

# Spatial Estimation of Soil Erosion Using RUSLE Modeling: the Case of kaffa Zone, South western Ethiopia

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## Research Article

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## Abstract

This research was administered to spatially predict the soil loss rate of kaffa zone using model estimate and GIS. Revised Universal Soil Loss Equation (RUSLE) adapted to Ethiopian conditions was accustomed estimate potential soil losses by utilizing information on rainfall erosivity (R) using interpolation of rainfall data, soil erodibility (K) using DSMW soil map, vegetation cover (C) using Sentinel-2A satellite images, topography (LS) using Digital Elevation Model (DEM) and conservation practices (P) using DEM and satellite images. supported the analysis, the mean and total annual soil loss potential of the study area was 30 tons ha<sup>-1</sup> year<sup>-1</sup> and 36264.5tons ha<sup>-1</sup> year<sup>-1</sup>, respectively. The result also showed that about 2.89, 8.02, 15.31 and 73.78% of the study area were classified a slight, moderate, high and very high with values ranging 0 to 15 ,15 to50,50 to 200, and > 200 tons ha<sup>-1</sup> year<sup>-1</sup>, respectively. The study demonstrates that the RUSLE using GIS and RS provides great advantage to spatially analyze multi-layer of knowledge. The expected amount of soil loss and its spatial distribution could facilitate sustainable land use and management.

## Introduction

The worldwide annual rate of eroding from agricultural land ranges from 22 to 100 t ha<sup>-1</sup> and declines in productivity the maximum amount as 15–30% annually(Morgan,2005 ). consistent with Morgan(2005), soil erosion costs the US economy between US\$30 billion and US\$44 billion annually associated with on-site (cost of production and production loss) and of-site (pollution and sedimentation of downstream water resources) effects of wearing away.

Soil erosion could be a common phenomenon within the east Africa highlands, where it causes widespread soil degradation (Gachene, 1995; Vaezi et al., 2007). Especially ,in ethiopia highlands are vulnerable to severe erosion (Bewket and Tefleri,2009;Gelagy and Minale,2016;Haregeweyn et al.,2017) due to extreme deforestation ,rugged topography ,historical settellement,burning of crop residue, exploitative varieties of agriculture and improper/inappropriate land management practices (Bewket and Teferi, 2009; Reusing et al., 2000; Hurni et al., 2015).

Several studies reported that majority of cultivated lands within the highlands of Ethiopia have beyond the tolerable soil loss (TSL) rate, which is between 5 to11 t ha<sup>-1</sup> yr<sup>-1</sup> (Moges and Bhat, 2017; Gashaw, 2018; Renard *et al.*,1997). Unless the present soil loss rate is averted, it will hamper agricultural production and economic development (Wischmeier and Smith, 1978; Blanco and Lal, 2008).Water-induced wearing has also caused sedimentations of water and power supply reservoirs (Wolancho, 2012). Moreover, eroding was also affecting the standard of potable, which required significant investment for water treatment services.

The severe soil erosion and its environmental and socioeconomic impacts warrant investigating different land and water management practices that will reduce erosion. Such practices include intensive cultivation ,extensive cultivation ,filter strip ,tracing ,stone or soil bunds ,agro-forestation and area enclosure (Betrie *et al.*,2011;Tamene et la.,2017).Although several models exist to estimate erosion, the Revised Universal Soil Loss Equation (RUSLE) model (Renard *et al.*, 1997) is useful in identifying erosion hot spot areas and suggesting appropriate conservation measures in data scare areas like the Ethiopian highlands. Since direct field measurements of erosion at permanent research or experimental stations using runoff plots with the know area ,slope gradient slope length , and soil type could give reliable runoff and soil loss (Hurni et al.,2010) for experimental purposes, however, it is costly, labor-intensive, and time consuming (Alemayehu& Alamirew,2012).

Soil erosion and land degradation is additionally becoming a significant challenge for food production within the kaffa zone. Rapid increase population growth, cultivation on steep slopes, clearing of vegetation, and overgrazing are the most factors that

accelerate soil erosion and land degradation within the study area .Therefore, the target of the study was to assess soil loss rate and identify hot spot areas using USLE of kaffa zone, in central Ethiopia.

## Study Area

This study was conducted in Kaffa Zone which is located between 6°24' to 8°13' North latitude and 35°30' to 36°46' East longitude in South Western part of South, Nation, Nationalities and Peoples Region. The Zone has a total area of 10,602.7 km<sup>2</sup> which accounts 7.06 % of the total area of the region. Administratively, Kaffa Zone is divided into twelve districts and has three conventional climatic zones based on variations in altitude and temperature. These are highland (2500 - 3000 m a.s.l), midland (1500 - 2500 m a.s.l) and lowland (500 – 1500 m a.s.l) (KZBoFED, 2014). Out of the total area of the Zone, highland, midland and lowland cover 11.6%, 59.5% and 28.9%. The mean annual temperature of the area ranges 10.1 °C – 27.5 °C. The warmest months are February, March and April while the coldest months are July and August. According to the meteorological data obtained from the Zone, the annual rainfall ranges from 1001-2200mm (KZBoFED, 2014). Kaffa Zone is a part of the South West Ethiopian regions which receive the highest amount of rainfall. This is attributable to the presence of the evergreen forest cover on top of the windward location to the moist monsoon winds.

