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Research article

Quantification of soil erosion and sediment yield using the RUSLE model in Boyo watershed, central Rift Valley Basin of Ethiopia

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A R T I C L E I N F O

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A B S T R A C T

Changes in land use and land cover (LULC) are becoming recognized as critical to sustainability research, particularly in the context of changing landscapes. Soil erosion is one of the most important environmental challenges today, particularly in developing countries like Ethiopia. The objective of this study was evaluating the dynamics of soil loss, quantifying sediment yield, and detecting soil erosion hotspot fields in the Boyo watershed. To quantify the soil erosion risks, the Revised Universal Soil Loss Equation (RUSLE) model was used combined with remote sensing (RS) and geographic information system (GIS) technology, with land use/land cover, rainfall, soil, and management approaches as input variables. The sediment yield was estimated using the sediment delivery ratio (SDR) method. In contrast to a loss in forest land (1.7 %), water bodies (3.0 %), wetlands (1.5 %), and grassland (1.7 %), the analysis of LULC change (1991–2020) showed a yearly increase in the area of cultivated land (1.4 %), built-up land (0.8 %), and bare land (3.5 %). In 1991, 2000, and 2020, respectively, the watershed's mean annual soil loss increases by 15.5, 35.9, and 38.3 t/ha/y. Approximately 36 cm of the watershed's economically productive topsoil was lost throughout the study's twenty-nine-year period (1991–2020). According to the degree of erosion, 16 % of the watershed was deemed seriously damaged, while 70 % was deemed slightly degraded. Additionally, it is estimated for the year 2020 that 74,147.25 t/y of sediment (8.52 % of the total annual soil loss of 870,763.12 t) reach the Boyo watershed outlet. SW4 and SW5 were the two sub-watersheds with the highest erosion rates, requiring immediate conservation intervention to restore the ecology of the Boyo watershed.

1. Introduction

The bio-geo-chemical and hydrological cycles are controlled by soil, which also provides a variety of resources, goods, and services to human communities [1,2]. Land degradation has been one of the major issues impairing the global ecology of the planet [3,4]. Contrary to nature, land use and land cover changes (LULC) cause soil erosion by water to increase, which is thought to be the most significant environmental hazard [5].

The erosion of soil, a key cause of deterioration of land with detrimental effects on social, economic, and environmental development, is a global issue [6]. Severe land degradation is recorded in Sub-Saharan Africa compared with the rest part of the world [7]. On the contrary, the majority of the livelihoods of most people in these nations rely largely on their abundant supply base [8].

According to Fenta et al. [9], Ethiopia's highlands were amongst the furthermost damaged regions in Sub-Saharan Africa (SSA).

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According to recent study, yearly soil loss in Ethiopia's major river basins was projected to be 1.9×10^9 t/y, while sediment yield was 410×10^6 t/y [10]. A recent report has shown that the national mean annual soil loss in south-eastern Ethiopia was 0 t/ha/year while in the western highlands of Ethiopia was 100 t/ha/y [11].

More than two-thirds of cultivated farms in Sub-Saharan Africa (SSA) have deteriorated, and subsequent losses in crop production are largely attributable to the deterioration of land. The erosion of soil is also the primary source of several other economic and environmental issues [12,13]. These areas face fundamental issues with the decline of agricultural productivity, food security, and mental health [14]. In contrast to SSA, the highlands of Ethiopia experience the greatest soil erosion, which consequences in the disappearance of soil fertility and a decrease in agricultural production [15,16]. According to Hurni [17], land degradation in Ethiopia's highlands is diminishing soil productivity at a rate of 3 percent each year.

Additionally, Yitaferu [18] has estimated the sedimentation in the Lake Tana Basin revealed that the rate of sediment loading was 14.84 million tons annually. Extreme soil erosion and subsequent siltation caused the destruction of Lake Haramaya [19], and the marshland of Cheleleka in Lake Hawassa watershed, southern Ethiopia [20]. The storage capacity at Gilgel Gibe-I hydropower dam has been impacted by siltation and nutrient enrichment issues [21].

Ashiagbor et al. [22] reported that global soil erosion was estimated from 12 t/ha/y to 15 t/ha/y whereas, according to Tesfaye et al. [23], the soil erosion rate due to water varies from 16 to over 300 t/ha/y, in Ethiopia, predominantly dependent on the steepness of the gradient, the amount/types of land cover/land use, and the intensity of the rainfall the country. In Ethiopian ungagged watersheds, which are susceptible to high soil erosion and sediment yield, estimating sediment yield by combining soil loss with sediment delivery ratio (SDR) is uncommon.

The need for adequate management strategies is necessary given the brutality of land degradation and its effects so development conservation efforts require a thorough extensive knowledge of the regional heterogeneity of deterioration of soil resources [24]. Soil erosion models in conjunction with GIS are powerful tools for assessing the spatial scattering of losses of the soil, identifying regions severely affected by erosion, and simulating various management scenarios [25,26]. The Water Erosion Prediction Project [27], the Soil and Water Assessment Tool [28], and the Revised Universal Soil Loss Equation [29,30] were the empirical models for assessing soil loss, in which these models are decidedly valid for broad geographic regions in the world. The Revised Universal Soil Loss Equation (RUSLE) model is made up of relatively simple response functions that have been calibrated to fit a limited set of statistical observations. Even though RUSLE subsequently replaced the original concept, USLE is still frequently employed due to its ease of use [31].

Boyo watershed is one of the parts that practice soil erosion in the Ethiopian Rift Valley Basin [32]. Sheet erosion is the prevailing kind of soil erosion in the highlands of Ethiopia as well as this watershed [33]. It was hypothesized that combined effects of rainfall, landscape positions, nature of soil and land management practices had influenced soil erosion rates in Boyo watershed.

It was discovered that the integration of RUSLE and sediment deriver ratio (SDR) in an arc GIS context was a crucial approach for envisaging the soil loss and sediment yield in limited data situations like the Boyo watershed [32,34], and the RUSLE has been used extensively and is an excellent tool for determining the extent of soil loss and locating geographic areas susceptible to soil erosion [35–37]. The revised universal soil loss equation model has so far been used in extensive research in Ethiopia to quantify soil erosion [38,39]. Soil loss per grid cell of an area can be quantified by employing RUSLE and it has a special advantage over the USLE since it incorporates process-based and empirical characteristics [40].

Though quantifying soil loss and prioritizing erosion-prone areas are essential for successful preservation development [41], and estimating sediment yield crucial for the development new interventions related to ecosystem restoration; few studies have been conducted to estimate erosion rates in the Boyo watershed. Moreover, a detailed study of soil erosion in terms of soil depth as new approach for this study, and soil loss assessment using geospatial technologies at the watershed level has not yet been conducted in the

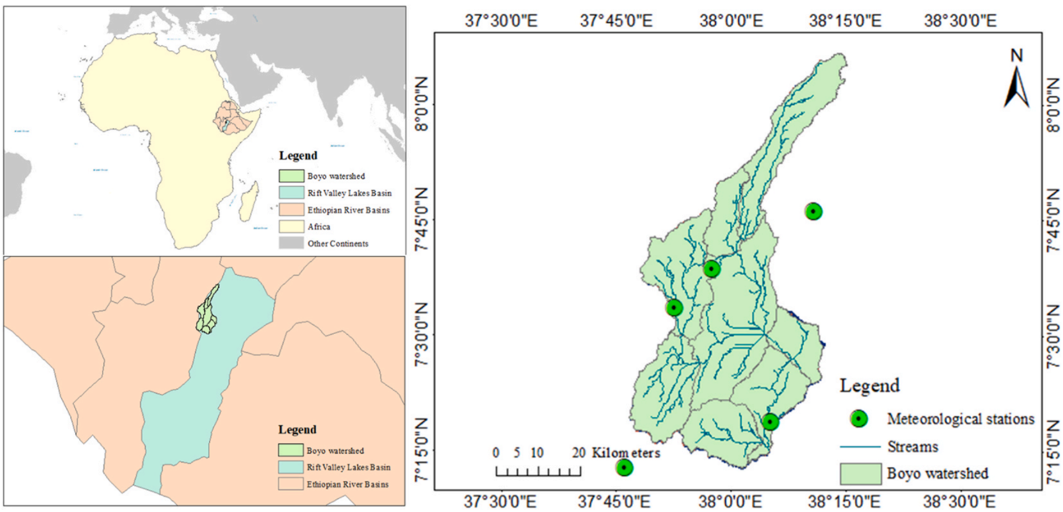

Fig. 1. Boyo watershed location map.

study area. Similarly, in spite of the presence of erosion in the present study area, the rate of soil loss and its spatial patterns are poorly understood.

