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Developing GIS-Based Soil Erosion Map Using RUSLE of Andit Tid Watershed, Central Highlands of Ethiopia

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Authors' contributions

This work was carried out in collaboration between all authors. The first Author AD performed the statistical analysis, wrote the protocol, wrote the first draft of the manuscript and re-wrote the suggested articles during reviewing of this scientific paper. The second Author AT designed the study, collected and organized raw data and managed the literature searches. The third Author FT performed statistical analysis and literature search. All authors read and approved the final manuscript.

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ABSTRACT

Soil erosion is a common phenomenon and major threat in many parts of Ethiopian highlands and it remains difficult to quantify and measure the amount of soil erosion. Geographic Information System (GIS) provides spatial information to identify erosion potential areas and useful tools to estimate the annual soil loss based on Universal Soil Loss Equation (USLE). This research was conducted in Central Highlands of Ethiopia, Andit Tid watershed which is 180 Km far from Addis Ababa north direction and covers 475 ha area. The aim of this research was to estimate the annual soil loss from the watershed and to map the topographic and anthropogenic factors for the planning and implementations of sustainable soil conservation and management system in the watershed. A Revised Universal Soil Loss Equation (RUSLE) preferred for Ethiopian conditions and GIS was used

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to estimate soil losses and identify potential effect of erosion factors. We employed IDW-interpolation map for rainfall erosivity (R) factor, soil map for soil erodibility (K) factor, a 30m*30m Digital Elevation Model (DEM) for topography (LS) factor, satellite image for vegetation cover (C) factor, land use and slope class map for management (P) factor. We also made the long-term correlation matrix among discharge, sediment loss and rainfall of the watershed. The result revealed that the annual soil erosion potential of the watershed ranges between 0-291 ton.ha^{-1}yr^{-1}with an average of 22.3 ton.ha^{-1}yr^{-1}. Therefore, GIS-based soil erosion model is a cost-effective method to estimate soil erosion as well as to identify priority area for sustainable land management practices.

Keywords: DEM; soil erosion; RUSLE; Andit Tid.

1. INTRODUCTION

The Ethiopian highlands account 43% of the country and dominated by high soil fertility that covers 95% of the cultivated land. According to [1] and [2], the annual soil loss of the Ethiopian highlands range between 200 to 300 tons per hectare and have an impact on loss of fertile soil. Soil erosion affects 50% of the agricultural area and 88% of the total population of the country [3]. The situation is more prevalent and determinant in the study region (Amhara region). However, there is a lack of evidence on the potential amount of erosion being eroded and erosion hotspot area for possible soil conservation interventions to alleviate soil degradation.

The influences of soil erosion on soil degradation, agricultural production, water quality, hydrological systems, and environments, have been recognized as severe problems for human sustainability [4]. However, estimation of soil erosion loss often difficult due to the complex interplay of many factors, such as climate, biophysical, social, economic, and political factors [5]. In this regard, GIS is a vital tool that provides spatial soil erosion model.

The methods of quantifying soil loss based on erosion plots possess many limitations in terms of cost, representativeness, and reliability of the resulting data. They cannot provide a spatial distribution of soil erosion loss due to the constraint of limited samples in complex environments for a geospatial analysis of environmental complexity, contingency, and unpredictability [6] and [7]. Thus, mapping soil erosion in large areas is often very difficult using these traditional methods. Universal Soil Loss Equation (USLE) and later the Revised Universal Soil Loss Equation (RUSLE) has been the most widely used model for predicting soil erosion loss [8]. RUSLE represents how climate, soil, topography, and land use affect rill and inter-rill soil erosion caused by raindrop impact and surface runoff [9]. It has been extensively used to estimate soil erosion loss, to assess soil erosion risk, and to guide development and conservation plans in order to control erosion under different land-cover conditions [10]. There are five major factors that are used to calculate the soil loss for a given site (Equation 3). Each parameter is the arithmetic estimate of a specific condition that affects the severity of soil erosion at a particular location. Thus, the erosion values obtained from the RUSLE more accurately represents long-term averages.

Therefore, the purposes of this research are (1) To develop a GIS-based soil erosion potential model of the Andit Tid Watershed; (2) To estimate soil erosion potential for the entire watershed and to identify high soil erosion potential area and (3) To develop a correlation among recorded rainfall, discharge, and sediment loss. This study provides insightful information the potential soil erosion problem in Andit Tid watershed with longterm metrological analysis. This study might be used as an outline for researchers, academicians and government and nongovernment organizations working on soil erosion. The next section of this paper is organized as: section two provides the material and methods used; section three reveals the results and discussions and finally, conclusion and remarks are provided in section four.

2. MATERIALS AND METHODS

2.1 Description of the Study Area

Andit Tid watershed is one of the catchments of the Soil Conservation Research Programme (SCRP) of the Amhara Regional Agricultural Research Institute (ARARI). The SCRP was initiated in 1981 by the Institute of Geography of the University of Bern (Switzerland). Hence in the study area, there is a huge amount of collected and available data for the last 25-30 years. The watershed is situated at 39°43’E longitudes and

9°48'N latitudes (Fig. 1) 180 km northeast of capital city Addis Ababa. The watershed covers a total area of 475 ha, and the altitude of the catchment ranges from 3040 to 3550 m.a.s.l. The mean annual rainfall is 1651 mm, the minimum and maximum temperatures are7°C and 17°C, respectively. The minimum and maximum average soil temperatures are 8°C and 20°C, respectively. The agro-climatic zone of the watershed is moist wurch.