## Methodology

The overall methodology involved the utilization of the RUSLE during a GIS environment with factors obtained from meteorological stations, soil map, topographic map, Satellite Images and DEM as shown in equation 1, Figure 2. Individual GIS layers were built for every think about the RUSLE and combined by cell-grid modeling procedures in ArcGIS to predict soil loss in a very spatial domain (Eastman, 1999). Annual soil loss rate determined by multiplying the respective RUSLE factor values interactively using “Spatial Analyst Tool Map Algebra Raster Calculator” in ArcGIS 10.5 environment as shown equation (1) adopted from the recommendation of Hurin (1985) and Gebreselassie(1996). Soil loss potential of the study area was then categorized into different severity classes adapted from FAO (1984), like slight (0–15 t ha<sup>-1</sup> yr<sup>-1</sup>), Moderate (15–50 t ha<sup>-1</sup> yr<sup>-1</sup>), High (50–200 t ha<sup>-1</sup> yr<sup>-1</sup>), Very high (>200 t ha<sup>-1</sup> yr<sup>-1</sup>).

$$A = R \times K \times LS \times C \times P \dots\dots\dots\text{Equation (1)}$$

Where A is that the annual soil loss (metric tons ha<sup>-1</sup> year<sup>-1</sup>); R is that the rainfall erosivity factor [MJ mm h<sup>-1</sup> ha<sup>1</sup> year<sup>-1</sup>]; K is soil erodibility factor [metric tons ha<sup>-1</sup> MJ <sup>-1</sup> mm<sup>-1</sup>]; LS = slope length factor (dimensionless); C is land cover and management factor (dimensionless) and P is conservation practice factor (dimensionless). Selected GPS points were used for checking and validation of results. All the maps were geo-referenced with Universal Transverse Mercator (UTM) coordinate system.

Table1.Summary of data types and their sources.

Data Type	sources	Purpose
Rainfall data(1980-2019)	NMA	To develop Rainfall erosivity factor (R-value)
Spot6 satellite image with1.5m resouition	USGS	To develop LULC then from LULC to dervive the crop factor (C) and conservation practice factor (P)
soil data(silt,sand,organic &clay)	DSMW	To develop Soil erodibility factor (K value)
SRTMDEM with 30 m resolution	USGS	to develop Slope length and slope gradient factor (LS value)& conservation practice factor (P value)
Ground truth data	Field servey,2021	Selected GPS points were used for checking and validation of results

Table 2: Software and materials employed in the study

Software used	Purpose
ERDAS IMAGIN 2015	Image processing and data analysis
ArcGIS 10.5	Data base creation, land use/cover, Raster Calculator, map preparation
GPS(Global Position System)	For collecting of GCP points which were created at random for the study area using Arc GIS 10.5 used mainly for accuracy assessment area measurement

## Results And Discussion

### 3.1 Determination of Soil Loss Factors

#### 3.1.1 Rainfall Erosivity Factor

The erosivity factor R was calculated using the equation given in Hurini (1985) adapted for the Ethiopian condition which has been derived from spatial regression analysis (Helldén, 1987). (Eq.2). Other studies have also reported successfully using the equation (Amsalu *et al.*, 2014; Asmamaw & Mohammed, 2019; Bewket & Teferi, 2009; Gashaw *et al.*, 2018; Meshesha *et al.*, 2012; Shiferaw, 2011; Wolka *et al.*, 2015). The R-factor is given by a regression equation as:

$$R = -8.12 + 0.562P \dots \dots \dots \text{Equation (2)}$$

Where R is the erosivity factor and P is the mean annual rainfall (mm year<sup>-1</sup>).

To compute R factor, mean annual rainfall of thirty six years (1980 – 2019) was collected from 19 metrological stations were found within the zone boundary. After calculating average 39 years of rainfall for each station, the R factor was computed using the above formula and converted in to raster surface using IDW (Inverse Distance weighted) interpolation methods in ArcGIS software (Figure 3).

