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ORIGINAL ARTICLE

Soil erosion modelling using GIS and revised universal soil loss equation approach: a case study of Guna-Tana landscape, Northern Ethiopia

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Abstract

An attempt has been made in this study to quantify the soil loss rate in Guna-Tana Landscape, Ethiopia. A Digital Elevation Model (12 m by 12 m spatial resolution), rainfall data over 10 years, soil, and land cover/land use extracted were used as an input to calculate soil loss rates. GIS-based RUSLE factors were integrated and analyzed in the ArcGIS 10.3 plate form. The results showed that 12-monthly loss of soil in the study area ranges from zero in the lower, middle, upper, and steeper slope parts of the watershed to 4735 t/ha/year with a mean annual soil loss of 3627.5 t/ha/year. The overall annual soil loss in the study area is 14,335,517.8 tonnes. Approximately 681.21 ha of the area is within the extreme and very extreme erosion clusters which demand immediate controlling measures.

Keywords GIS · RUSLE · Soil erosion · Guna-Tana landscape · Ethiopia

Introduction

Socio-economic factors and limited resources have accelerated soil erosion in developing countries (Bayramin et al. 2003). According to the researchers (Edwards 1979; Gachene 1995; Tiffen et al. 1994), widespread soil erosion occurs in East African highlands. According to Hurni (1985), an annual soil loss of Ethiopian highland reaches up to 300 t/ha/year. This leads to a reduction in the productivity of Ethiopian land (Sertsu 2000). Another research done by Taddese (2001) showed that Ethiopia loses over 1.5×106 metric tons of soil each year by erosion. The accelerated soil loss rate in Ethiopian highlands is attributed to multiple factors including the shifting cultivation on the hill slopes and non-adoption of soil conservation techniques (Bewket 2002; Nyssen et al. 2004; Amsalu et al. 2007; Tamene and Vlek 2008; Fazzini et al. 2015).

Different scholars applied the Revised Universal Soil Loss Equation (RUSLE) model to estimate soil loss estimation for different land-use practices on steep slopes (Renard et al. 1996; Dunn and Hickey 1998; Mekuriaw et al. 2018; Miheretu and Yimer 2018).

Geographic Information System (GIS) is a powerful tool in demarcating the spatial distribution of soil loss rates. For example, soil erosion modeling of Gumara watershed (Ethiopia) has been done by Imran (2018) using GIS coupled with RUSLE. GIS coupled with RUSLE factors provides a better opportunity to assess the soil loss distribution, identify hotspot areas, and simulate possible management measures (Stillhardt et al. 2002; Nyssen et al. 2004; Kaltenrieder 2007; Woldeamlak and Ermias 2009). Better conservation

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planning requires a sound knowledge of spatial variations in soil erosion (Lulseged et al. 2006).

Therefore, RUSLE integrated with GIS is best suited for this research in the Guna-Tana Landscape, Ethiopia; the Guna-Tana Landscape where information on soil loss and risk assessment of potential soil erosion is not documented well. The main objectives of this study area: (a) to identify the soil erosion hazard areas spatially and (b) to estimate the soil loss rates spatially, so that necessary steps could be taken to control the severe soil loss for better watershed management.

Research methods

Description of study area

Guna-Tana landscape was located in the South Gondar zone of the Amhara Region in the eastern part of the Lake Tana basin of Ethiopia. The catchment covers the 349,292.53 ha area (Fig. 1). The watershed extends from 337,239 to 417,206 m longitude and 1,280,022–1,352,403 m latitude. The elevation ranges from 4108 m in the highland to around 1774 m in the floodplain. The catchment was drained by Gumara and Ribb rivers which were originated from Guna Mountain and, finally, joins Lake Tana in the vicinity where rivers cause flooding. An undulating and rugged topography is dominating the basin containing steep slopes in the mountainous region in the east and more gentle slopes towards Lake Tana.

Meteorological conditions

There are about eight Woredas in the watershed. The average yearly rainfall of the study area was 1368.61 mm, (Fig. 2). The important input parameters used in this study were DEM, precipitation, and soil (Table 1).

Sources of data

The soil data, DEM, land use/cover, and rainfall records (Table 1) were used to achieve the output of the study.