For successful conservation planning, it is vital to measure soil loss and delineate degraded regions [41]; however, there haven't been many studies done to do so in the Boyo watershed. Because different parts of the landscape respond differently to erosion due to differences in slope, soil, and land use and cover attributes. Therefore, the objective of this study was to estimate soil loss rates with the help of RUSLE model in GIS environment, and prioritize areas for specific soil conservation plans.

2. Materials and methods

2.1. Description of the research watershed

The Boyo watershed is situated in the Rift Valley Basin. It is geographically located 7° 12'– 8° 8' N Latitude and 37° 42'– 38° 13'E Longitude (Fig. 1). The watershed covered an area of about 223,370 ha (2233.70 km^2), it is 200 km south of the capital, Addis Ababa. Parts of Hadiya, Silte, Kembata, and Gurage are among the four administrative zones that comprise the Boyo watershed. Mostly located in the west in the Hadiya zone; the catchment also extends to the north in the Gurage zone, the east in the Silte zone, and the south in the Kambata zone.

The majority of the watershed is made up of the wet Woina Dega and moist Dega agro-ecological zones. The watershed's primary agro-ecological zone, known as moist Woina Dega, makes up around 66.40 % of the entire watershed. The watershed rainfall is bimodal, with low rainfall during the dry season (March to May) and substantial rainfall during the foremost rainy season (June to September). The twenty-nine years (1991–2020) climatic data of the Boyo watershed from three stations indicated that the mean annual temperature is 18.8 °C and the mean annual maximum and minimum are 26.7 °C and 10.9 °C, respectively (Fig. 2). Mean annual rainfall for 29 years calculated from meteorological station varies from 1054 to 1565 mm with a mean yearly rainfall of 1317 mm.

The altitude of the area ranges from 1676.9 to 3372.2 m above sea level. Around 45 % of the watershed is between 2400 and 3200 m above sea level. The remaining 40 % of the territory is between 1500 and 2400 m above mean sea level, whereas only 15 % of it is between 3200 and 3700 m above mean sea level. The Boyo watershed has a diversified nature landscape, ranging from flat to bleak hilly topography. Boyo lake plain falls within the lowest elevation which is about 1900 m whereas the northern end of the watershed. The slopes of the study area range from gentle slopes (<5 %) to very steep slopes (>50 %) and are dominated by gentle slopes (Fig. 3).

The soil map of the Boyo watershed was generated by Fischer et al. [42] using the study area boundary aided by the Analysis tool extension in the ArcGIS 10.4 software. Accordingly, there were eleven soil types in the study area. However, there were six major soil types examined for this research in the study area; Fluvic Vetric Andosols, Loamic Mollic Solonchaks, Ochric Pellic Vertisols, Ochric Eutric Fluvisols, Hypereutric Chromic Luvisols and Fluvic Dystric Leptosols (Fig. 4).

2.2. Land use and land cover (LULC) data

The examined Landsat image findings for the period 1991–2020 revealed that the study watershed has seven land use land cover classes. The most common land use type is cultivated land, which accounts for 41 % of the total area, and cereal crops are mostly grown in the watershed in 2020. The major crops grown in the study area were maize, haricot bean, teff, and wheat. The other land use types were grassland (6.2 %), forest land (7.7 %), wetland (11.7 %), built-up (18.3 %), barren land (14.2 %), and water body (0.1 %).

To validate the correctness of the LULC cover map for 2020, 211 ground-truth points were gathered by direct and field observations utilizing the global positioning system (GPS). For the remaining study years, 102 and 163 reference points were obtained using the

Fig. 2. Mean monthly rainfall and temperature of the Boyo watershed (1991–2020).

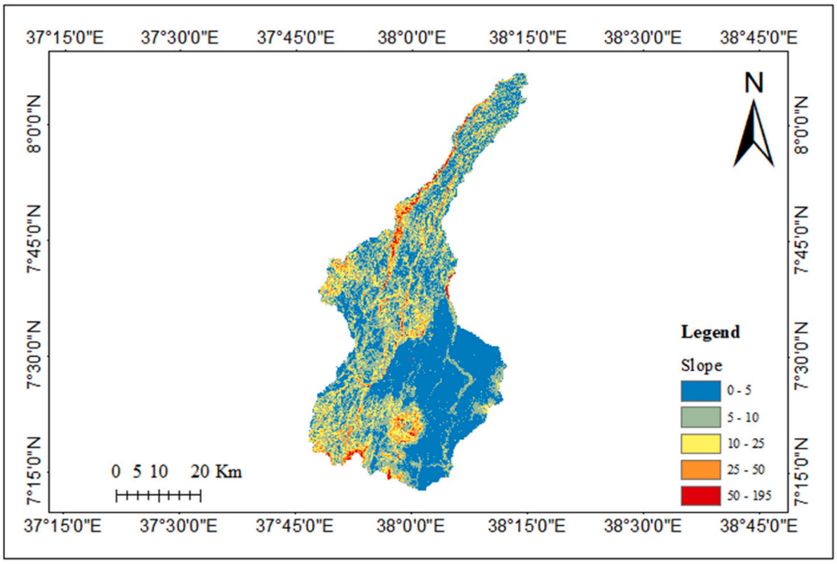

Fig. 3. Slope ranges of the Boyo watershed.

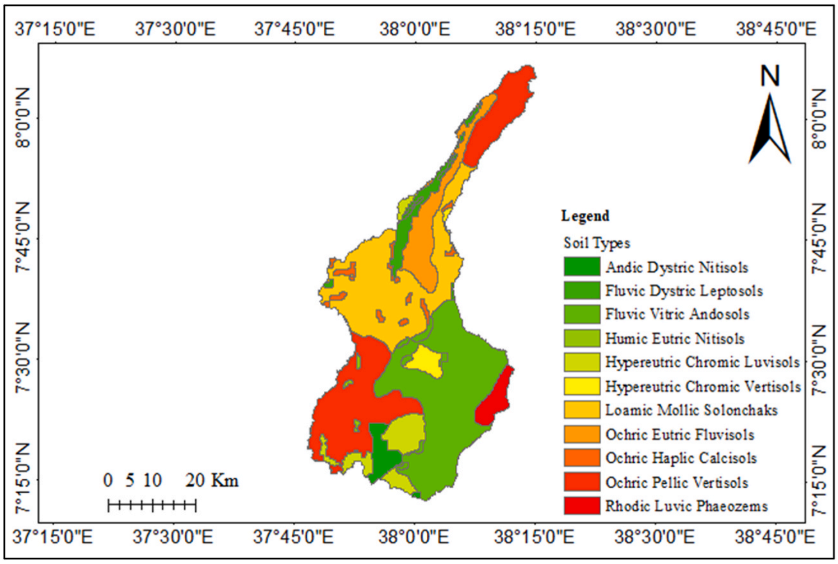

Fig. 4. Boyo watershed soil map.

LULC maps for Google Earth in 1991 and 2000, respectively. Multi-temporal Landsat images from the three study periods (Landsat-5TM 1991, Landsat 2000, and Landsat-8 OLI-TIRS 2020) were used (Table 1). Soil data, watershed shape information, and soil conservation techniques were obtained from the required government offices in the research area. It proceeded to the website of the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov/).

The study watershed's Digital Elevation Model (DEM) at a resolution of 30 m by 30 m was used. The watershed was automatically delineated using the DEM, which was also utilized to construct the stream network using slope. The Landsat images were TM, ETM+,

Table 1
Features of Landsat images utilized in LULC change investigation.

Path	Row	Sensor	Acquisition Date	Spatial Resolution (m)
169	55	TM	November 09, 1991	30 × 30
169	55	ETM+	December 02, 2000	30 × 30
169	55	OLI	November 11, 2020	30 × 30

and OLI with medium resolution at 30 m by 30 m. To detect changes in this watershed using images from three years, data collection and image tenacity must be as analogous as probable (Table 2). Each pixel was classified using the maximizing likelihood function statistical view based on the accepted ground truth [43]. Google Earth and field observation over the study period of 1991–2020 enabled to verify of the changes in LULC [44,45].

2.3. Image classification and accuracy assessment

Perhaps the most basic form of LULC analysis within the field of remote sensing is LULC classification, which involves the association of features within remotely sensed imagery with specific LULC maps [46,47]. Classification of the images was performed based on the classes defined in the classification scheme using Supervised (Maximum Likelihood) classification algorithm available in Erdas Imagine software version 2014.

The accuracy of categorization was assessed in this study using accuracy matrix analysis, user and producer accuracies, and kappa coefficient investigation. The interpreter agreement is measured using the Kappa coefficient, and the error matrix is stated in terms of user accuracy and producer accuracy [48]. The estimation of the user's and producer's accuracy was done using the error matrix, which considered the kappa coefficient and overall accuracy [49,50]. Consequently, for the three research years, the kappa coefficient value and overall accuracy were both above 85 %.