#### 3.1.2 Soil Erodibility Factor

The soil erodibility factor (K) measures the susceptible soil types and their particles to detachment and transport by rainfall and runoff. The K factor influenced by soil texture, organic matter, soil structure, and permeability of the soil profile (Erencin *et al.* 2000). The equation provided by reference used to estimate the soil loss (Kouli *et al.* 2009).

$$K = F_{csand} * F_{si-cl} * F_{orgc} * F_{hisand} * 0.1317 \dots \dots \dots \text{Equation (3)}$$

Where

$$F_{csand} = \left[ 0.2 + 0.3 \exp \left( -0.0256 SAN \left( 1 - \frac{SIL}{100} \right) \right) \right], \dots \dots \dots \text{Equation (4)}$$

$$F_{si-cl} = \left[ \frac{SIL}{CLA+SIL} \right]^{0.3}, \dots \dots \dots \text{Equation (5)}$$

$$F_{orgc} = \left[ 1.0 - \frac{0.25C}{C + \exp(3.72 - 2.95C)} \right], \dots \dots \dots \text{Equation (6)}$$

$$F_{hisand} = \left[ 1.0 - \frac{0.70SN1}{SN1 + \exp(-5.51 + 22.9NS1)} \right], \dots \dots \dots \text{Equation (7)}$$

Where SAN, SIL and CLA are % sand, silt and clay, respectively; C is the organic carbon content; and SN1 sand content subtracted from 1 and divided by 100. F<sub>csand</sub>=low soil erodibility factor for soil F<sub>si-cl</sub>=low soil erodibility factor with high clay to silt ratio. F<sub>orgc</sub>=factor that reduces soil erodibility for soil with high organic content. F<sub>hisand</sub>=factor that reduces soil erodibility for soil with high sand content (Table 2 and Figure 4).

Table 2 .Method to calculate KUSLE value

Soil unit symbol	sand % topsoil	silt % topsoil	clay % topsoil	OC % topsoil	FcSand	fcl-si	Forganic	fhisand	Kusle	K=KUSLE * 0.1317
NE	68.4	10.5	21.2	0.6	0.200000047	0.717859	0.96653	0.962738	0.133596	0.017595
NE	68.4	10.5	21.2	0.6	0.200000047	0.717859	0.96653	0.962738	0.133596	0.017595
BE	36.4	37.2	26.4	1.07	0.200862282	0.851385	0.761202	0.999948	0.130167	0.017143
BE	36.4	37.2	26.4	1.07	0.200862282	0.851385	0.761202	0.999948	0.130167	0.017143
JC	39.6	39.9	20.6	0.65	0.200677792	0.882603	0.957979	0.999897	0.169659	0.022344
VC	22.4	24.5	53	0.69	0.203952351	0.707879	0.949806	0.999997	0.137127	0.01806

### 3.1.3 Slope Length and Slope Steepness Factor

The 30 m spatial resolutions DEM (digital elevation model) were accustomed generate slope by using “Spatial Analyst Tool Surface Slope” in ArcGIS 10.5 environment. The flow accumulation and slope steepens were computed from DEM using Arc GIS. Flow Accumulation was derived from hydrologically corrected DEM after conducting FILL and Flow Direction processes by Arc Hydro tools, GIS software. Flow accumulation and slope maps were multiplied by using spatial analyst tool map algebra raster calculator in arc GIS to calculate and map the slope length (LS factor) as shown in equation (8) and defined by Wischmeier and Smith (1978).

$$LS = (\text{Flow Accumulation} \times \text{Cell size} / 22.13)^{0.4} \times (\text{Sin slope} / 0.896)^{1.3} \dots \dots \dots \text{Equation (8)}$$

Where cell size represents the field slope length and 22.13 is the length of the research field plot.

### 3.1.4 Crop cover and management (C factor)

The cover management factor represents the ratio of soil loss under a given cover there to of the bottom soil (Morgan, 1994). Land cover includes a profound impact on erosion and deposition. Surface cover, like vegetation or plant residue may intercept and reduce raindrop erosivity, increase infiltration, bog down runoff and reduce transporting capacity of water flow. The land use /land cover map was used for the estimation of C-value. The raster land use/land cover map was converted to a vector format and a corresponding C-value was assigned to every land use classes supported cover values proposed by various authors, but mainly Hurni (1985)(Table3).Finally, using reclassification and vector to raster conversion the land use/ land cover map was converted to C factor map (Figure 6).

Table 3 Land use, area coverage, and cover management factor for the study area

LU/LC Categories	Area (ha)	Area (%)	C -factor Value	Reference
water body	823.150507	0.039772	0	(Erdogan <i>et al.</i> ,2006)
Forestland	434825.211	21.0094	0.01	Hurni (1985a,1985b)
Grassland	371155.181	17.93306	0.1	Hurni (1985)
Bare Land	258688.907	12.49904	1	Hurni (1985)
Cropland	995845.13	48.11613	0.15	(Hurni 1985;Truneh&Ayalew,2015)
Settlement	8332.59112	0.402605	0.15	Hurni (1985)

### 3.1.5 Erosion management practice (P factor)

The conservation practices factor (p-values) reflects the consequences of practices which will reduce the number and rate of the water runoff and thus reduce the number of abrasion. AS data were lacking on permanent management factors and there have been no management practices ,we used the p-values suggested by Bewket and Teferi(2009);Wischmeier and Smith(1978);Shi, Cai, Ding, Li, Wang and Sun (2002) that consider only two varieties of land uses (agricultural and non-agricultural) and land slopes. Thus, the agricultural lands were classified into six slope categories and assigned P-values while all non-agricultural lands are assigned a P-value of 1 (Table4 and Figure 7).