2.2 Data Sources and Conceptual Framework

The research has been used both primary and secondary data. Secondary data (Satellite image, aerial photo, topographic map, meteorological data and others) were collected from different governmental and non-governmental organizations. In addition, a Global Positioning System (GPS) data collection was carried out to generate primary information regarding the ground truth for image classification and soil loss vulnerability verification.

Data analysis and processing were made by digitizing, calculating and classifying the necessary information of each thematic layers using Arc GIS 10.1 software. Furthermore, some simple statistical methods, such as percentage, average and graphic tabulation were also employed for the analysis and interpretations. The basic methodological approach followed in RUSLE has been detailed in the following simplified flow chart (Fig. 2).

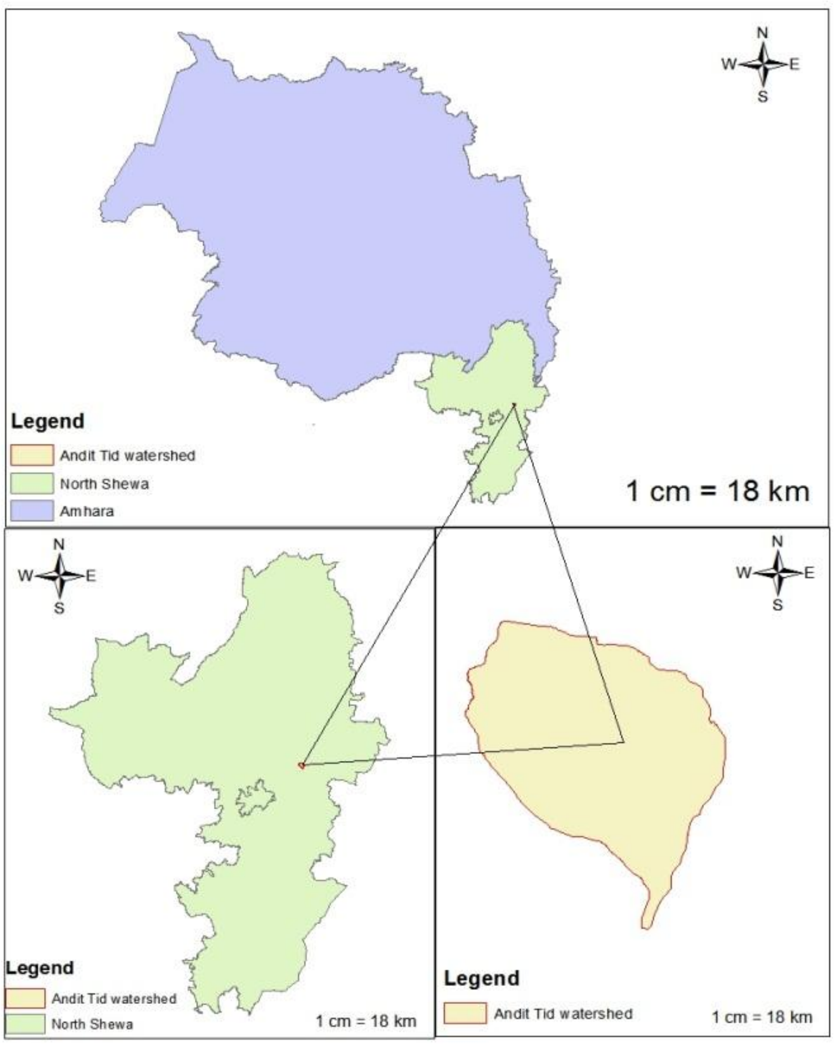

Fig.1. Map of Andit Tid watershed

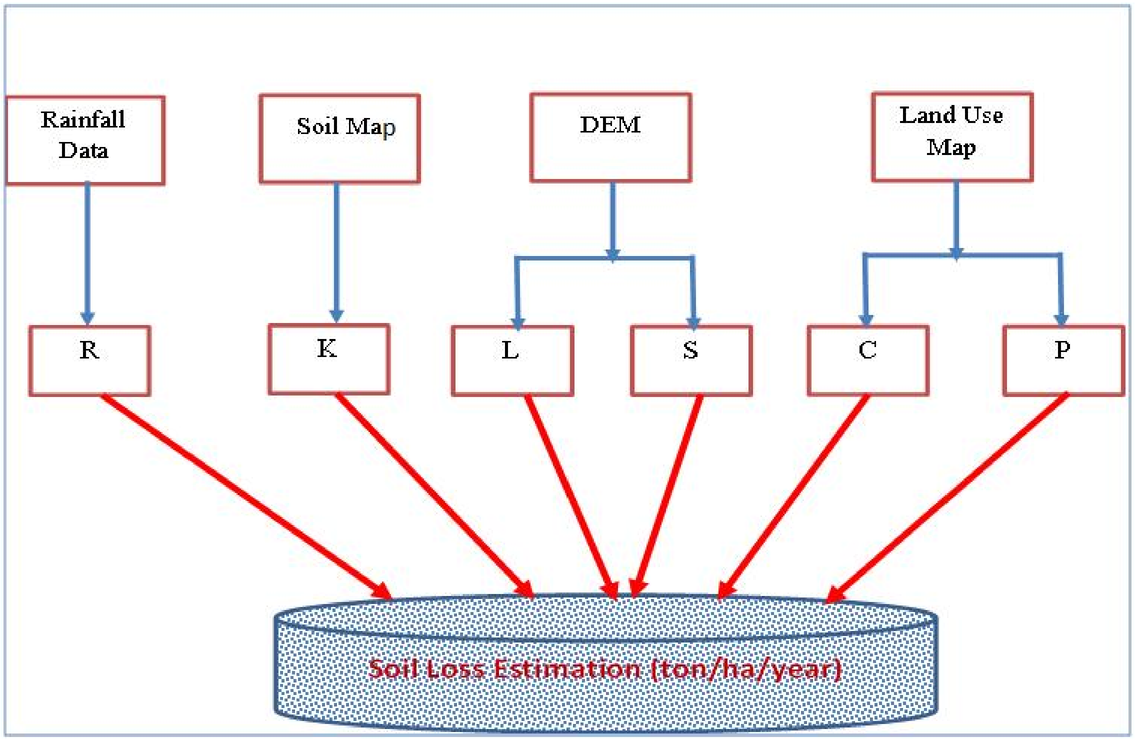

Fig. 2. Conceptual framework of soil loss estimation (Authors developed)