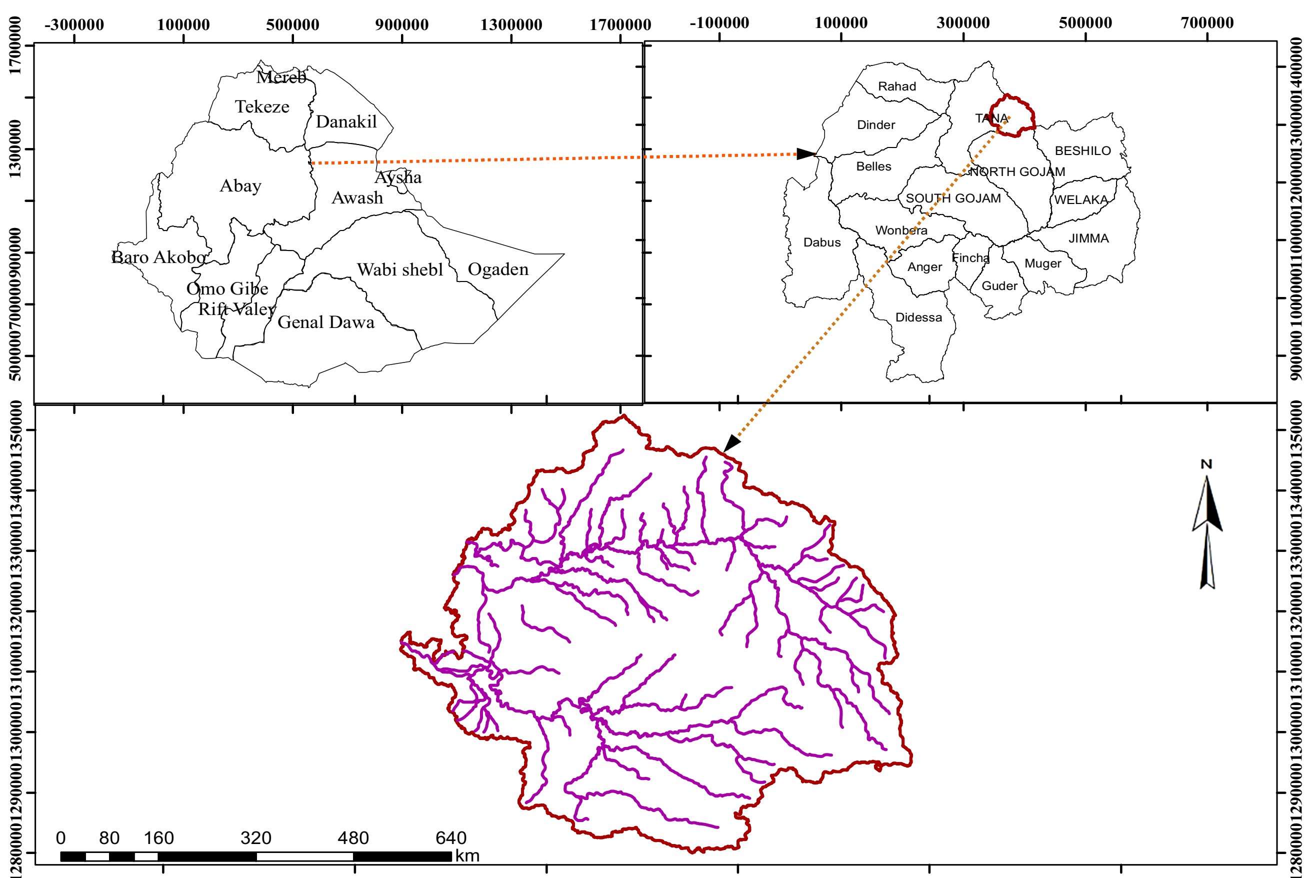

Fig. 1 Situation of the study area

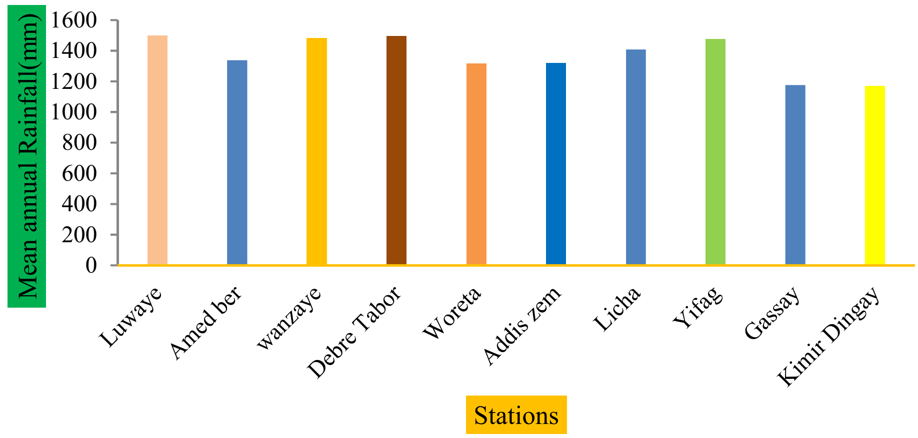

Fig. 2 Mean annual rainfall of Guna-Tana landscape

Table 1 Source of data and description

No	Data type	Source	Description
1	DEM	vertex.daac.asf.alaska.edu	12 m × 12 m resolution DEM from Alaska satellite facility's
2	Rainfall data	ANMA Bahir Dar	Precipitation data for 19 years (1997–2016) of ten hydrometer stations
3	Soil data	Blue Nile Basin soil map	The soil map prepared by ANMA, (2014)
4	Land use	Blue Nile Basin land-use map	Extracted from Blue Nile Basin land-use map

Soil loss estimation parameters

As stated by different scholars, there was a limitation to apply USLE for estimating soil loss in different situations due to it was applicable only for specific situations like cultivated land rather than for different land-cover types and could not applicable for complex topographical landforms. Hence, RUSLE was applicable for such types of landscapes and mathematically expressed as:

$$A = R * K * \mathrm{LS} * C * P, \quad (1)$$

where *A* average yearly soil loss (metric t/ha/year). *R* rainfall erosivity factor (Mega Joules mm perh/ha/year). *K* soil erodibility factor (metric t/ha/MJ/mm). *LS* slope length-steepness factor (dimensionless). *C* cover and management factor (dimensionless). *P* erosion support practice or land management factor (dimensionless).