Table 4. Conservation practices factor (P-value)

Land use	Slope category (%)	P factors	Reference
Cultivated land	0_5	0.1	(Wischmeier and Smith ,1978;
	5_10	0.12	Hurni ,1985;
	10_20	0.14	Bewket and Teferi ,2009;
	20_30	0.19	Gelagay and
	30_50	0.25	Minale ,2016)
	50_100	0.33	
Other land use	All	1	

### 3.2 Soil Loss Estimation and Prioritization for Soil Conservation Planning

All the layers of the RUSLE factors viz. R, K, LS, C and P with 1.5 X 1.5 m output cell size were generated within the GIS environment and were crossed to obtained the product, which provides annual soil loss (A) for the kaffa zone. These values gave annual soil loss per hectare per year at pixel level. Supported the analysis, the mean annual soil loss of the study area was found to be 30 ton ha<sup>-1</sup> year<sup>-1</sup> with a range of 0 to 36264.6ton ha<sup>-1</sup> year<sup>-1</sup>.

The finding of this study is in agreement with the findings of previous studies tired the other parts of the country. For instance, in line with Hurni *et al.* (2010), reported eating away from cultivation land in Ethiopian highlands reaches 130 - 170 ton ha<sup>-1</sup> year<sup>-1</sup>. Bewket and Teferi (2009), have found mean annual soil loss starting from 7-243 t/ha/yr for a catchment within the Blue Nile basin while Hawando (1995), found the annual soil loss of Ethiopia highlands ranges from 16-300 ton ha<sup>-1</sup> year<sup>-1</sup> from pasture ranges and cultivated fields.

As demonstrated in Table 5, the spatial patterns of annual average soil loss distribution were grouped into four erosion intensity classes, which were adapted from FAO (1984), like slight (0–15 t ha<sup>-1</sup> yr<sup>-1</sup>), Moderate (15–50 t ha<sup>-1</sup> yr<sup>-1</sup>), High (50–200 t ha<sup>-1</sup> yr<sup>-1</sup>), Very high (>200 t ha<sup>-1</sup> yr<sup>-1</sup>). Accordingly, about 712529.87ha(73.78%) of the study area experiences Slight rates of soil erosion, whereas areas affected by Moderate and High rates of soil loss encompass 147848.63ha(15.31%) and 77451.04ha(8.02%) respectively. In total, areas affected by Very high soil loss rates cover approximately27946.38ha (2.89%) (Table 5). This implies that most of the total soil loss was generated from the small areas which experiences high erosion rates (Fig.8)

It will be observed from the assigned class that the various priority areas contributed differently to the entire erosion rate. For example, priority class 1<sup>st</sup> covers 2.89% of the whole the study area, 2<sup>nd</sup>, 3<sup>rd</sup>and 4<sup>th</sup> cover combined 97.11 % the study area. These priority classes highly contributed to soil loss (Shiferaw, 2011).

Table 5. Annual soil loss rate, severity class and priority areas in the Kaffa Zone

Class	Soil loss (t ha <sup>1</sup> yr <sup>1</sup> )	Description	Area(ha)	Area (%)	Priority classes
I	0-15	Slight	712529.87	73.78	4th
II	15-50	Moderate	147848.63	15.31	3rd
III	50-200	High	77451.04	8.02	2nd
IV	>200	Very high	27946.38	2.89	1st

## Conclusion

The severity assessment of erosion GIS –based RUSLE equation considering rainfall, soil, DEM, land use, and land cover. The erosion rate categorized into four classes supported its severity, and 73.78% of the regions found under severe (0-15t ha<sup>-1</sup> yr<sup>-1</sup>) 2.89% of areas remained during a Very high. This show area with high elevation together with prompt rainfall liable to eating away. The anticipated severity can provide a basis for conservation and planning processes at the decision-makers. The regions with high to very severe wearing warrant special priority and control measures. While this model forms a basis on mapping and

prediction using remote sensing and GIS-based analysis for vulnerability zones, such studies suggested for conservation and refining the model within the future.

## Declarations

### Ethics approval and consent to participate

Informed consent was obtained from all student participants involved in the study. All participants freely agreed to participate in the study without reservation.

### Funding

The authors are not received any fund.

### Consent for publication

Consent to publish individual data in any form was obtained from the participants interviewed.

### Availability of data and materials

Not applicable' for that section

### Competing interest

The authors declare no competing interests.

### Authors' contributions

Mesfin Anteneh and Dereje Biru conceived and designed the work validated the method section. Both authors participated in the analysis, validation and writing of the paper. Both authors read and approved the final manuscript.

