in East African countries [99] by RUSLE model indicated that the mean soil loss rate of the region is about $6.3 \text{ t ha}^{-1} \text{ yr}^{-1}$ and about 50% of the regional soil loss is originated from Ethiopia. According to this study, the country-level soil loss rate of Ethiopia is found around $16.9 \text{ t ha}^{-1} \text{ yr}^{-1}$ which is almost similar to the soil loss of Anjeb watershed ($17.3 \text{ t ha}^{-1} \text{ yr}^{-1}$). According to the report, the high soil loss was mainly caused by high rainfall erosivity and steep topography that results in higher LS-factor which are the characteristics of the highland parts of East African countries. Generally, the result of this study lies in between the previous studies conducted in the adjacent areas and other countries, and it could be concluded that the study is reliable to take remedial actions in reducing erosion in the watershed.

The average sediment delivery capacity of the watershed (12.2%) lies between studies such as 10% [100] in Australia; 37% in Iguatu experimental watershed [101] in a semiarid climate of Brazil, 2% in Kapgari watershed [7] of a subtropical climate in India, 13% in Tapacurá catchment [102] of Brazil having a humid-tropical climate. The Anjeb watershed has a lower sediment delivery compared to Iguatu experimental Watershed since it has lower ranges of slopes, and it has a higher sediment delivery than Kapgari watershed because of its higher slope values. The

Table 10 Soil loss estimation conducted in highlands of Ethiopia

Study area	Annual rainfall (mm)	Climate	Elevation m a.s.l	Slope %	Mean annual soil loss ($\text{t ha}^{-1} \text{ yr}^{-1}$)	References
Dembecha district	1182–1880	Subtropical climate	1021–2516	0–58.5	49	[87]
Koga watershed	1628	Subtropical climate	1885–3131	0–100	47	[88]
Gumara watershed	2078.1	Subtropical climate	1864–3235	0–100	42.7	[89]
Megech watershed	1038–2187	Subtropical climate	1755–2974	0–> 30	41.5	[90]
Gilgel Abay watershed	1200–2400	Subtropical climate	1695–3512	0–59	32.8	[91]
Jabi-Tehinan district	800–2090	Subtropical climate	1500–2300	0–> 30	30.6	[92]
Gelda watershed	1024–1759	Subtropical climate	1791–2472	0–5	23.7	[93]
Enfranz watershed	1200–1500	Subtropical climate	1825–2000	0–49.4	4.8	[94]
Zingin watershed	1500–2000	Subtropical climate	2315–2874	0–100	9.1	[95]
Medego Watershed	600–700	Dry tropical climate	2000–2700	< 2–> 50	9.6	[96]
Dijo watershed	1004	Tropical to subtropical	1578–3179	0–> 50	2.2	[97]

slope of Iguatu and Kapgari watersheds is 0–60.7% and up to 17.7%, respectively. The study watershed has almost the same amount of sediment delivery to Tapacurá catchment, and this might be due to their similar slope values. The analysis shows that sediment delivery is greatly related to the slope values of this study watershed. This shows that the SDR value found in this study is reliable for sediment yield studies in the watershed. High sediment delivery capacity ($> 15\%$) is found in the higher slopes and tributary channels, and a lower sediment delivery ($< 15\%$) is observed along the main channel of the watershed.

5 Conclusions

Anjeb watershed situated in the middle of Northwest Ethiopian Highlands is an agriculture-dominated (mainly crop cultivation) area. Basic data sets were organized and analyzed for estimating soil loss, SDR, and sediment yield. The result revealed that the spatial data-processing efficiency of GIS integrating with RUSLE is capable of quantifying soil loss, SDR, and sediment yield of the Anjeb watershed. The study generated a 30×30 m resolution soil erosion layer by employing RUSLE which is integrated with a GIS analysis for the Anjeb watershed. The result of this study provides an understanding of the risks of soil erosion and the main factors that are contributing to the susceptibility of the watershed to erosion. It can be concluded that the dominant contributors to erosion in the watershed are R-factor and LS-factor. The result discovered that the slope and LS-factor were highly matched with the soil loss layer of the watershed and played a larger role in its soil erosion. The soil loss of the watershed is comparable to similar studies in the nearby Ethiopia Highlands in particular and countrywide erosion levels in general. The watershed was categorized into six classes of erosion: slight (0–5), moderate (5–10), high (10–15), very high (15–30), severe (30–50), and very severe (> 50) $\text{t ha}^{-1} \text{yr}^{-1}$. Soil loss ranges between 0 and $195 \text{ t ha}^{-1} \text{yr}^{-1}$, and the average soil loss was $17.3 \text{ t ha}^{-1} \text{yr}^{-1}$. More than 50% of the watershed area is under the slight (average loss of $2.5 \text{ t ha}^{-1} \text{yr}^{-1}$) class of erosion that dominates lower slopes and accounts for only 8.4% of the soil loss of the watershed. More than 50% of soil loss is from 7% of the area (under the very severe class of erosion) which is located in the steeper slopes of the watershed.

It is found that the SDR value varies between 0.03 and 0.214 and the average value was 0.122 (12.2%). This indicated that a significant proportion of the gross soil loss (12.2%) has been delivered into the channel networks. Higher SDR values (> 0.2) were observed along the higher channel slopes (0.06–0.09). A majority of watersheds in Ethiopia lack observed data especially sediments so that sediment yield could not be analyzed to use as

input for watershed-level management planning. Sediment yield estimated by analyzing the soil loss and SDR of the watershed was categorized into classes of low (0–5), moderate (5–10), high (10–15), very high (15–30), severe (30–50), and very severe (> 50) $\text{t ha}^{-1} \text{yr}^{-1}$. The average sediment yield ranges between 2.5 and $157 \text{ t ha}^{-1} \text{yr}^{-1}$. It is estimated that a total of 20,125.5 tons of soil was eroded from the watershed and 2254.5 tons of sediment was deposited to the stream channels per year. The sediment yield at the point of the outlet was 2012.5 t yr^{-1} .

Because of lack of decision support studies for watershed-level resource management in the area, the Anjeb reservoir which has been designed to serve for 43 years is currently reducing in its size due to sediment accumulation from its upstream. Therefore, the result of this study is important to design and implement conservation measures to reduce soil loss in the watershed and sediment accumulation to the reservoir. The limitation of the study is that the results were not validated with measured values because of a lack of ground measurements since we encountered limited resources and time to undertake ground verifications. Based on our study, we recommend researchers incorporate more soil erosion models for comparison to find out the best results and to validate the estimations with measurements. We also recommend local land managers to design and construct conservation measures suitable for the land use and adaptable to the slope to reduce soil loss in the watershed. The model could be adapted to similar studies in the area following appropriate adjustments, and this study could be a source of information for related researches that will be conducted in the area.

Acknowledgement We provide our gratitude to Bahir Dar University for its grant support for the work. We also express our heartfelt gratitude to Ethiopian Meteorological Agency for providing meteorological data to be considered for this study.

Funding This work was supported by Bahir Dar University (BDU), Ethiopia.

Declaration

Conflicts of interest We the authors declare that we 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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