As indicated in the conceptual framework diagram (Fig. 3), all factors estimated based on the recommendation of different scholars and Hurni (1985).

Rainfall erosivity *R*-factor vs soil loss

The estimation of soil loss was affected by rainfall and rate of runoff which was influenced by rainfall erosivity factor (Xu et al. 2008). The map of the *R*-factor for the study area was prepared by using the following step in the GIS environment.

1. Preparation of mean annual rainfall (*P*).
2. Applying interpolation techniques by Inverse Distance Weighted (IDW) in the ArcGIS 10.3 platform.
3. Calculating the corresponding factor by considering the condition for Ethiopia using Eq. (2) and see Table 2 below
4. $$R = -8.12 + (0.562 * P) \quad (2)$$

K factor (soil erodibility)

This factor used to quantify soil resistivity to transport by shear stress on ground flow and raindrops. Based on the recommendation of different scholars (Tirkey et al. 2013; Wischmeier and Smith 1978) and kinds of literature the researcher reclassifying the soil of the study area and assigned k values based on the colors of the soils (Table 3).

Slope length–steepness (LS) factor

The LS factor of the study area has been generated from DEM using the following steps in the GIS environment.

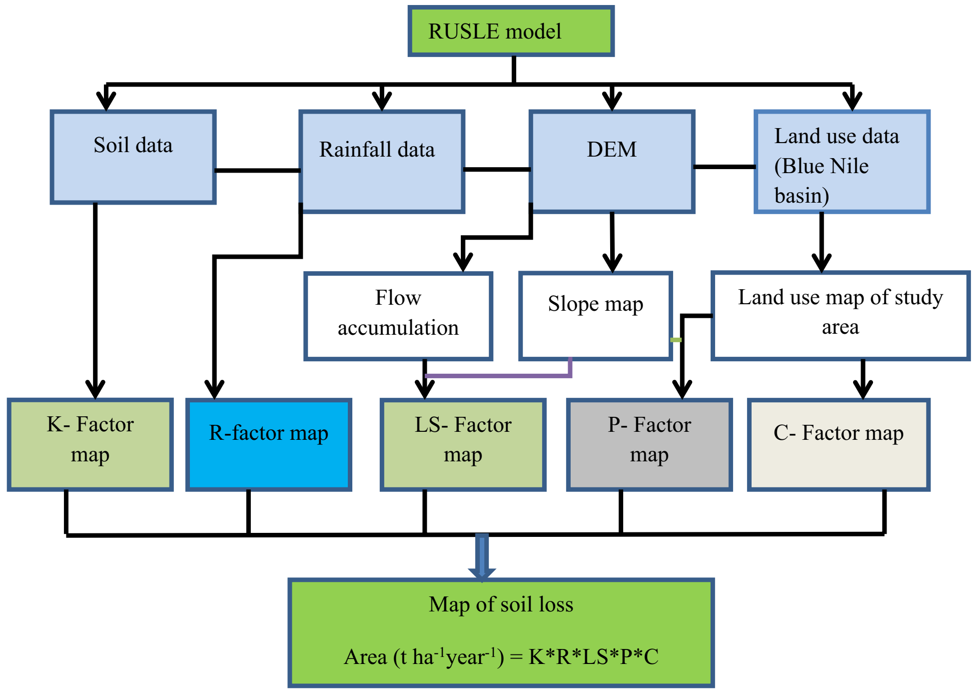

Fig. 3 The conceptual framework of soil loss analysis by RUSLE model

Table 2 Mean annual rainfall and the corresponding *R*-factor value

No	Station name	Lat (m)	Long (m)	Elev (m)	Mean annual rainfall (mm)	*R* values
1	Luwaye	11.72	38.07	2709	1500.46	835.14
2	Amed ber	11.91	37.89	2051	1338.49	744.11
3	Wanzaye	11.78	37.68	1830	1483.58	825.65
4	Debre Tabor	11.85	38.01	2612	1496.44	832.88
5	Woreta	11.90	37.68	1798	1315.47	731.18
6	Addis zem	12.10	37.87	1936	1320.86	734.20
7	Licha	11.2	36.74	2319	1409.17	783.83
8	Yifag	10.92	37.25	1901	1476.69	821.78
9	Gassay	11.70	38.43	2795	1176.33	652.98
10	Kimir Dingay	12.75	37.63	2983	1168.65	648.66

R = Mega Joules mm perh/ha/year

Table 3 *K* values based on colors

No	Soil color	Name/class	*K* values (metric t/ha/MJ/mm)
1	Brown	Chronic Luvisols/Haplic Luvisols/Urban, etc	0.2
2	Yelow	Eutric Fluvisols/Eutric Leptosols	0.3
4	Block	Eutric Vertisols etc	0.15
6	Red	Haplic Nitisols, Alisols, etc.	0.25
8	Blue	Water	0

1. Filling of sinks of DEM of the study area;
2. Generation of S factor using filled-in DEM as an input;
3. Generation of flow direction using filled DEM as an input.
4. Computing flow accumulation raster using flow direction raster as an input;
5. Generating the slope of the study area in degree
6. Calculating LS factor using flow accumulation slope raster as an input.