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## Figures

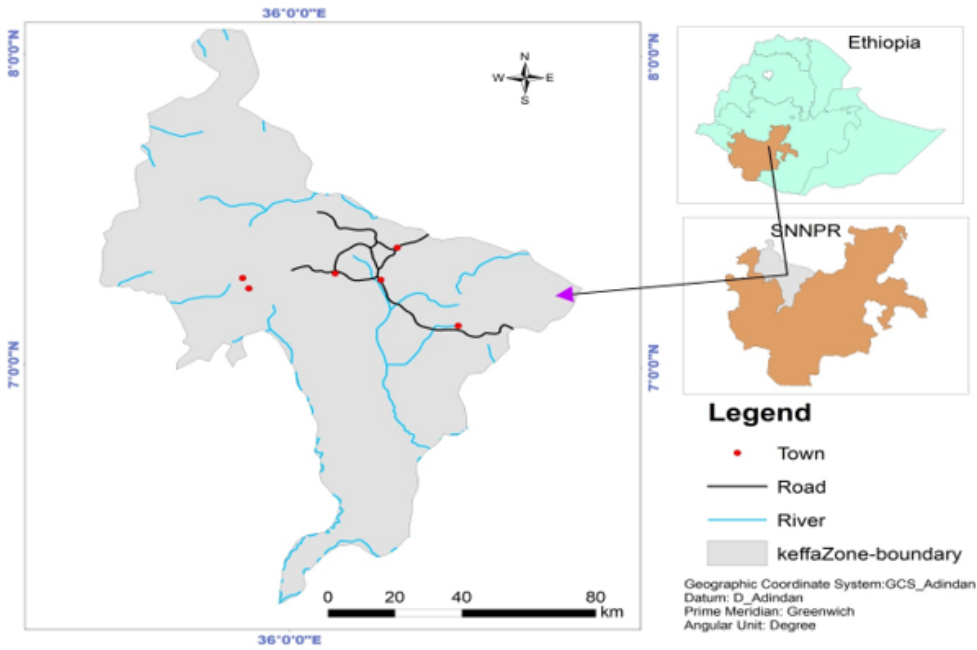


Figure 1

Location map of Kaffa Zone.