2.3 Data Measurement

2.3.1 Rainfall erosivity (R) factor

Daily rainfall records from the watershed rain gauge stations covering the period 1995-2014 were used to calculate the rainfall erosivity Factor (R-value). The mean annual rainfall was first generated for getting continuous rainfall data for each grid cell. Then, the R-value corresponds to the mean annual rainfall of the watershed was found using the R-correlation established by [11] to Ethiopia condition.

$$R = -8.12 + 0.562 * P \quad (1)$$

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

2.3.2 Soil erodibility (K) factor

The soil erodibility (K) factor for the watershed was estimated based on soil unit types referred from soil database adapted to Ethiopia by [11] and [12]. Finally, the shapefile results were changed to a raster with a cell size of 30x30 m. The raster map was then re-classified based on their erodibility value as shown in Table 1.

2.3.3 Slope length and slope steepness (LS) factor

The 30m spatial resolution DEM was employed to map the flow accumulation and slope gradient the study watershed from Nile basin DEM data by using Arc GIS 10.1 software. Then by using spatial analyst tool – map algebra- raster calculator in Arc GIS 10.1 we could calculate and map the slope length and steepness (LS) factor based on equation 2 as defined in [13].

LS = pow [(flow accumulation) * cell size/22.1,0.6] * pow [sin (slope) * 0.01745/0.09,1.3] (2)

2.3.4 Crop management (C) factor

A land use and land cover map of the study watershed was prepared from LANDSAT through supervised digital image classification technique using ENVI 5.0 software. A field checking effort was also made in order to collect ground truth information. In supervised image classification technique, land use and land cover types were classified so as to use the classified image as an input for generating crop management (C) factor and support practice (P) factor. Based on the

Table 1. Soil types and their corresponding K value

Soil type	Area (Ha)	Soil color	K-value
Eutric leptosol	275	Black	0.15
Eutric cambisol	30.5	Black	0.15
Lithic leptosol	169.5	Brown	0.2

land cover classification map the corresponding C-values obtained from [11] for all land use types were assigned in a GIS environment.

2.3.5 Erosion management practice factor (P-value)

The P-factor was assessed using major land cover and slope interaction adopted by [8] for Ethiopia condition. The corresponding P values were assigned to each land use land cover and slope classes. The P factor map then was produced through analyst tool, extract and the intersection of land use and slope class map in Arc GIS environment.

2.3.6 Total soil loss analysis

Average annual soil loss rate was determined by a cell-by-cell analysis of the soil loss surface by superimposing and multiplying the respective RUSLE factor values (R, K, LS, C, and P) interactively by using "Spatial Analyst Tool- Map Algebra -Raster Calculator" in Arc GIS 10.1 environment as shown equation (3) adopted by [11].

$$A= R^* K^* LS^* C^* P \quad (3)$$

Where, A is the average annual potential soil loss in ton.ha^{-1}yr^{-1}; R is the rainfall-runoff erosivity factor; K is the soil erodibility factor; LS is the slope length and degree; C is the land-cover management factor; P is the conservation practice factor.

2.3.7 Correlation among rainfall, discharge and sediment loss

The 19 years average monthly relationship between rainfall and discharge, rainfall and sediment loss, and discharge and sediment loss was done using Stata 22.0 statistical software.

3. RESULTS AND DISCUSSION

3.1 Rainfall Erosivity Factor (R)

The soil loss is closely related to rainfall partly through the detaching power of raindrop striking the soil surface and partly through the contribution of rain to runoff. The rainfall data records from the station covering the period 1995-2014 were used to calculate the rainfall erosivity (R). The mean annual rainfall from 4 rain gauge sites (Andit Tid, Gudi Bado, Wani Gedeland on-station) of the watershed was first generated (Table 2) to get continuous rainfall data for each grid cell. Then the R-value corresponds to the mean annual rainfall of the watershed was found using the R correlation established in [11] to Ethiopia condition.

R-factor was computed using conversion tool (equation 1) in raster surface using IDW (Inverse Distance-Weighted) interpolation methods in Arc GIS software. As shown in the map below the maximum R-value is 949 whereas the minimum R-value is 840. Hence the watershed is dominated by maximum and near maximum R-factor value except for the northwestern parts of the watershed. The erosivity factor result is presented in Fig. 3.

3.2 Soil Erodibility Factor (K)

Main determinants of soil erodibility are soil structural stability and the soils ability to absorb rainfall. The value of K ranges from 0 to 1. [14] Developed a USLE for Ethiopian condition by adopting different sources and proposed the K values of the soil based on their color. Spatial analysis tool extract by the mask in GIS environment was used to obtain soil unit map of the study watershed from Amhara region digital soil map with 1: 50,000 scales developed by [15]. Soil erodibility factor for the watershed was estimated based on soil unit types referred from soil database adapted to Ethiopian by [11] and [14]. Finally, the resulting shapefile was changed to a raster with a cell size of 30 m*30 m the raster map was reclassified based on their erodibility value as showed in Table 2. The K-value of the watershed is presented in Table 3.