The output LS-factor raster map of the Guna-Tana landscape is shown in Fig. 6. As revealed by Moore and Wilson (1992), LS factor is important parameters in RUSLE to measure sediment transport capacity of the flow. It is important to consider the upslope contributing area to estimate the LS factor for the spatial distribution of soil erosion in a given catchment area (Moore and Burch 1986a, b; Mitas and Tarasova 1996; Simms et al. 2003). Hence, this study used the following advanced method of calculating the LS factor in the ArcGIS environment (Eq. 3):

$$\mathrm{LS} = \mathrm{Power}\left(\mathrm{Flow\ accumulation} * \frac{\mathrm{Cell\ size}}{22.13}, 0.4\right) * \mathrm{Power}\left(\frac{\sin(\mathrm{slope}\ 0.01745}{0.09}, 1.4\right) * 1.4. \quad (3)$$

Support practice (*P*) factor

In this study, the *P*-factor values were assigned according to the suggestion of different academics and considering the indigenous managing performs (Table 4). Based on the land-use/land-cover thematic map of the study area, the *p* values suggested by different scholars were assigned (Fig. 3).

Cover and management (*C*) factor

The major land-use/land-cover types in the watershed were extracted from the land-use/land-cover types of Blue Nile Basin and assigning the corresponding *C*-factor value obtained from different revisions (Fig. 6 and Table 5).

Table 4 *P* factor with corresponding land-use types

Land use/land cover	*P* factor
Afro-alpine	1
Dominantly cultivated	0.8
Moderately cultivated	0.9
Grassland	0.9
Water body	0
Swamp	1
Plantations	1
Shrubland	0.9
Urban area	0.003

P = dimensionless

Table 5 Land-cover classes and relevant *C*-factor value

Land use/land cover	Area (km^2)	Area (%)	*C* factor
Afro-alpine	2867.81	0.816	0.1
Dominantly cultivated	223,714.41	63.633	0.15
Moderately cultivated	94,948.9	27.007	0.1
Grassland	23,674.15	6.734	0.01
water body	8.41	0.002	0
Swamp	1984.76	0.565	0.045
Plantations	883.05	0.251	0.02
Shrub land	3229.44	0.919	0.014
Urban	260.71	0.074	0.09

Results and discussion

Rainfall erosivity factor (*R*)

In the current investigation, the average annual rainfall was used for the calculation of the *R* factor as indicated in (Eq. 2). The value of *R* ranges from 648.66 to 835.14 MJ/mm/ha/h/year. Inverse Distance Weighted (IDW) used for the spatial average rainfall distribution in the study area. In the IDW process, rainfall data from 19 (1997–2016) years were considered for ten rainfall stations (Fig. 4) in and around the study area. Figure 4 shows the erosivity map of the rain prepared by the rainfall data of the study area.

Soil erodibility factor (*K*)

The value of the *K* factor generated from the respective soil types to obtain a map of the soil erodibility at Guna-Tana landscape. The lowest value of *K* is associated with soils that have a low moisture content, low permeability, and so on. The Guna-Tana soil map has been reclassified with the given value of *K* (Fig. 5). The value of *K* ranges from 0 to 0.3, values close to 0 being less prone to soil erosion were prepared.

Topographic factor (LS)

The topographic aspect represents the impact of the length of the given slope and its steepness in the erosion process. The LS factor was estimated by taking into account the accumulation of the flow and the slope in percentage. Based on the analysis, the value of the topographic factor increases in a range from 0 to 223 as flow accumulation