2.4. Estimation of RUSLE factors

The process of soil erosion is predisposed by physical landscapes and the study of water in certain watersheds [51]. In this research, RUSLE together with Arc GIS was used to estimate the soil loss [7]. This model is widely applied throughout the world where data sources are scarce [6,7,26,52]. The soil loss estimation using RUSLE in arc GIS approaches embroils the amalgamation of five various inputs (R, K, LS, C, and P) as shown in equation (1) below [52].

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

Where A - mean yearly soil loss per unit of area (ton/ha/year)

R refers to the rainfall erosivity factor (MJ mm/ha/h/y)

K denotes soil erodibility factor (t/ha/h/MJ/mm)

LS denotes the topographic factor.

C refers to the land cover and management factor.

P refers to the conservation practice factor.

Rainfall erosivity (R) index quantified the sediments transported from sheet and rill erosion by the impact of rainfall [29]. Rainfall information from five weather stations situated in and around the research area. Using the GIS raster calculator tool, the rainfall erosive factor value for each station was computed and plotted, and an R factor map was produced as raster data. Equation (2) has been used to obtain the R factor for every metrological station consuming data on the average yearly rainfall from Hurni's [53] regression equation:

$$\mathrm{R} = 0.562 \times \mathrm{M}\text{-}8.12 \tag{2}$$

Where R refers to erosivity factor and M is the average yearly rainfall (mm)

The soil erodability (K) is natural struggle with particle disintegration and movement by rainfall is expressed by the soil's erodibility. For typical circumstances of bare soil, recently tilled up-and-down with a slope without conservation methods, and on a slope of 50 and 22 m length [54]. Eleven soil types were identified for this investigation, and the K factor suggested for Ethiopian circumstances was taken from Hurni [53].

Topographic (LS) factor, which measures slope length and steepness, illustrates how topography affects the process of soil erosion. The risk of erosion increases with slope steepness and length [37,55,56]. Once the slope gradient had been retrieved from the DEM, the gradient length and angle were estimated via the subsequent equations (3)–(5) respectively [29].

Table 2
LULC classified description in the Boyo watershed.

LULC Classes	Description
Grassland	Small grasses and other natural plants grow on grazing grounds.
Forestland	Trees greater than 2.5 m, higher than 22 % of the area surrounded by trees, and an area larger than 5000m^2.
Barren land	Extreme degradation of the land, generally with unprotected rocks and no vegetation.
Cultivated land	The vegetation on farmland is diverse and includes fallow fields, irrigated areas, and areas used for rain-fed crops.
Built up	The portion of an urbanized region that belongs to a small town, together with its shops, streets, and associations like departments and health centers.
Wetland	The open water in a wetland, lakes, ponds, and the courses of rivers and streams
Water body	It is defined as regions that sustain hydrophytes plants that are swampy or meadow-like, either temporarily or permanently waterlogged due to human activity.

$$LS = \frac{\left[\left(A_{ij} - in + D^2\right)^{m+1} - \left(A_{ij} - in^{m+1}\right)\right]}{\left(C^{m+2}\right) \times \left(X_{ij} m\right) \times (22.13)^m} \tag{3}$$

Where LS denotes the slope length factor for the grid cell.

A denotes flow accumulation.

C is the size of the grid cell

m is the gradient length exponent [57].

$$m = \frac{B}{(B+1)} \tag{4}$$

$$B = \frac{\left(\frac{\sin \theta}{0.0896}\right)}{3\left[\sin \theta^{0.8} + 0.56\right]} \tag{5}$$

Where θ denotes the slope angle (degree)

The cropping and management (C) impact on soil erosion rates is reproduced in the crop cover and management (C) indicator [52]. Moreover, it has no dimensions and has a value ranging from zero which showed well-protected and maintained land and to a value of one which depicts a significant due to a lack of covering crops [4,56,58]. In this study, seven LULC categories were recognized; such as cultivated land, forest land, grassland, bare land, built-up, wetland, and water body (Table 3).

The soil conservation practice (P) factor is the judgment of the soil loss caused by a particular conservation measure to the equivalent soil loss caused by cropping patterns [29]. Its ratings varied from 0 to 1, with 0 denoting appropriate conservation practices and an erosion-resistant facility and 1 denoting poor practices [58]. Due to the scarcity of verified field measured data in Ethiopia, the soil conservation practice factor values suggested for Ethiopia conditions by Bewket and Teferi [26] and Hurni [53] were agreed upon and allotted to the classified land use and land cover (Table 4).

2.5. *Estimation of the sediment yield*

The sediment delivery ratio (SDR) is explained by Endalew and Biru [67], as the percentage of gross erosion from the watershed upstream of the measurement site to the sediment production at a specific stream cross section. The sediment yield at the watershed outflow was calculated using the following empirical formulae in equation (6):

$$\mathrm{SDR} = \mathrm{A}^{-0.2} \tag{6}$$

Where, SDR indicates the sediment delivery ratio and A indicates area of the study watershed.

Physically, the SDR refers to the ratio of sediment delivered to the outlet throughout the watershed, including both channel and overland. Empirical equation (7) is a standard method for estimating sediment yield [67].

$$\mathrm{SY} = \mathrm{E} \times \frac{1}{A^{0.2}} \tag{7}$$

Where SY is sediment yield (ton), E is annual soil loss (t/y) and A is entire area of the watershed (ha)

The soil depth removed due to erosion in the Boyo watershed was estimated using equation (8) as described in Dinka [66].

$$\text{Soil depth removed (mm)} = \frac{\mathrm{ER}}{\mathrm{BD}} \times \frac{1}{10} \tag{8}$$

Where ER refers to erosion rate (ton/ha), BD refers to soil bulk density (g/cm^3)

2.6. *Validation of model results*

One of the limitations of the RUSLE and perhaps many soil erosion models is the lack of data for validating the model outputs.

Table 3
Land use/land cover classes and their corresponding C factor values in the Boyo watershed.

Land use and land cover class	C value	References
Cultivated land	0.15	[53,59]
Forest land	0.01	[55,60]
Grassland	0.05	[55,60]
Barren land	0.60	[53,60]
Built up	0.05	[61]
Wetland	0.05	[62]
Water body	0.00	[63]

Table 4
Soil conservation practice (P) factor value adopted of the Boyo watershed.

Land use/land cover	P factor	References
Cultivated land	0.9	[64]
Grassland	0.6	[65]
Forest land	0.53	[64]
Barren land	1.0	[64]
Built up	0.63	[64]
Wetland	1.0	[66]
Water body	0.9	[40]

Benavidez et al. [68] indicated that validating the soil erosion rates estimated by the RUSLE is difficult because of the lack of easily available measured soil erosion records, especially in data-sparse regions.

For validating model results, studies suggest that ground-truthing is an important method, as the areas of severe erosion threat can be verified for physical proof of soil loss incidence [69]. The soil loss estimates can also be validated by comparing results with soil erosion studies of similar watersheds or larger-scale national or regional scale [70]. In this study, due to a lack of measured data specific to the study area, the validity of the model outputs was compared with the results of other studies conducted in Ethiopia to check the validity of the outputs. In addition, field observations were carried out to identify severely erosion affected areas [69,71].

2.7. RUSLE parameters sensitivity analysis

Sensitivity analysis measures how much the model's output changes in response to how much the model's input parameter values vary in response to those changes [72]. To determine the most sensitive criteria that guide focused and deliberate actions, sensitivity analysis was done [7,71]. Using the five RUSLE parameters' mean value as a baseline, the sensitivity analysis was performed. The one-at-a-time procedure, which entails altering the value of one variable per scenario one at a time, is the most often used technique for carrying out model sensitivity analysis [73]. Therefore, in this study tornado chart was used for ranking sensitivity of the RUSLE parameters [74]. Finally, equation (9) used to do a sensitivity index analysis in order to determine the relative relevance of each parameter.

$$SI = \frac{(Px - Mx)}{Baseline} \times 100 \tag{9}$$

where SI is sensitivity index, PX is model output with X is increase of the variable, MX is model output with X is decrease of the variable.

3. Results and discussions

3.1. The land use and land cover categorization assessment

Using GIS techniques, the LULC in the Boyo watershed was categorized into seven classes, including forest land, grassland, cultivated land, barren land, built-up area, wetland, and water body (Table 5). Cultivated and barren lands extended from 28.83 % to 41.75 % and 6.34 %–14.21 % respectively, whereas forestland and grassland decreased from 14.45 % to 7.74 %, and from 11.6 % to 6.18 %, correspondingly between 1991 and 2020 (Table 5).