In this study, the analysis of K factor was obtained from Ministry of Agriculture and Rural Development based on FAO standard soil type classification and three major soil types such as

Eutricleptosol, Eutriccambisol, and Lithic leptosol were identified for the study area. After changing the vector format into the grid dataset and was reclassified based on K-values adopted by [11].

The results indicated that soil erodibility value in the study watershed is 0.15 for Eutric leptosol and Eutric cambisol whereas 0.2 (Lithic leptosol) as shown in the following map Fig. 4. From the map, we could conclude that the larger area of the watershed has the K value of 0.15 in the north, northeastern and northwest parts of the watershed whereas the south and southeastern part have the K value of 0.15.

Table 2. Mean annual rainfall and erosivity factor (R) result

Rain gauge station	Coordinate points			Mean annual rainfall (mm)	R-value
	X	Y	Z		
Andit Tid	577951	1084936	3050	1656.4	922.78
Wani Gedel	579049	1084944	3221	1703.1	949.03
Gudi Bado	579488	1083468	3403	1651.8	920.19
On-Station	577928	1084868	3031	1508.3	839.54

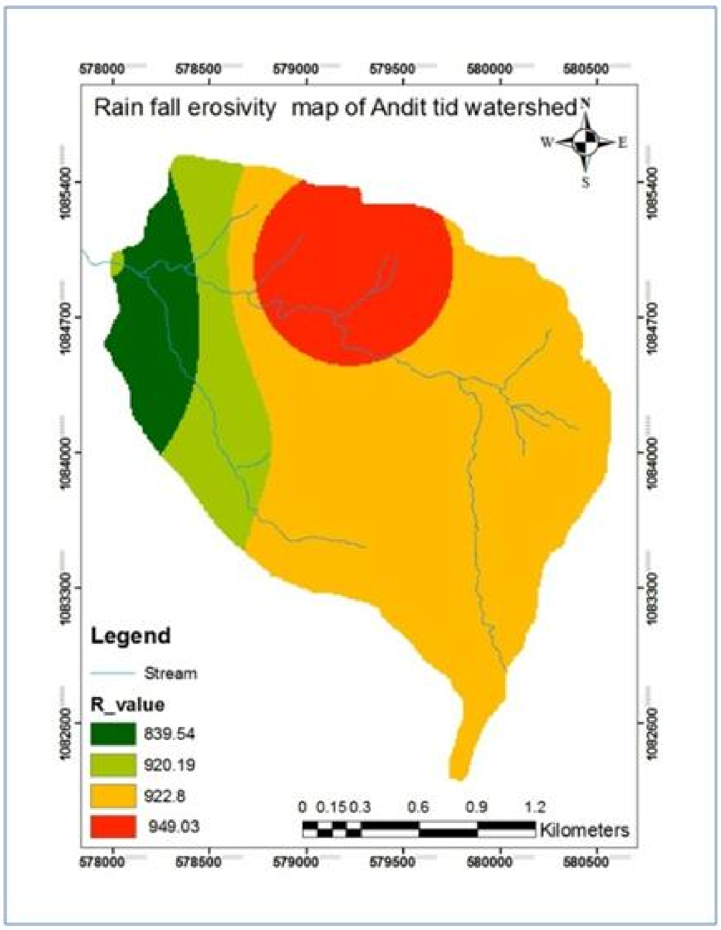

Fig. 3. Rainfall erosivity factor (R-value) map

Table 3. Soil color and corresponding K value (Hellden, 1987)

Soil color	Black	Brown	Red	Yellow	Grey	White
K factor	0.15	0.2	0.25	0.3	0.35	0.40