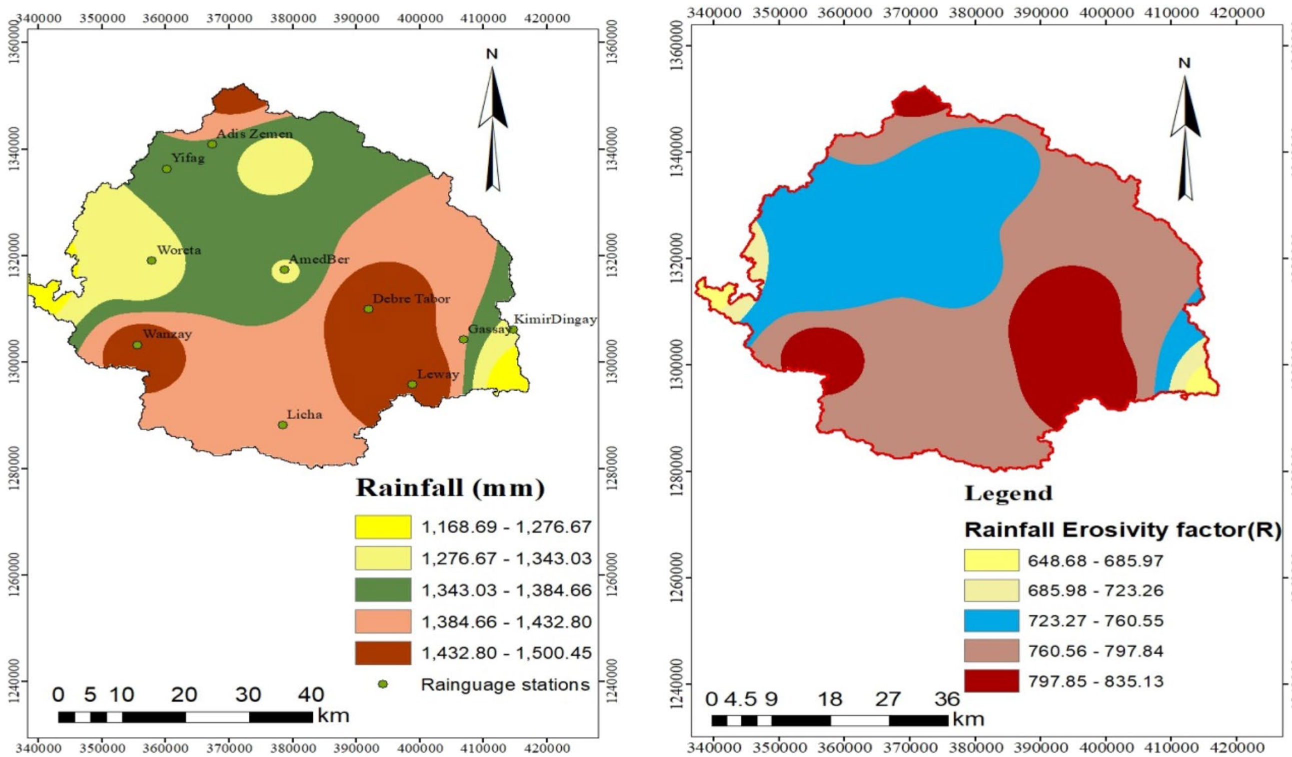

Fig. 4 Maximum slope is positively correlated with the maximum interval of LS-factor values in the study area

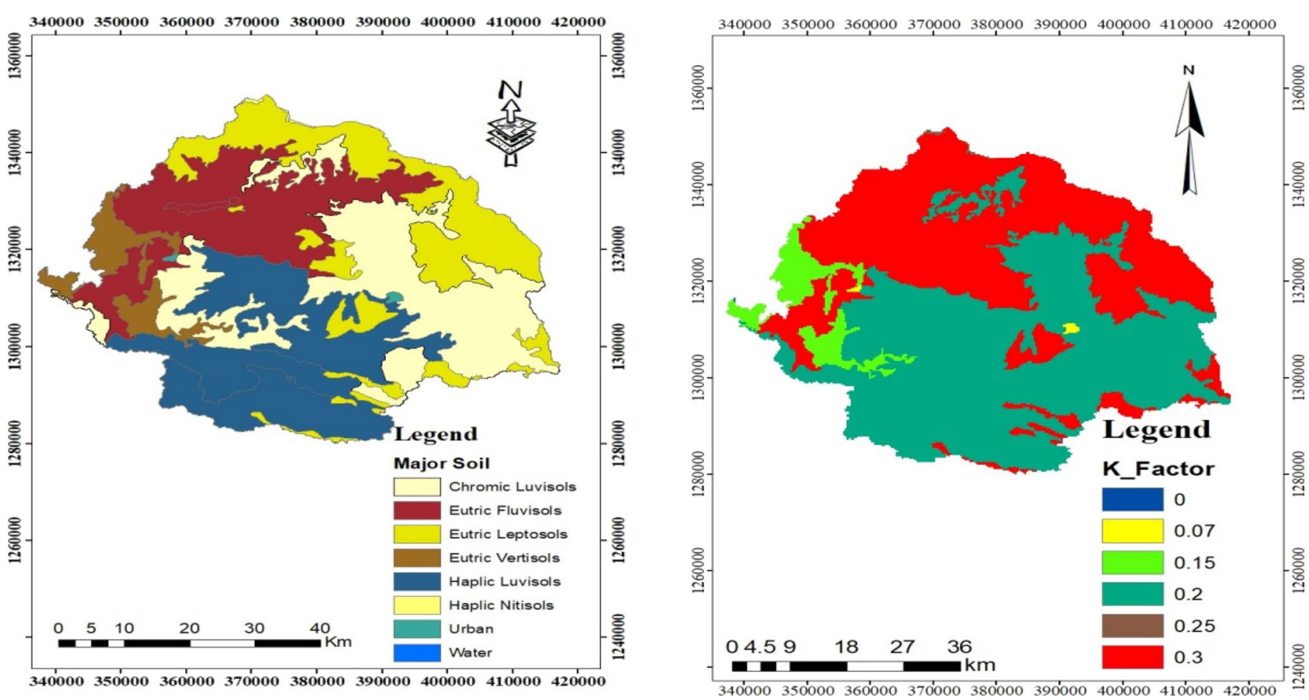

Fig. 5 Rainfall and rainfall erosivity map (*R*)