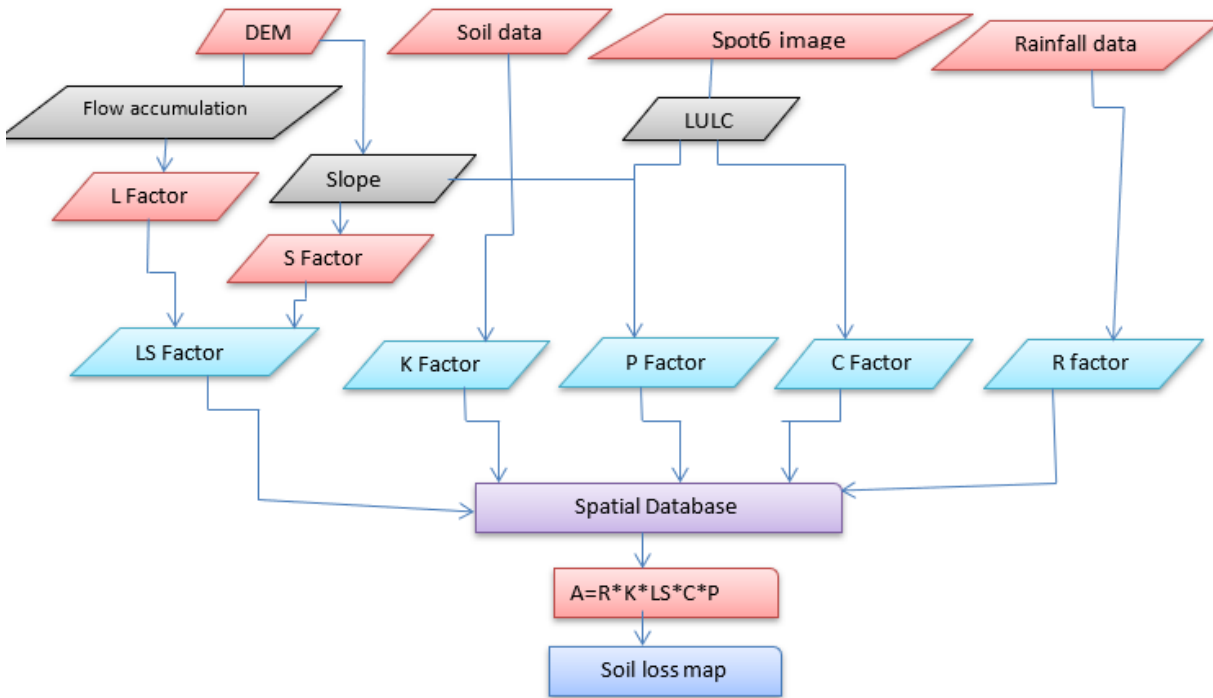


Figure 2

Soil Loss (Erosion) Estimation Flow Chart using RUSLE Model

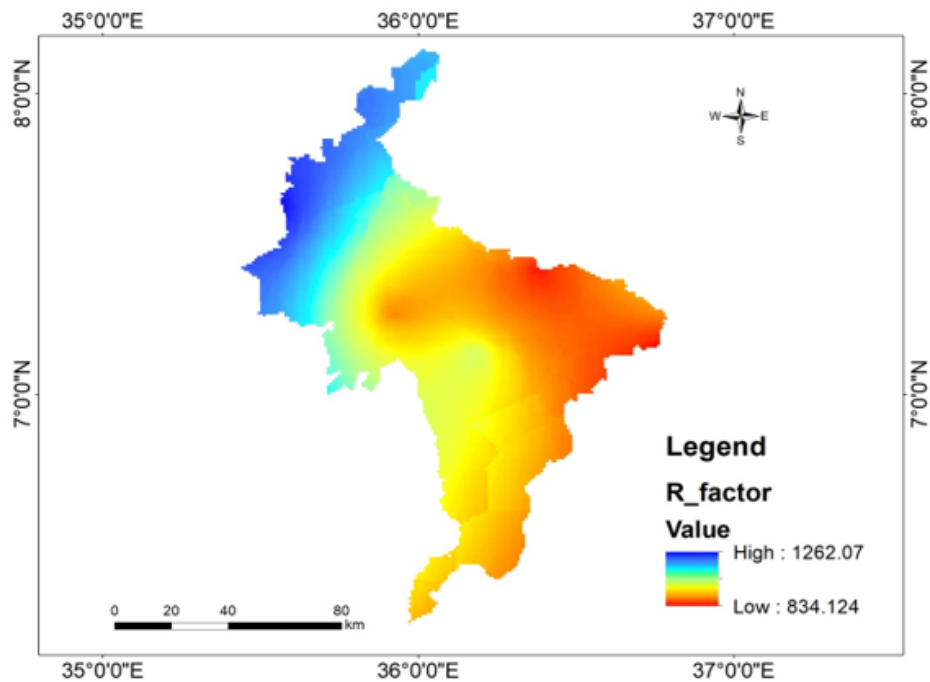


Figure 3

Map of Rainfall Erosivity Factor generated from the mean annual rainfall of Kaffa Zone