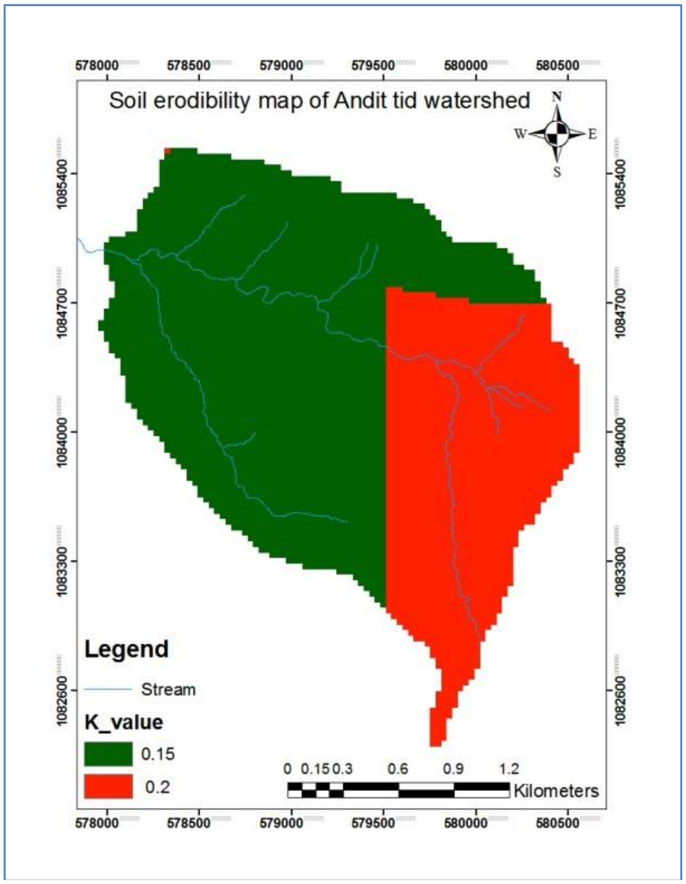

Fig. 4. Soil erodibility (K) factor map

3.3 Slope Length and Steepness Factor (LS)

The topographic factors L and S are used to adjust the erosion rated based upon the length and steepness of the slope. The erosivity of runoff increases with the velocity of the runoff water. Steep slopes produce high runoff velocities. Soil loss increases with increasing slope due to the greater volume of runoff accumulating on the longer slope lengths. The slope length is the distance from the point of origin of the runoff to the point where the slope steepness decreases sufficiently to cause deposition or to the point where runoff enters a well-defined channel. The slope length and slope steepness can be used in a single index LS, which expresses the ratio of soil loss as defined by [8]. Slope steepness has been considered one of the most model parameters in RUSLE analysis due to the fact that the steeper the slope of a field, the more it is pushed downhill, the faster the water runs and the greater will be the amount of soil loss from erosion by water. Soil erosion by water also increases as the slope length increases due to the greater accumulation of runoff (Fig. 5c). The modified equation for computing the topographic factor (LS factor) in GIS environment is employed as indicated in equation (2).

Where flow accumulation (Fig. 5b) is derived from the DEM after conducting fill, flow direction and flow accumulation processes in Arc GIS. Cell size is the size of the cells being used in the grid-based representation of the landscape. Finally, the LS factor map was derived using the above formula in Arc GIS spatial analysis raster calculator function (Fig. 5a).

The maximum LS value was 7.46 and the minimum value was 0 in the plain parts of the watershed, it was calculated after generating flow accumulation and slope class map from DEM and by using Raster Calculator through applying the following equation.

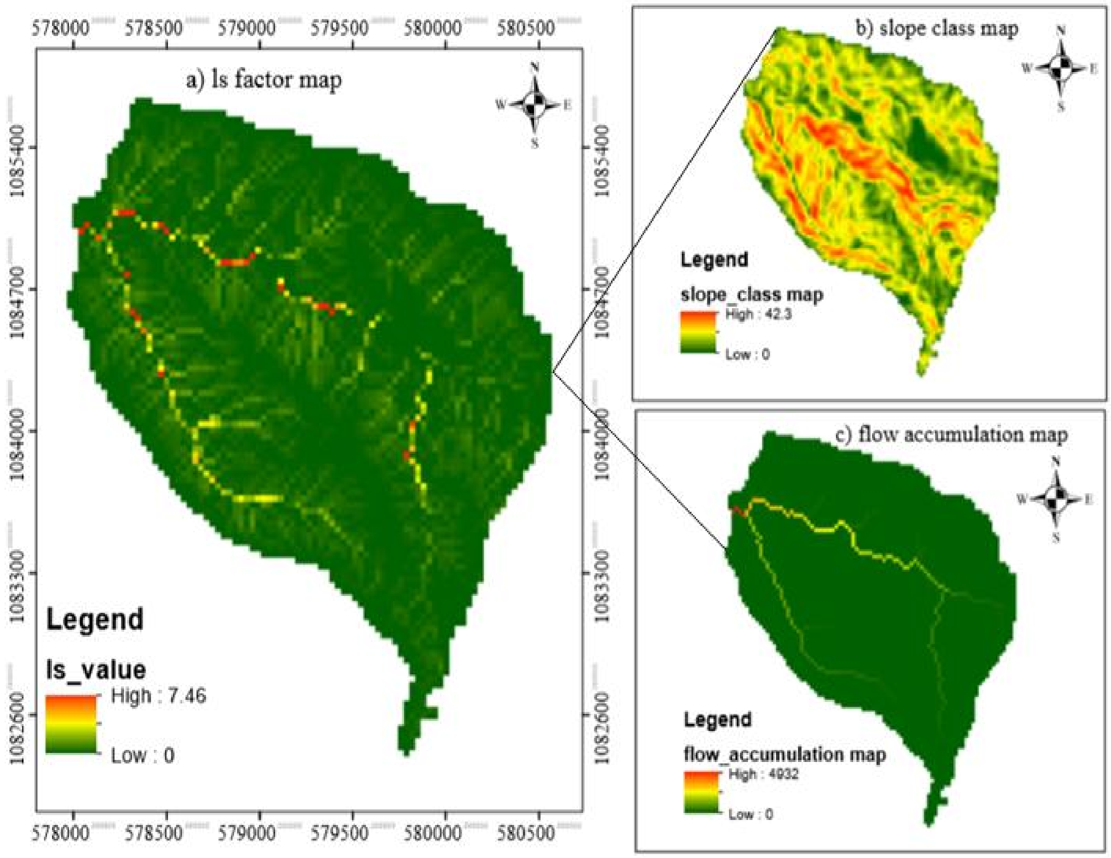

Fig. 5. LS factor map

3.4 Cover Management Factor (C)

The crop management factor represents the ratio of soil loss under a given crop to that of the base soil [16]. The land use map was used for analyzing the c-value. The raster land use/land cover map was converted to a vector format and a corresponding C-value was assigned to each land use classes based on cover values proposed by [11] (Table 4). Finally, using reclassification and vector to raster conversion the land use/ land cover map was converted to C factor map (Fig. 6).

The result indicated that five land use and land-cover classes were recognized in the watershed, dominantly by cultivated land (35.49%) followed by dense grassland (25.65%). Crop management C factor values of the study watershed were ranging from 0.001 for dense forest land to 0.40 to the open grassland/bad land soft.