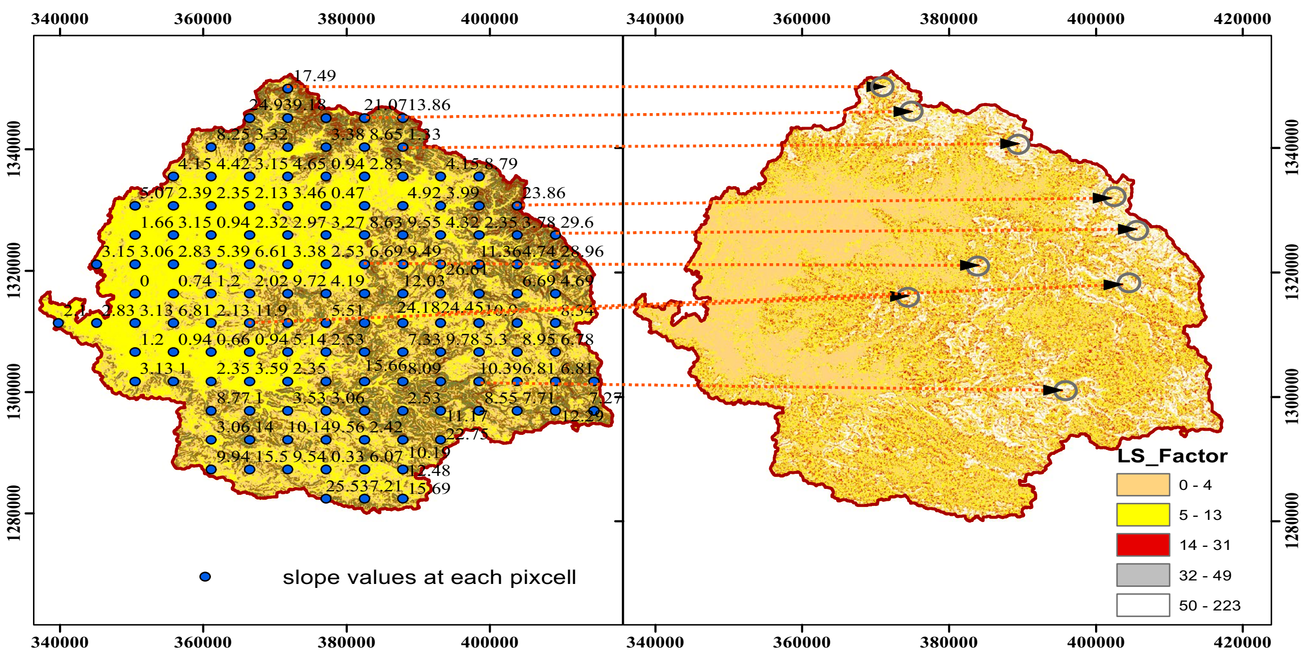

Fig. 6 Soil and soil erodibility map (*K*)

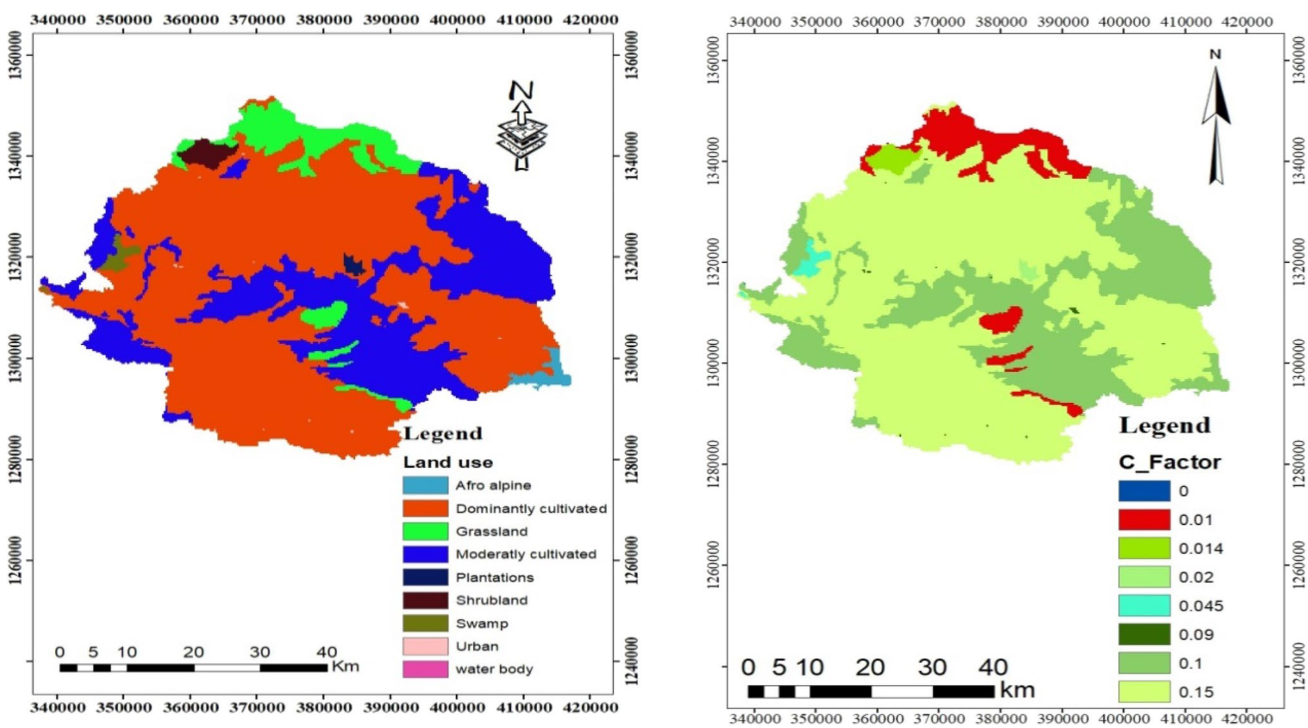

Fig. 7 Crop management factor (*C*) with LULC

and slope increase. The minimum slopw and maximum slope at each pixel were calculated using fishnet and the corresponding maximum slope with LS-factor is indicated in the following map (Fig. 6).