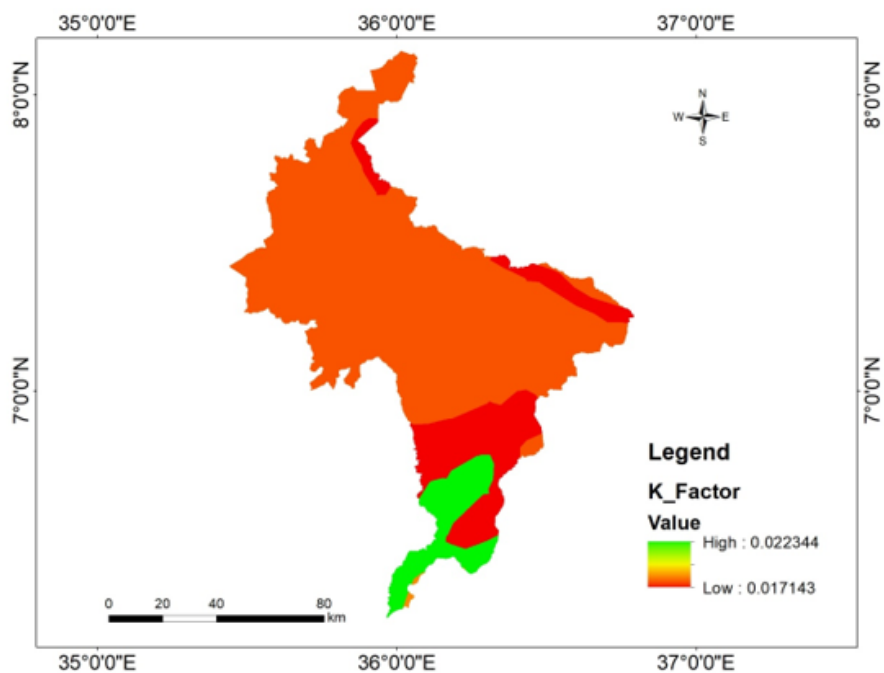


Figure 4

Map of Soil Erodibility Factor generated from the DSMW for Kaffa Zone

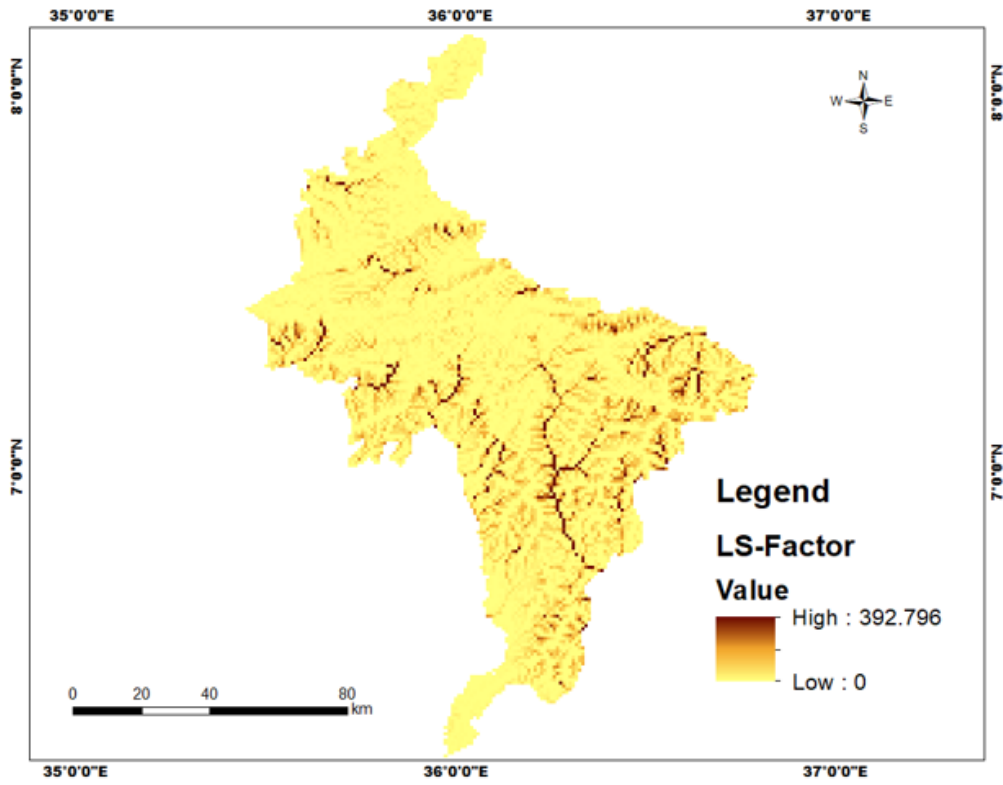


Figure 5

Map of slope length and steepness (LS) factor generated from the DEM and topographic map of the study area.