Table 4. The land use land cover class and their corresponding C-values

Land use type	Area (ha)	C-value
Cultivated land	169.1	0.1
Open grassland	73.7	0.4
Degraded land	92.3	0.15
Dense forest	17.6	0.001
Dense grassland	122.3	0.01
Total area	475	

Source: [11]

3.5 Erosion Management Practice Factor (P-value)

The erosion management practice, P-value, is also one factor that governs the soil erosion rate. The P-value ranges from 0-1 depending on the soil management activities employed in the specific plot of land. These management activities highly depend on the slope of the area. [8] Calculated the P-value by delineating the land into two major lands uses agricultural land and other land use. The agricultural land subdivided

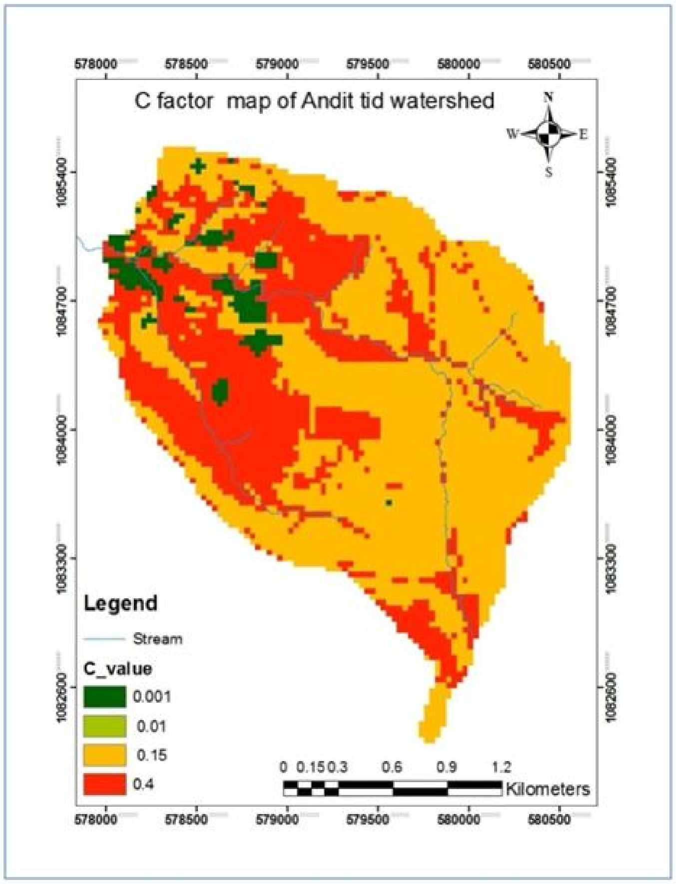

Fig. 6. Land use and Cover management (C) factor map

into six classes based on the slope percent to assign different P-value (Table 5). In this study, we were employed same technique to assign the P-value of the watershed. After assessing the conservation practice and their respective values, P actor map was developed in Arc GIS using land use/land cover map of the study area (Fig. 7).

Erosion management practices are the practices that reduce the velocity of runoff and the tendency of runoff to flow directly down-slope reduce the P factor. In the study area, there is only a small area that has been treated with terracing through the agricultural extension program of the government and these are poorly maintained as implementation was performed without the participation of the local people. As data were lacking on permanent management factors and there were no management practices, the P-values suggested in [17] were used. Thus, the agricultural lands are classified into five slope categories and assigned P-values while all non-agricultural lands are assigned a P-value of 1.00 (Fig. 6). The maximum P-value is1; it was the value for all land use types excluding cultivated land, whereas the P-values were varied for the cultivated land of different slope class. In general, the minimum p-value is 0.1 for the cultivated land with a slope of less than 5%.

Table 5. P-value of different land use types

Land use type	Slope (%)	P-factor
	0-5	0.1
	5-10	0.12
Agricultural land	10-20	0.14
	20-30	0.19
	30-50	0.25
	50-100	0.33
Other Land	All	1.00

Source: [8]