The most recent image (2020) has a kappa value of 0.87 and an overall accuracy of 92.5 % (Table 6). Therefore, the Kappa statistics of this investigation demonstrated a significant agreement for the recently categorized image, and the total accuracy was within the acceptable range for further LULC changes analysis [50,67]. According to Congalton and Green [50], the use of classification measures such as overall accuracy, Kappa statistics, producer's accuracy, and user's accuracy is quite common and all accuracy measures are acceptable if greater than 85 %.

Table 5
Extent of LULC changes amongst 1991 and 2020.

Land use/land cover types	1991		2000		2020	
	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
Cultivated land	64397	28.83	74816	33.49	93248	41.75
Wetland	43752	19.59	27429	12.28	26209	11.73
Forestland	32285	14.45	25292	11.32	17294	7.74
Barren land	14158	6.34	19879	8.90	31742	14.21
Built up	41615	18.63	37999	17.01	40890	18.31
Grassland	25905	11.60	37122	16.62	13809	6.18
Water body	1258	0.56	833	0.37	177	0.08
Total	223370	100	223370	100	223370	100

Table 6
Accuracy assessment for 1991, 2000 and 2020 LULC Map classification.

No.	LULC	1991		2000		2020	
		PA (%)	UA (%)	PA (%)	UA (%)	PA (%)	UA (%)
1.	Cultivated land	87.89	82.19	91.5	89.42	93.42	90.53
2.	Wetland	94.0	89.190	91.45	89.20	91.40	92.59
3.	Forestland	94.34	96.39	93.20	93.45	92.86	90.70
4.	Barren land	72.70	94.12	82.34	94.34	96.04	95.04
5.	Built up	91.30	93.33	92.31	94.12	93.28	94.67
6.	Grassland	80.00	82.00	85.45	88.30	91.37	94.00
7.	Water body	95.00	95.00	94.15	94.30	93.20	94.20
–	Overall accuracy (%)		91.50		95.40		92.50
–	Kappa coefficient (%)		89.0		93.00		87.00

PA-producer accuracy, UA-user accuracy.

The result of accuracy assessment for the image in 1991, 2000 and 2020 indicated an overall accuracy of 91.50, 95.40 and 92.50 %, respectively, while corresponding kappa statistics of 89.00, 93.00 and 87.00 % for Landsat images respectively (Table 6). The producer's accuracies (PA) in the classified maps of 1991 and 2020 were 72–96 %, and 88–96 %, respectively, while the user's accuracies (UA) were greater than 80 % for a Landsat image and greater than 90 % for the Sentinel image; similar results produced elswhere in the country [75].

The spatial pattern and extent of LULC classes play a significant role in reducing raindrop impacts on soil particles [76]. Tropical regions with poor surface cover are highly susceptible to soil erosion and consequent soil loss following rainfall. The spatial pattern and magnitude of LULC classes extracted from classified images revealed that cultivated land was the most dominant in the study watershed in 1991, 2000 and 2020. For agricultural domain in Africa, Brink and Eva [77] analyzed a 57 % increase from the year

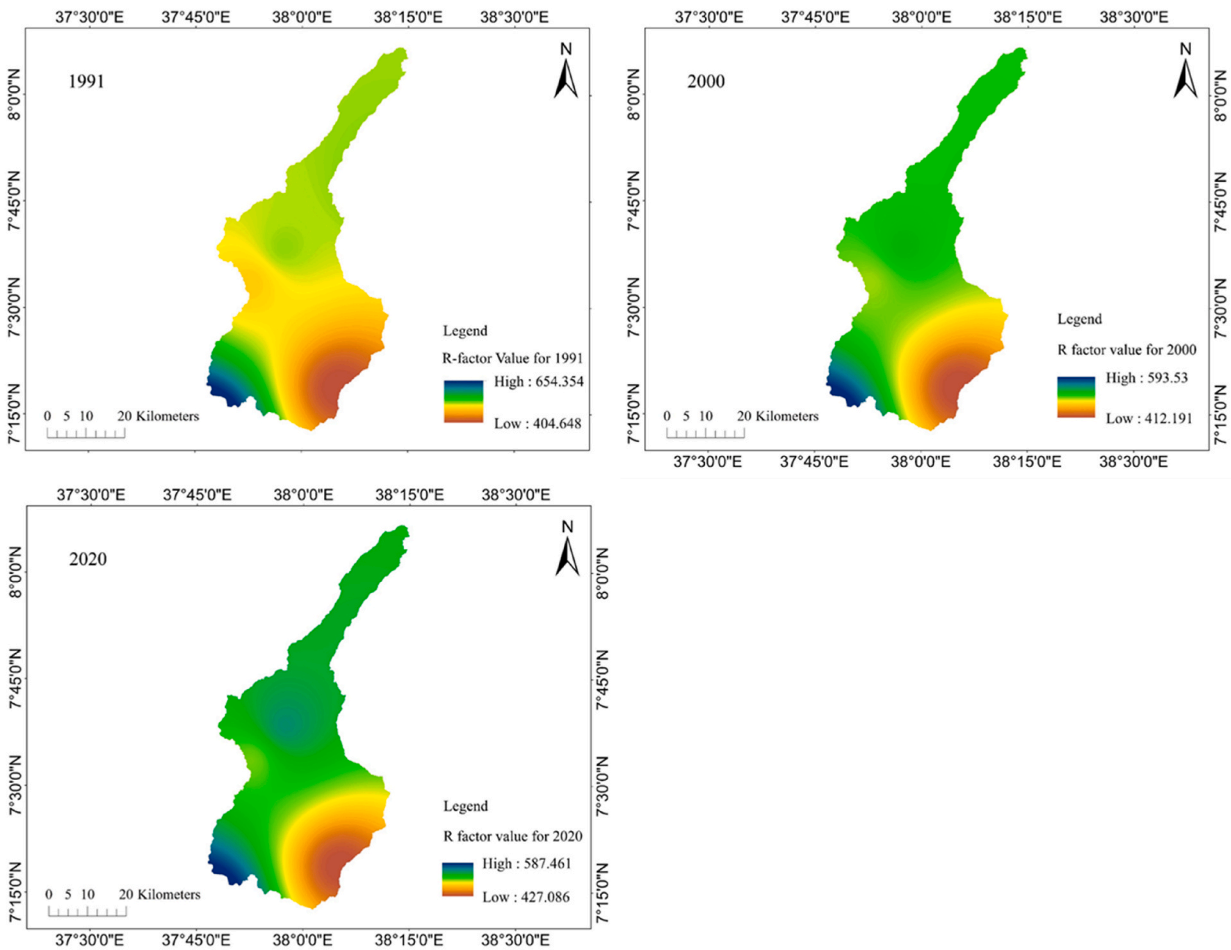

Fig. 5. Spatial variability of erosivity (R-factor) for 1991, 2000 and 2020 of the Boyo watershed.

1975–2000. Similar studies conducted in the highlands of Ethiopia indicated an increase in agricultural land from 43 to 57 % [78] and 47.9–64.4 % [79].

The major changes were expansion of cropland at the expense of other LULC classes at the rate of 29.56 % in 1978, 38.91 % in 1987, 46.62 % in 2001 and 52.74 % in 2015 [80]. It has gained about 160,736.08 ha with an annual average increment of 4344.22 ha. In another study by Mathewos et al. [49] in 1985, shrub and grassland made up the majority of the land, followed by cultivated land (23.35 %) and forestland (9.38 %). In the Gumara watershed of the Lake Tana Basin, northwestern Ethiopia, between 1957 and 2005, it was found that cultivated and settlement land increased by 21.9 %, whereas forestland, shrubland, grassland, and wetland decreased by 85.3, 91.3, 76.1, and 72.54 %, respectively [81].

Getachew and Melesse [82] noted that although forest and rangeland decreased, built-up and agricultural land rose. While grazing land and Acacia forests decreased, bare land, cultivated land, and shrubland increased in the central Rift Valley Basin [83]. The results of this study are in line with those of other studies conducted across the nation. For instance, Zeleke and Hurni [84] in the Dembecha region of northwest Ethiopia reported that between 1957 and 1995, 99 % of the forest cover was converted into cropland. Similar to this, Kindu et al. [85] reported that nearly 66.2 % of woodland has been converted to agricultural land in the Munessa-Shashemene environment of the Ethiopian highlands. Several new local-level LULC dynamics research works designated related trends [82,86–88].