Crop management factor (*C*)

Available land-use data provide a good understanding of the land-use characteristics of surface water, wastelands,

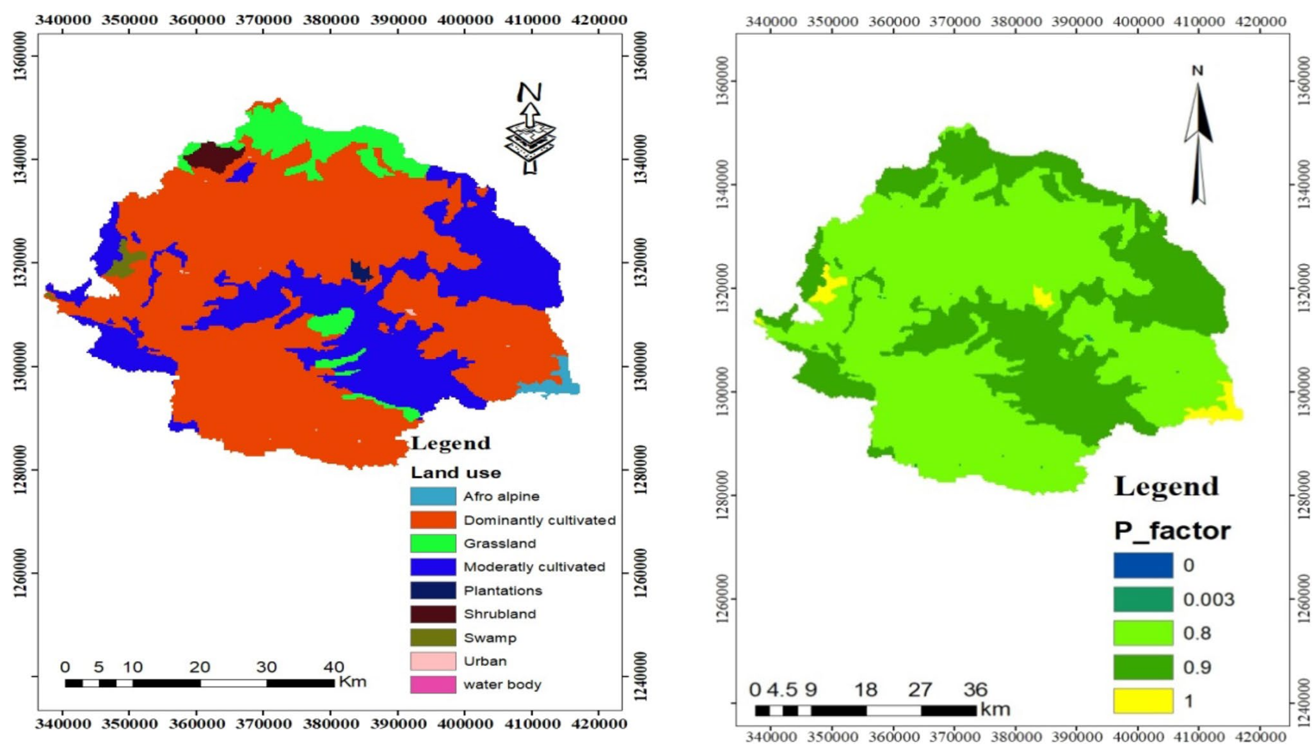

Fig. 8 Land use/land cover and *P*-factor

cropping patterns, forests, and fallow land, which are essential for studies of soil erosion or development planning. The values of *C* are given in Table 4. The value of the *C* factor determined using the land-use map (Fig. 7).

Conservation support practice factor (*P*)

The *P* factor explains the mechanism that reduces the erosion possible of runoff by influencing runoff concentration, hydraulic forces, and runoff velocity, drainage patterns, applied by surface runoff. The value of the *P* factor varies from 0.003 to 1, the value which closes to 0.003 shows good protection practices. and on the other hand, the value close to 1 shows bad protection practices (Fig. 8).

Soil erosion (loss) probability zones

The calculation of the main factors contributing to soil loss, which is the key input of the RUSLE model for calculating soil erosion, was performed using several procedures documented by many researchers (Renard et al. 1996; Wischmeier and Smith 1978; Hurni 1985). The map (Fig. 9) is generated by a cell to cell multiplication overlay of raster maps of six RUSLE input factors (soil erodibility, slope gradient, rainfall erosivity, conservation practice, and cropping and management factor and slope length). Overall results in the Guna-Tana Landscape show that soil loss values ranging from 0 to 4735 t/ha/year were obtained. All maps were categorized into six erosion potential classes, which range from low erosion hazard (≤ 60 t/ha/year) to very extreme erosion hazard (refer Table 6). Nearly 85.9% of the watershed area produces low erosion of 90, 01,559.4 t annually, while extreme probability zone covers about 0.02% of the watershed area and yields soil erosion of 226,439.25t annually.