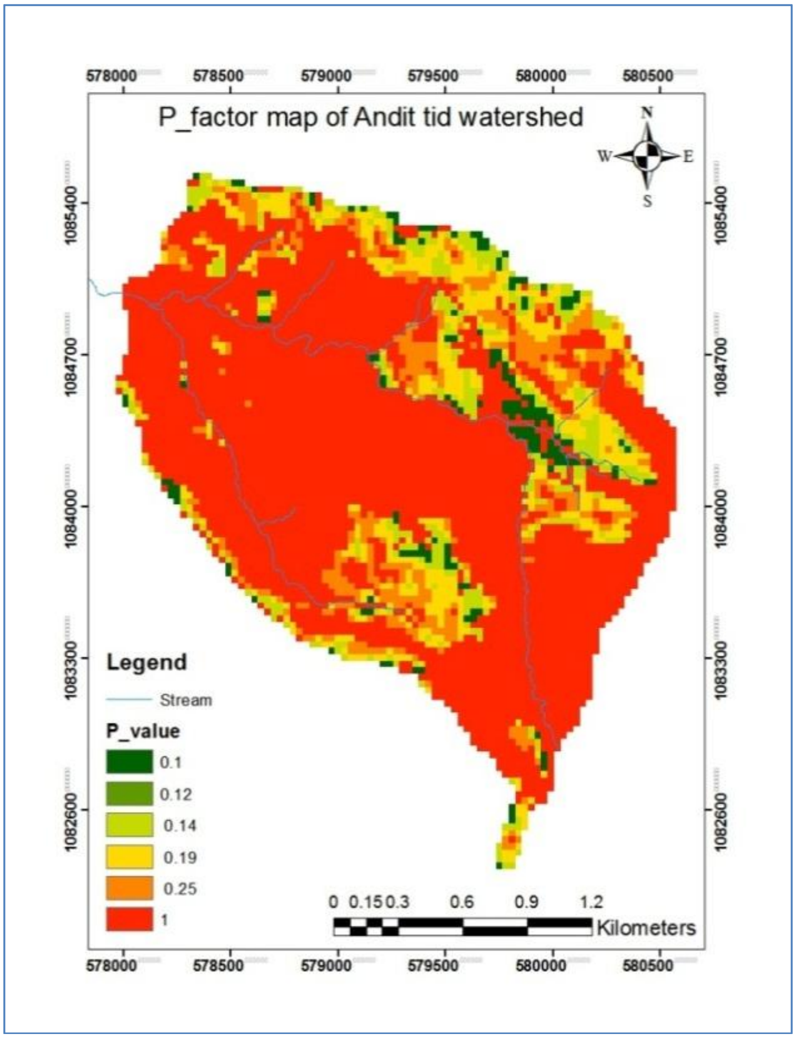

Fig. 7. Erosion management practice (P) factor map

3.6 Total Annual Average Soil Loss

The spatial distributions of the amount of soil loss in the study area are quite different and range nearly insignificant 0 ton $ha^{-1}yr^{-1}$ in the north, east and central parts of the study area to extremely high 291.02 ton.$ha^{-1}yr^{-1}$ in the west and northwest parts of the catchments (Fig. 8). The mean annual soil loss from the area is 22.3 ton $ha^{-1}yr^{-1}$ and a total soil loss of 10, 601 ton.yr^{-1} from the entire 475 ha area of the watershed. Since the west and northwest parts of the catchments are dominated by steeply sloping areas, an estimated soil loss in this area is almost in the range of the soil loss estimation of the Ethiopian highlands.

The average soil loss rate estimated for the study/ AnditTid watershed is 22.3 ton.$ha^{-1}yr^{-1}$, which is relatively consistent with the average soil loss rate reported by other studies such as [11] 18 ton.$ha^{-1}yr^{-1}$for Ethiopia highlands, [18] 24.95 ton.$ha^{-1}yr^{-1}$for Zingin watershed, northwestern Ethiopia and [19] 30.6 ton.$ha^{-1}yr^{-1}$for jabiTehinan watershed in the North Western Highlands of Ethiopia. In contrast, [15] reported that an average soil erosion rate of 35 ton.$ha^{-1}yr^{-1}$for the Central and Northern Highlands of Ethiopia. However, [17] found an average soil loss rate of 93 ton.$ha^{-1}yr^{-1}$ in Chemoga watershed of Blue Nile basin in the Northwestern highlands of Ethiopia.