3.2. Estimation of soil loss factors

The erosivity factor (R) result showed in 1991, the mean erosivity in the studied area was 522 MJ mm/ha/y with a range of 461.8–602.9 MJ mm/ha/y (Fig. 5). For the years 1991, 2000, and 2020, Table 7 below presents the yearly rainfall and computed erosivity values of the different stations. The south-western portion of the research watershed has higher R value and tends to decline towards the south-eastern and northern part of the Boyo watershed. The central part of the Boyo Lake plain has the erosivity value which ranges 492–524 MJ mm/ha/y.

The watershed's erodibility K value varied from 0.15 to 0. 27 t h/ha/MJ/mm, with a mean K value of 0.17 t h/ha/MJ/mm. This variation can be attributed to the soil types and prevailing soil color. While the highest K values are clustered in high elevation places, the lowest K values are concentrated in lowlands (Fig. 6). Ochric Pellic Vertisols and Hypereutric Chromic Luvisols had higher erodibility values than other soil types, making them more prone to soil erosion (Table 8).

The slope length and steepness (LS) value varied from 0 to 129.3 (Fig. 7). The areas having steep slopes and high elevation are characterized by high LS values indicating the higher vulnerability of the soil to erosion (Table 9). This is in agreement with study conducted by Gelagay and Minale [89], Kayet et al. [90] and Yadeta et al. [91] who observed the significant influence of LS factor on soil erosion in steep areas of the catchment.

The cover and management (C) factor concerning, the major LULC class of the watershed was found to be cultivated land which is dominantly distributed throughout the entire watershed, while the rest of the LULC types showed a significant change throughout the study period. The effect of the C factor map (Fig. 8) showed that the C value ranges from 0 to 1. Higher C values were assigned to bare lands (1) with no land cover and cultivated land (0.15) signifying higher susceptibility to soil erosion whereas the lower C value was recorded in water body followed by the forested areas which are less vulnerable to soil erosion. For the other land use classes, moderate C values were assigned, indicating a moderate susceptibility to erosion.

The conservation practices (P) factor of the Boyo watershed ranges from 0.1 to 1 (Fig. 9), where values near zero indicates better conservation practice with minimum erosion, while values approaching one show low conservation practices.

3.3. Annual soil erosion

The Boyo watershed's calculated soil loss ranged from 0 to 132.5, 208.34, and 534. 10 t/ha/y in 1991, 2000, and 2020, respectively (Fig. 10). The mean yearly soil loss of the Boyo watershed varied from 15.54, 35.95 and 38.32 t/ha/y in 1991, 2000 and 2020 correspondingly. This showed that the predicted mean yearly soil loss rate for the study watershed surpasses the greatest allowable soil loss 8 t/ha/y suggested by Hurni [53] for various agro-ecological zones of Ethiopia.

A total soil loss for the Boyo watershed was established to be 352,259, 795,752.68, and 870,763.12 t/y in the year 1991, 2000 and 2020 respectively. This result was lower than the previously reported by FAO [92] for Ethiopian highlands of shrub and farmlands. The development of the watershed's soil erosion risk area was based on the severity categories established by Haregeweyn et al. [93], which classified the watershed into five erosion severity ranks based on their estimated erosion rates (Table 10).

The area with severe to very severe erosion potential (soil erosion rates over 30 t/ha/y made up 0.95 % of the entire Boyo

Table 7
Mean yearly rainfall and R factor of Boyo watershed.

Metrological stations	Yearly rainfall (mm)			Erosivity (MJ mm/ha/y)		
	1991	2000	2020	1991	2000	2020
Halaba	1150.7	1012.8	1054.1	461.8	412.2	427.1
Angacha	1494.5	1595.5	1565.2	585.6	622.0	602.9
Fonko	1542.5	1294.2	1368.6	602.9	513.5	540.3
Hosaina	1328.1	1234.0	1262.3	525.7	491.9	502.0
Wulbareg	1469.5	1282.0	1338.3	576.6	509.1	529.4

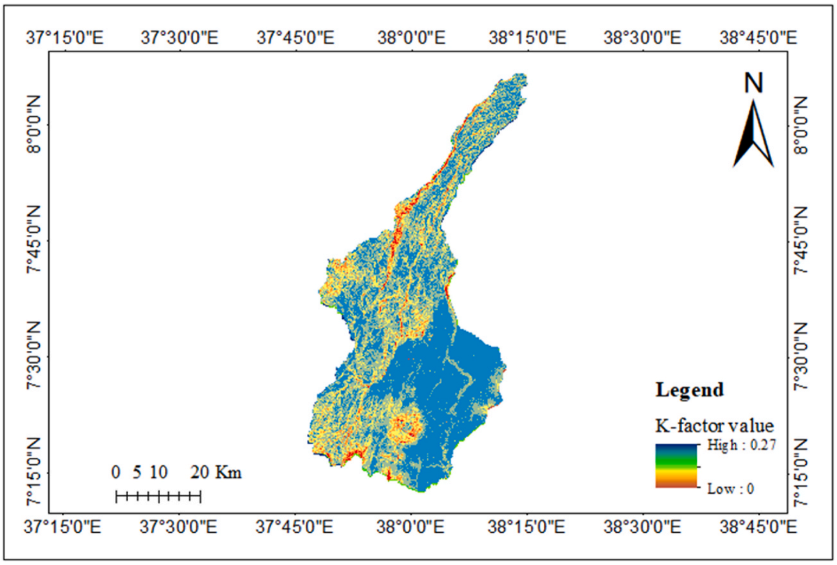

Fig. 6. Erodibility factor (K factor) map of Boyo watershed.

Table 8
Soil types and respective K values of Boyo watershed.

Soil types	Area (ha)	K value (t hr/ha/MJ/mm)	Colour
Fluvic Vitric andosols	60521.04	0.15	Black
Loamic Mollic Solonchaks	52253.43	0.15	Black
Ochric Pellic Vertisols	50908.71	0.20	Brown
Ochric Eutric Fluvisols	16920.13	0.15	Black
Hypereutric Chromic Luvisols	13543.29	0.15	Black
Fluvic Dystric Leptosols	7312.36	0.15	Black
Andic Dystric Nitisols	6012.03	0.15	Black
Rhodic Luvic Phaeozems	5461.55	0.15	Black
Ochric Haplic Calcisols	5169.92	0.20	Brown
Hypereutric Chromic Vertisols	4480.31	0.27	Red
Humic Eutric Nitisols	787.23	0.15	Dark brown

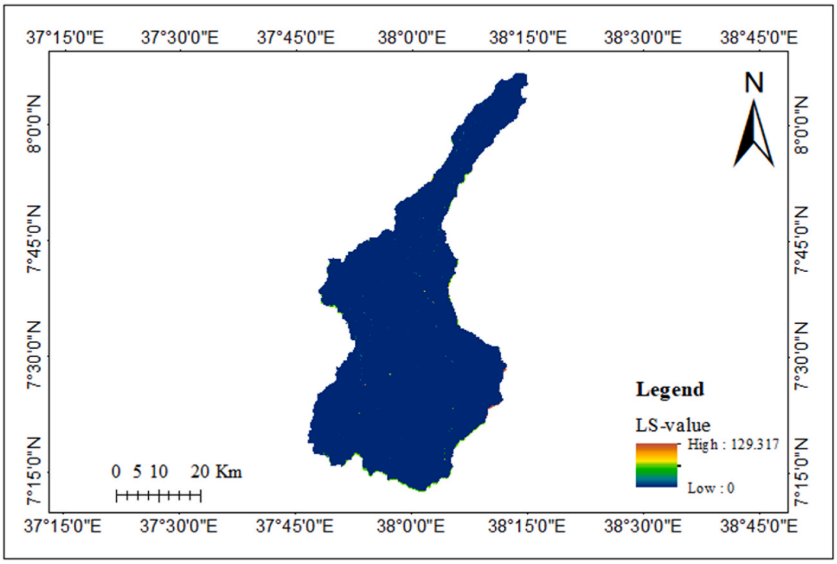

Fig. 7. Slope length and steepness factor (LS factor) map of Boyo watershed.

Table 9
Slope classes and its associated area of Boyo watershed.