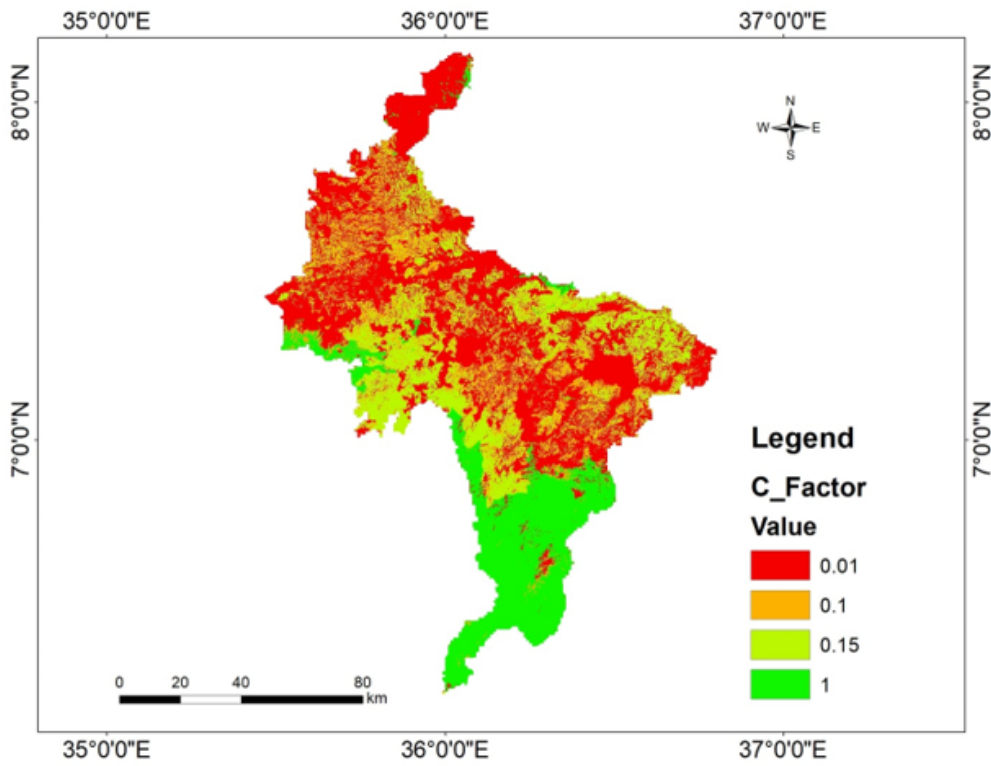


Figure 6

Map of Crop cover and management (C factor) generated from LULC

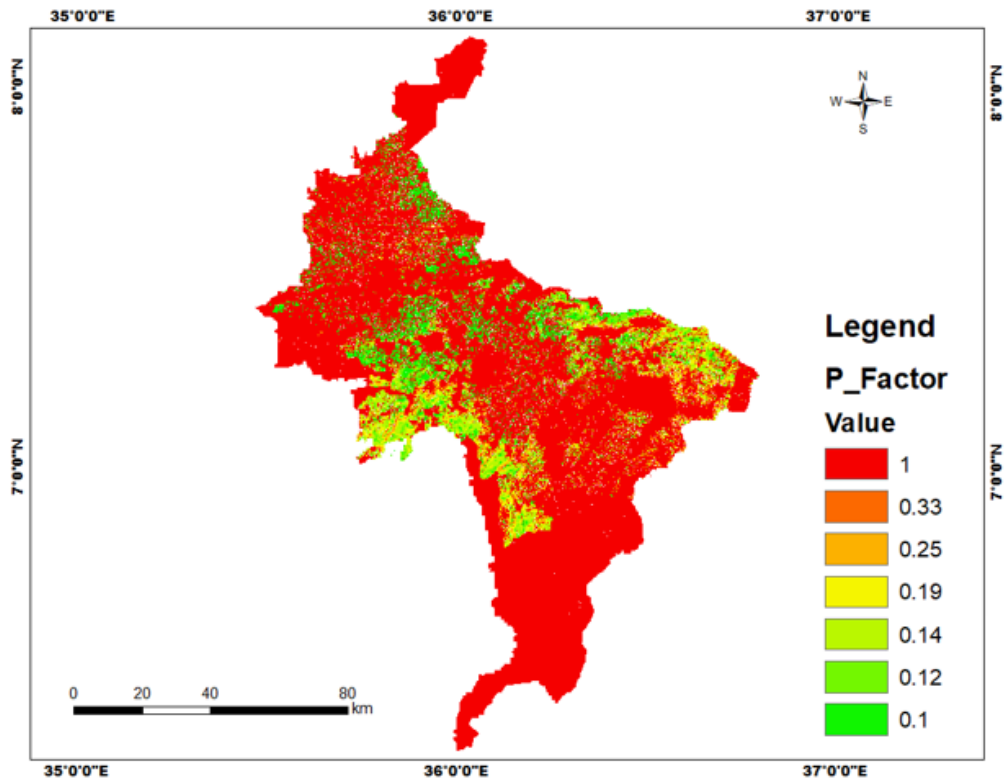


Figure 7

Map of conservation practices factor (p-values) generated from LULC & slope

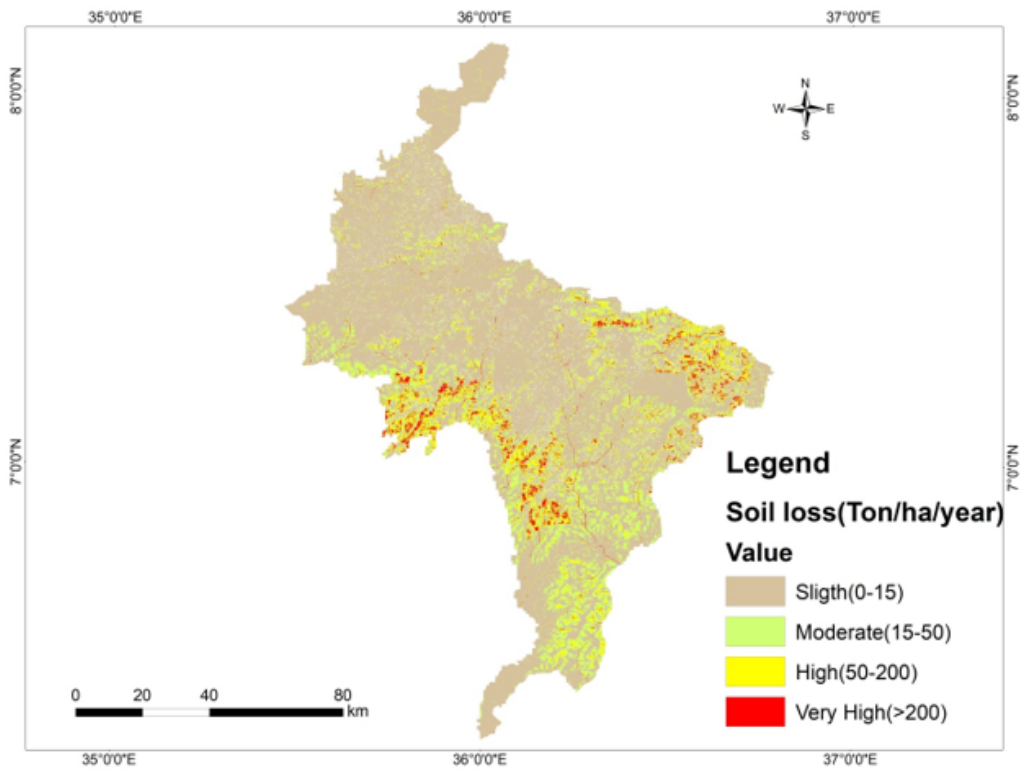


Figure 8

Map depicting spatial variation of soil erosion loss in Kaffa Zone