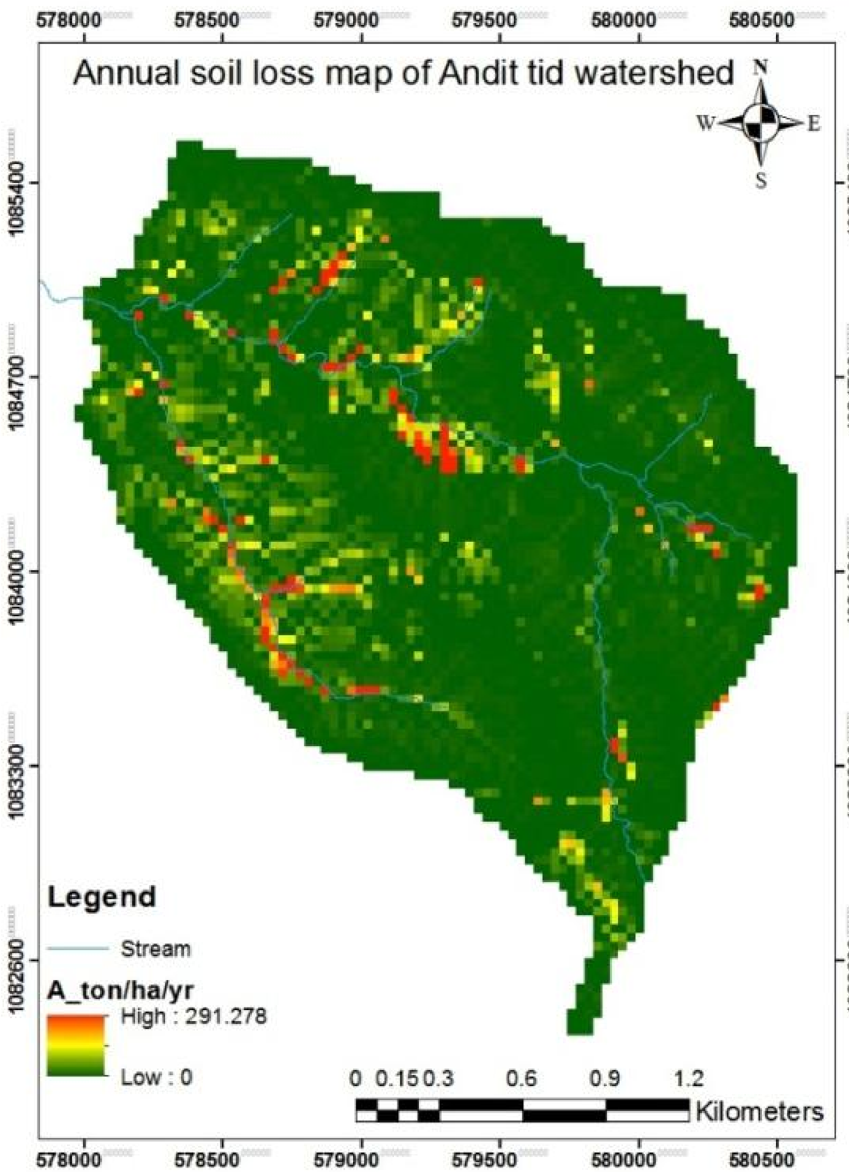

Fig. 8. Total annual soil loss map of AnditTid watershed

3.7 Correlation among Rainfall, River Discharge, and Sediment Loss

The hydrology relationship between rainfall, discharge and sediment loss is presented in Fig. 9. The result showed that the relationship between rainfall and river discharge in the watershed is 90.7%. The result demonstrated that increasing the rainfall amount in the watershed by 1mm will increase by 3.25 m^3. On the other hand, the relationship between rainfall and sediment loss is 89.4%. The result revealed that increasing the rainfall amount in the watershed by 1mm will cause 2.6kg of soil loss. Furthermore, the relationship between river discharge and sediment loss in Andit Tid watershed is 66.5%. The result indicated that as the river discharge increased by 10m^3 the sediment loss will increase by 7kg of sediment.

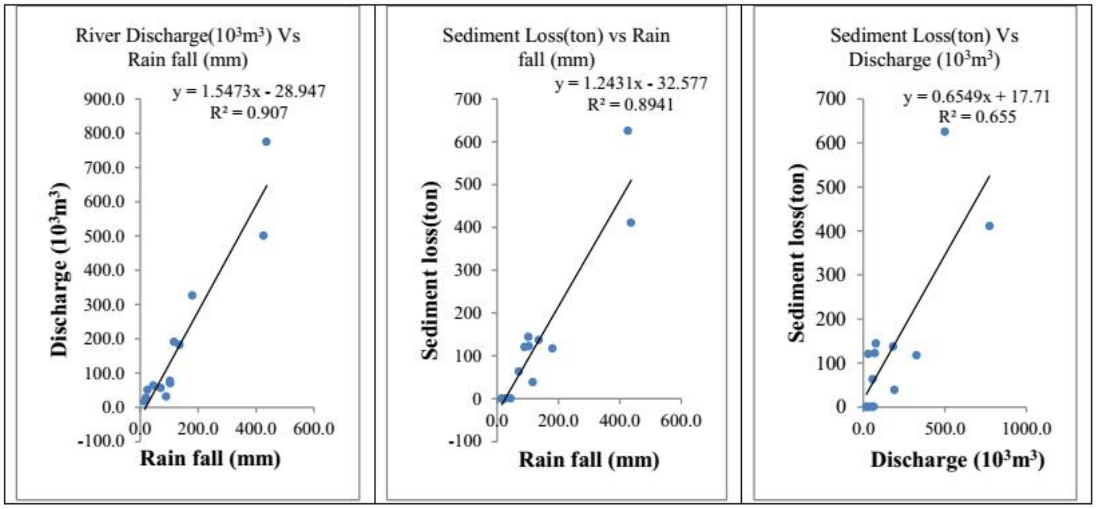

Fig. 9. Monthly average rainfall, discharge, sediment loss graphs (from 1995-2014)

4. CONCLUSION AND REMARKS

Assessment and quantifications of estimated values of soil loss can be well computed by the application of GIS and remote sensing techniques. However, the accuracy of results obtained is largely a function of the accuracy of input data such as topography (LS-factor), support practices (P-factor) and cover parameters (C-factor) which are location specific and need to be calibrated. Since the relation between rainfall and sediment loss is around 90.5%, we can conclude that rainfall is the main driving force for the formation of erosion. The C factor values used in this report were derived from a table originally developed by [11]. In connection with land use/land cover types, there is no distinct pattern observed but soil erosion vulnerability potential increases in bare and cultivated lands. Generally, the most cost-effective method of erosion reduction is re-plantation and reforestation of the environment. The increase in vegetation protects the soil surface from the erosive power of rainfall. The root systems of various plants, grasses, and trees also hold the soil layer together. Estimated soil loss was found to be different in different land use/land cover type and slope gradients. The estimated values of soil erosion have a direct relationship with slope gradients, even the highest soil erosion occurs on the steep slope area according to the soil loss map of the study watershed. The hydrology relationship between rainfall, discharge, and sediment is very strong. The soil loss can be used as one of the main inputs for decision-maker of soil resource management and it may influence policy decisions of land use planning in the study area.

Therefore, based on our findings we recommended that (1) Soil erosion hot spot areas that were identified in the soil erosion map should be given a serious attention and priorities for implementing soil conservation activities before the areas reached to irreversible soil degradations; (2) Since slope steepness and rainfall are the major driving force for soil loss the community should adopt physical soil conservation techniques such as bench terrace that can change the steepness of the slope in the long run; (3) The local communities should adopt immediate soil conservation measures in their cultivated lands by applying different soil protective methods like mulching, strip cropping, terracing, contour plowing, cover crops and other indigenous means of soil conservation; (4) Currently, there are no **C** factors defined specifically for local vegetation species but in order to use the RUSLE as a sustainable and accurate resource management tool, additional research to determine the **C**-factors for specific Andit Tid watershed trees and plants are so as to be needed; and finally (5) The management plan may implement certain vegetation types according to how effectively they reduce soil erosion. Mitigation measures that are effective in reducing the erosion rate and cost-effective may then be considered.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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