Slope steepness	Description	Area (ha)	Area (%)
0–1	Level slope	9256.4	4.1
1–5	Gentle slope	76574.4	34.3
5–10	Sloping	56779.8	25.4
10–15	Strongly sloping	32463.4	14.5
15–30	Moderately sloping	37626.6	16.8
30–45	Steep	7336.6	3.3
>45	Very steep	3332.8	1.6
Total		223,370	100

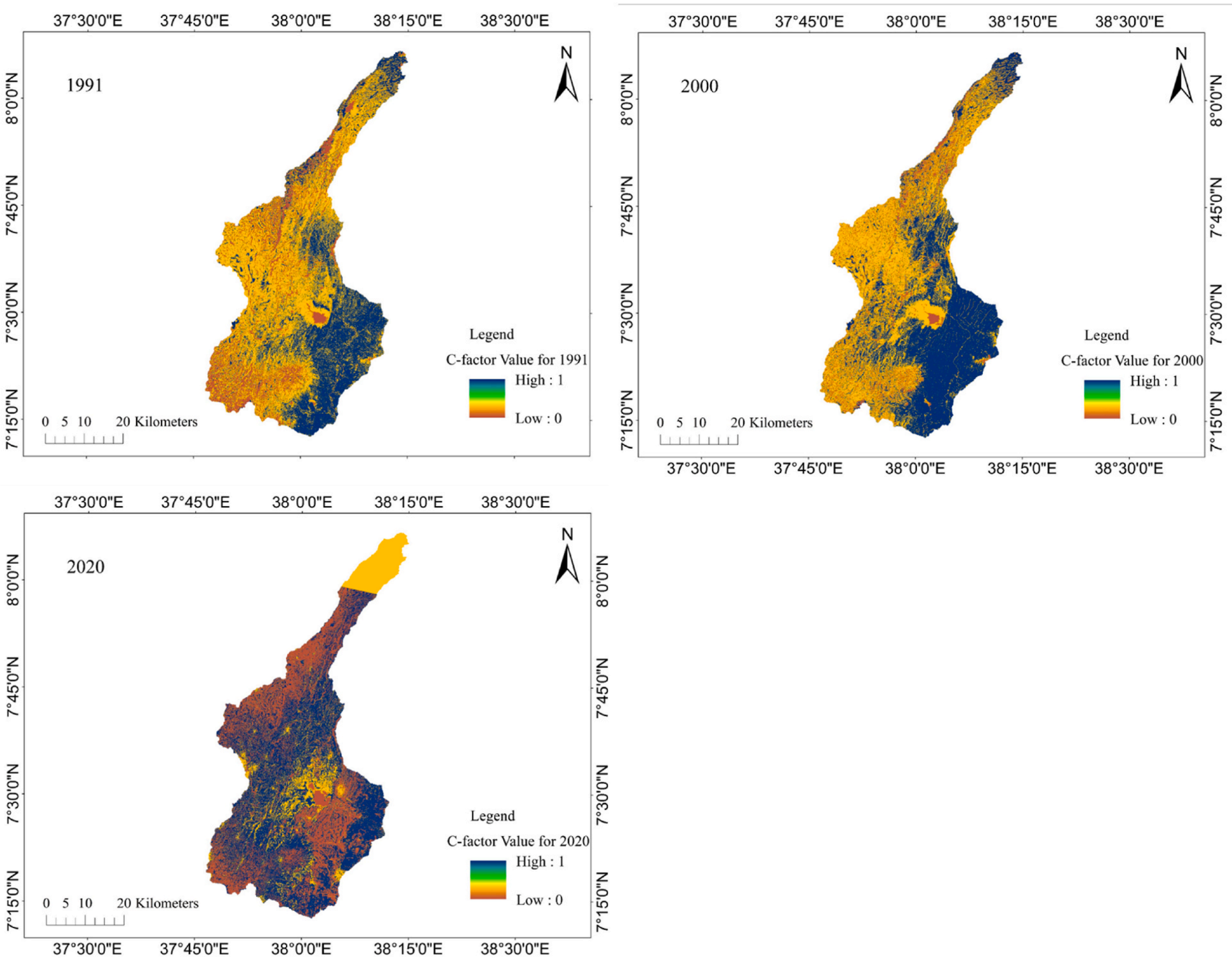

Fig. 8. Spatial distributions of cover and management factor (C- factor) for 1991, 2000 and 2020 of the Boyo watershed.

watershed, and the soil loss in this class accounted for 13.8 % of the overall probable soil erosion. About 48,720 ha of the soil loss is accounted for by this little area of the watershed.

The research output showed about 36 cm productive top soil in the watershed was lost during twenty nine years period (Table 11), this result was much higher than the findings of Dinka [66] who reported that 23 cm economically productive soil lost within 1965–2015 in Lake Basaka catchment in Central Rift Valley Region of Ethiopia.

3.4. Prioritization planning for erosion prone areas

The Boyo watershed is divided into eight sub-watersheds depending on their drainage systems to identify high erosion risk sections of the watershed for prioritizing. The soil loss values for each sub-watershed were obtained from the watershed's soil loss map, and a mean soil loss value was assigned to each sub-watershed (Table 12). It was estimated that SWs4 lost more soil each year than the

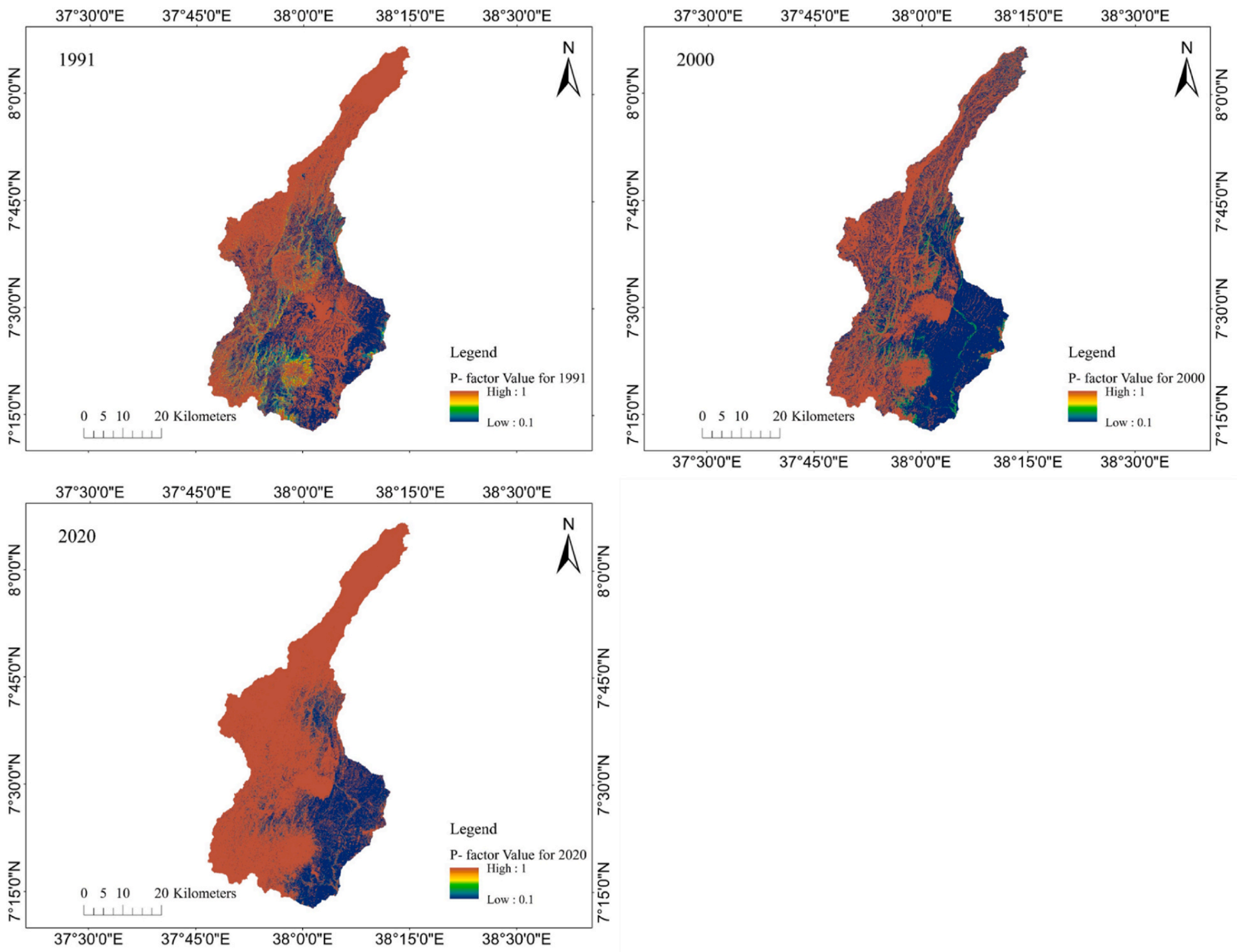

Fig. 9. Support practice (P factor) for 1991, 2000 and 2020 map of the Boyo watershed.

watershed as a whole (38.32 t/ha/y).