Conclusions

This study was designed to estimate soil loss and assess the erosion-prone areas of the Guna-Tana Landscape. The results of the study focused on the application of the RUSLE model associated with Geographic Information System (GIS) to assess erosion-prone areas and estimate soil loss in the study area. The outcomes of the study conclude that the mean 12-monthly loss of soil estimated with the RUSLE model is nearly 3627.5 t/ha year in the area. Also, it detected the amount of erosion varies mainly in LULC and topographic characteristics. The overplayed map showed that nearly 681.21 ha (0.2%) of the area is within the extreme and very extreme erosion clusters. Hence, the soil loss values/year of the study area were beyond the tolerable limits of soil loss, and it is necessary to implement adequate water and soil conservation practices in the study area. The faster increment in the

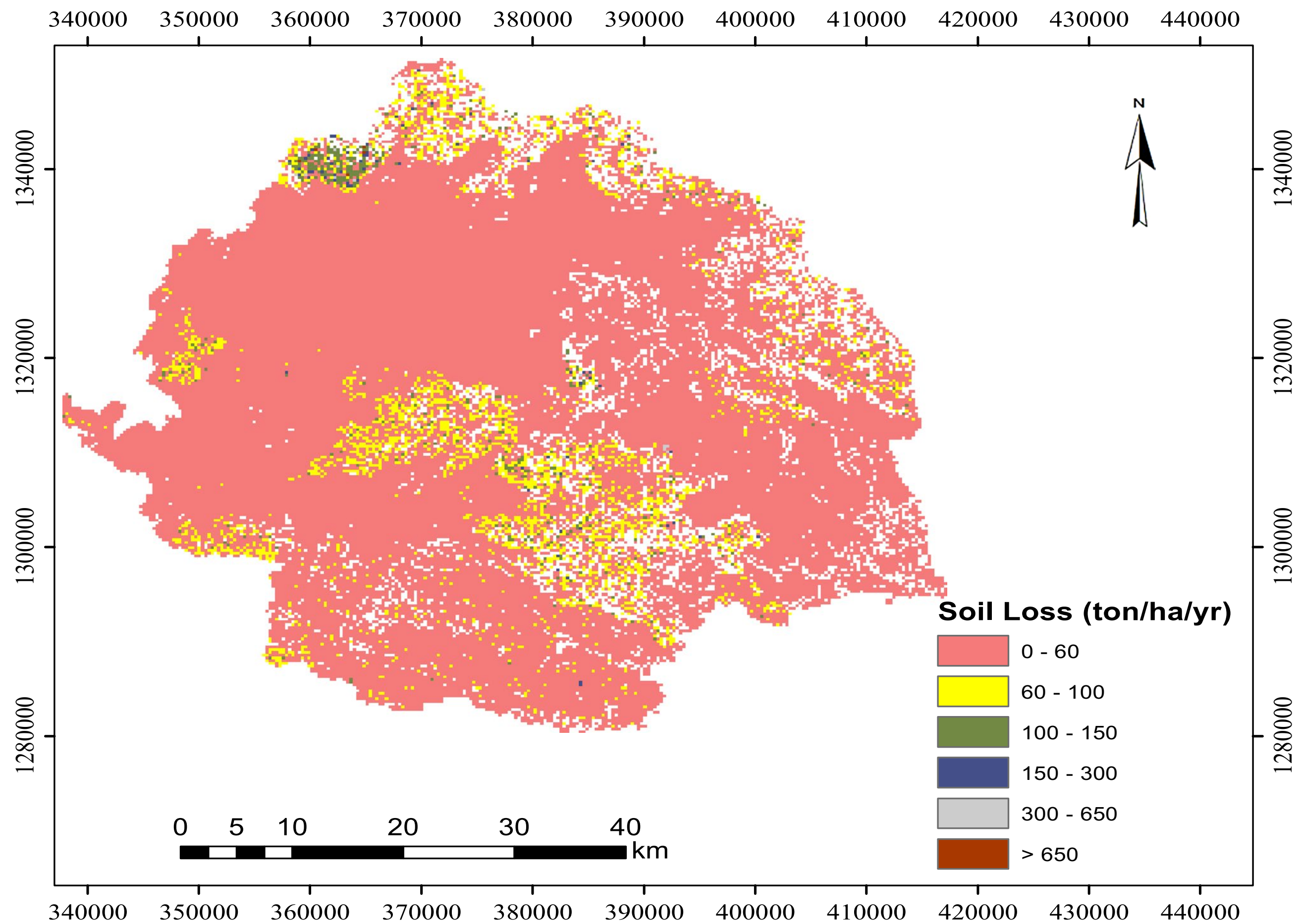

Fig. 9 Soil erosion probability map

Table 6 Numeric soil loss summary of the watershed

Numeric range of soil loss (t/ha/year)	Soil erosion risk class	Area (ha)	Area (%)	Annual soil loss (t/year)	Percentage of total soil loss
0–60	Low	300,051.98	85.90	9,001,559.4	62.79
60–100	Medium	34,380.08	9.84	2,750,406.4	19.19
100–150	High	11,168.48	3.20	1,396,060	9.74
150–300	Very high	3010.78	0.86	677,425.5	4.73
300–650	Extreme	597.11	0.17	283,627.25	1.98
> 650	Very extreme	84.1	0.02	226,439.25	1.58

farming area the more will be the risk of soil erosion due to farming practices. Comparing the potential loss of soil with the actual loss of soil supports the influence of several conservation measures and cropping systems on erosion. The result of the study implies the need for applying context-specific soil and water conservation techniques in 681.21 has of extremely and very extremely affected parts of the studied watershed.

Compliance with ethical standards

Conflict of interest No conflict of interest.

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