The average soil erosion rate for each sub-watershed was calculated for this study's prioritizing purposes, and it was then categorized into five soil erosion rate classes suggested by Pham et al. [94]. Accordingly soil loss rate is classified as slightly (0–11 t/ha/y), moderate (12–18 t/ha/y), high (19–30 t/ha/y), very high (31–50 t/ha/y), severe (>51 t/ha/y). Based on the mean soil loss values, the evaluated yearly average soil loss for the Boyo sub-watersheds were divided into various classes (Table 12).

According to the geographical arrangement of the identified soil erosion severity classes, the research area's central and south-western portions had the greatest priority areas, while the watershed's eastern, southern, and south-eastern regions had the lowest priority areas (Fig. 11).

SWs4, SWs5, SWs1, and SWs2 require rapid human intervention, because they have lost more soil than is necessary to maintain a high level. These sub watersheds contributes about 82.11 % of the total soil loss from the Boyo watershed. Irrespective of its area coverage SWs4 significantly contributed massive amount of soil loss (87,439 t/y) of soil loss from the watershed, whereas, SWs8 contributes the least erosion rate (5.8 %) of the watershed.

The result showed that sever soil loses (>50 t/ha/y) is observed in SWs4 which is the central part of the watershed accounted about 10 % of the aggregate soil loss. Three sub watersheds namely SWs1, SWs2 and SWs5 having an area of 76949.5 ha (34 %) of the entire watershed contributed 68 % of the total soil loss. The sub-watersheds SWs7 and SWs8 that are anticipated to experience a slight soil loss cover 20 % of the watershed area. The remaining sub watersheds experienced moderate and high severity class of the soil loss.

This output is in consistent with the findings of Tadesse and Abebe [95] investigated 30.4 t/ha/y for Jabi Tehinan woreda; whereas Kidane et al. [55] found about 30.30 t/ha/y for Guder sub watershed, Central highlands. The average soil loss rate obtained in this study watershed was lower than that in Koga watershed (42 t/ha/y) in the northern highlands of Ethiopia [96], as well as from Rib watershed (39.80 t/ha/y) [97].

The typical yearly soil erosion rate assessed for the whole watershed was 35.95 t/ha/y for 2020 which is similar to different findings by Yesuph and Dagne [71] for the highland of Ethiopia (37 t/ha/y), by Tadesse and Abebe [95] for the Jabitehinan watershed (30.4 t/ha/y) and by Degife et al. [69] for the Lake Hawassa watershed in the Rift Valley Basin (37 t/ha/y).

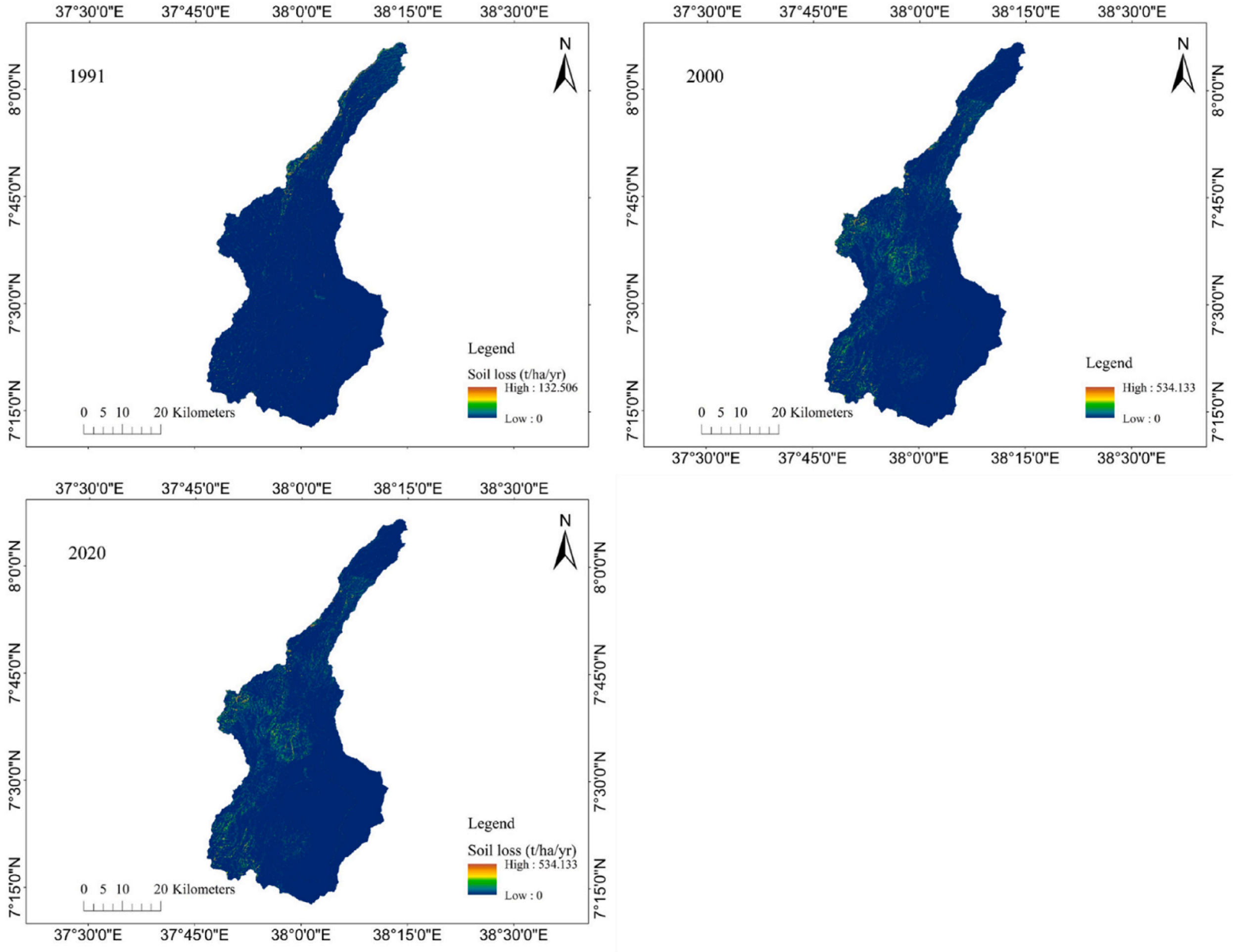

Fig. 10. Boyo watershed soil loss map for the years 1991, 2000 and 2020.

Table 10
Soil loss range, severity class, area coverage and their contribution in the study area in 1991.

Soil erosion rate (t/ha/y)	Severity class	Area (ha)	Area (%)	Soil loss (t/y)	Soil loss (%)
0–5	Very slight	217636.5	97.43	262197.8	74.43
5–15	Slight	2601.6	1.16	26015.7	7.39
15–30	Moderate	1021.7	0.46	15325.4	4.35
30–50	Severe	1105.7	0.50	14406.6	4.09
>50	Very severe	1004.5	0.45	34313.4	9.74
Total		223370	100.00	352259	100

Table 11
The rate of soil loss in the Boyo watershed.

Year	Min	Max	Mean	Overall soil loss (t/y)	Top soil lost (cm)
	(t/ha/y)				
1991	0	132.50	15.54	352,259	–
2000	0	208.34	22.76	795, 753	18.27
2020	0	534.10	31.32	870, 763	36.21

.Conversely, few studies revealed high disintegration rates in different regions of Ethiopia's high nations, which contradicts our findings. For instance, Bewket and Teferi [26] for the Chemoga watershed of the Blue Nile basin in the northwestern Ethiopia (93 t/ha/y) and Gelagay and Minale [89] for the Koga watershed (47.4 t/ha/y).

Table 12
Soil loss and priority sub-watershed in the year 2020.

Sub-watershed name	Area (ha)	Soil loss (t/y)	Soil loss (%)	Mean soil loss (t/ha/y)	Priority class
SWs1	13462.4	145121.8	16.67	24.2	III
SWs2	31348.0	129506.0	14.87	20.7	IV
SWs3	57644.7	110506.5	12.69	16.4	V
SWs4	28333.4	87439.3	10.04	59.3	I
SWs5	32139.1	317159.5	36.42	27.2	II
SWs6	15653.7	7429.5	0.85	9.4	VI
SWs7	23306.2	23122.7	2.66	4.3	VII
SWs8	21482.5	50476.9	5.80	1.4	VIII
Total	223370	870762.2	100		

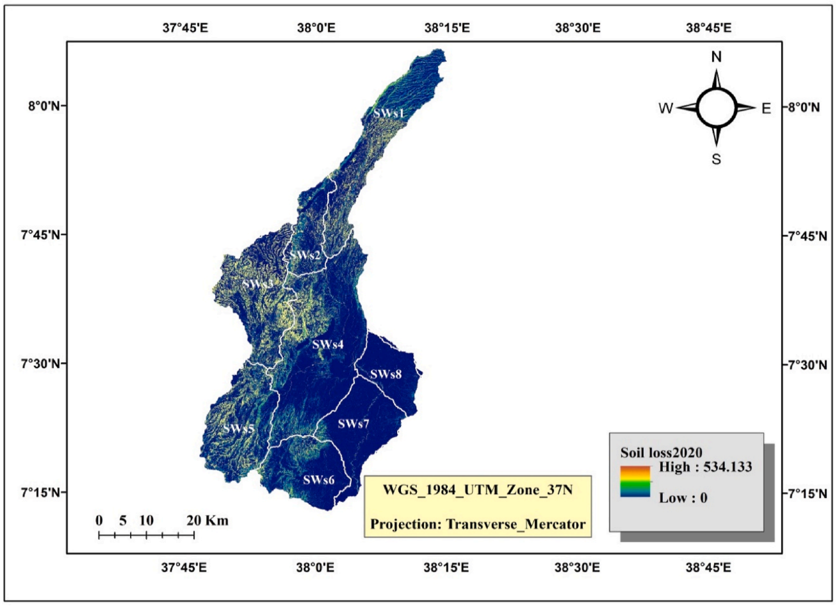

Fig. 11. Soil erosion severity class of study Boyo watershed.

Different investigations conveyed lower soil erosion rates than our findings, for example, Brhane and Mekonen [98] discovered 9.63 t/ha/y; Gizachew [99] found 9.1 t/ha/y and Tiruneh and Ayalew [100] found 4.81 t/ha/y in the highlands of Ethiopia.

In the Rift Valley Basin, various erosion rates reported by various author; Degife et al. [69] described 37 t/ha/y in the Lake Hawassa sub-basin, Jothimani [101] found 68 t/ha/y in the Weito watershed, Woldesenbet et al. [102] investigated 30.5 t/ha/y in Meki catchment, Meshesha et al. [103] reported 56 t/ha/y in southern RVB, Wolka et al. [104] found 45 t/ha/y in the central RVB and Abebe [105] investigated 68.7 t/ha/y in the Cheraqe catchment in lower Bilate sub-basin.

Lower results reported by various scholars, for instance, Mathewos et al. [6] at Matenchose watershed reported 21 t/ha/y; Kouli et al. [106] reported 10 t/ha′y; Haregeweyn et al. [107] described 29.9 t/ha/y in southern Ethiopia; Gerawork and Moges [108] explored 7.47 t/ha/y; Bekele and Gemi [109] reported 2.2 t/ha/y. The variety in the outcomes might be credited to the fluctuating soil factors in the different review regions.

A similar approach was implemented to estimate the soil erosion effect in various areas of the country [7,65,110]. In light of the designation of micro watersheds as erosion-prone regions based on the severity degree of soil loss, a targeted and cost-effective conservation planning strategy is emphasized [25].

3.5. Sensitivity analysis of RUSLE parameters

Instead of minimizing each RUSLE component's contribution, the aim of this sensitivity analysis is to arrange the components in the research watershed's unique context. It is an established fact that each and every RUSLE parameter has a substantial effect on soil erosion. This study showed that the primary sensitive variable impacting anticipated soil loss in RUSLE was land use and land cover (C factor), regardless of the range of estimations or the method utilized for parameter estimation (Fig. 12). The slope length and steepness (LS factor) also showed the second sensitive parameter in the model predictions.

The result of this study is supported by another study reported the C factor and topography were the most important factors driving predicted soil loss in RUSLE [111]. The study that provided evidence for this particular finding revealed the C and K factors as the main and second sensitive parameters of RUSLE that affect the amount of soil erosion [74]. According to the findings of the other study, rainfall erosivity (R) and topographic factor (LS) are important elements that limit soil loss and have a considerable impact on the amount of soil loss [112]. Due to significantly greater R values and prior sensitivity study in a subtropical zone [113], we thought the R factor to be more significant, but this factor was not the case in our study watershed.

3.6. Sediment yield

In similar manner of soil erosion, sediment yields were very high at the Boyo watershed outlet across the three research periods. The amount of erosion in the Boyo watershed was higher than the quantity of sediment exiting the watershed at the outlet point. The output revealed that from the gross 870,762.12 t/y of soil erosion, 74,147 t/y were calculated at the watershed outlet in 2020. In similar manner, 29,996 and 67,760 ton/year estimated in 1991 and 2000 respectively (Table 13).

Various scholars showed that there were a close connection between gross soil erosion and sediment delivery ratio; the sediment yield was assessed at the watershed outlet [67,114–116].

The outputs of the current research were consistent with previous findings by Fenta et al. [10] reported that the average sediment yield from the Abay Basin is 7 t/ha/y. Kidane et al. [55] investigated sediment yields for the three periods (1973, 1995 and 2015) in the Guder sub-catchment, showed average sediment yields of 6.79, 8.65 and 9.44 t/ha/y. In similar manner, Tamene et al. [110] from the Adikenafiz catchment, northern Ethiopia (45 t/ha/y) and Haregeweyn et al. [93] in the upper Blue Nile Basin reported similar results (7.34 t/ha/y). In addition, Leta et al. [117] in upper Blue Nile watershed using SWAT model reported the watershed's average yearly sediment of 25.96 t/ha/y and Gelagay [118] estimated the annual sediment yield rate of 5144 t/ha/y for the entire Koga watershed.

4. Conclusion

Land use and land cover changes were found to be pervasive, accelerating, and important processes in the watersheds studied. The RUSLE model was combined with arc GIS procedures used to estimate overall soil loss rates and average annual losses, and to evaluate the spatial distribution of soil loss rates among various sub-watersheds.

The study also demonstrated that, increasing the risk of soil erosion from 15.54 t/ha/y in 1991 to 35.95 t/ha/y in 2000, and then to 38.32 t/ha/y in 2020. The overall change in land use and cover over the course of the three research years had a significant impact on the watershed. The analysis showed that the biggest portion of LULC from all classes was dominated by cultivated land and the smallest area was covered by water body through the study period. Within the three decades, the cultivated land, bare land and built up showed increasing trend whereas forest land, grass land, wetland and water body classes were declined.

The study's key findings include a map of the watershed's soil erosion values and a ranking of sub-watersheds according to their conservation importance, which may be utilized to create a conservation strategy for managing the watershed.

It was discovered that the SDR mean value was 8.52 %. This demonstrated that a sizeable amount of the gross soil loss was transmitted through the channel networks. It is estimated for 2020 that 74,147.25 t/y (8.52 %) of the total 870,763.12 t/y of soil erosion reach the Boyo watershed outflow as sediment yield. This demonstrated that places with high elevation and frequent precipitation are vulnerable to erosion. It need priority by the decision-makers' in planning and conservation efforts to reverse land degradation on the Boyo watershed.

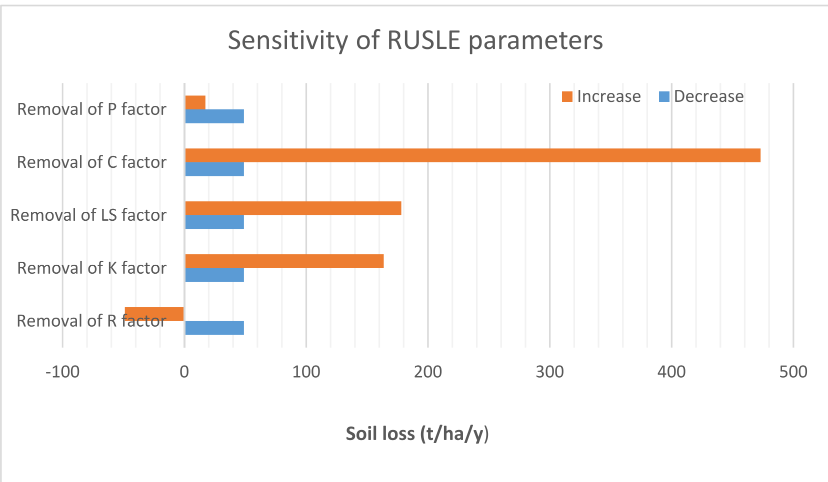

Fig. 12. The chart showing sensitivity index of the RUSLE parameters of Boyo watershed.

Table 13
The sediment yield in Boyo watershed.

Study year	Sediment yield (t)
1991	29,960
2000	67,760
2020	74,147

Data availability statement

The data included in article/supplementary material presented in the article.

CRediT authorship contribution statement

Markos Mathewos: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Dila Wosoro:** Writing – original draft, Software, Methodology, Investigation, Conceptualization. **Nigatu Wondrade:** Writing – review & editing, Validation, Supervision, Software, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e31246.

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