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A Geographic Information System Based Soil Loss and Sediment Estimation in Gerdi Watershed, Highlands of Ethiopia

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Abstract

This study was carried out to spatially predict the soil loss rate of Gerdi watershed with a Geographic Information System (GIS) and Remote Sensing (RS). RUSLE adapted to Ethiopian conditions was used to estimate potential soil losses by utilizing information on rainfall erosivity (R) using interpolation of rainfall data, soil erodibility (K) using soil map, vegetation cover (C) using satellite images, topography (LS) using Digital Elevation Model (DEM) and conservation practices (P) using satellite images. Based on the analysis, the total annual soil loss potential of the study watershed was 28,732.5 tons/yr. Out 147.9 ha (64%) of the land's watershed was categorized none to slight class which under soil loss tolerance (SLT) values ranging from 5 to 11 tons $ha^{-1}yr^{-1}$. The study results indicated that the rate of potential soil loss in the watershed ranged from very low to extremely high. The area covered by none to slight potential soil loss was about 147.9 ha (64%) whereas moderate to high soil loss potential covered about 202.1 ha (36%) of the study watershed. The study demonstrates that the RUSLE together with GIS provide a good estimate soil loss rate over areas.

Keywords: soil erosion; RUSLE; GIS; Gerdi watershed; Ethiopia

1. INTRODUCTION

Agriculture is the mainstay of the Ethiopia's economy where its production is highly dependent on natural resources (Akililu and Graaff, 2007). It accounts for the employment of 90% of its population, over 50% of the country's gross domestic product (GDP) and over 90% of foreign exchange earnings (ECACC, 2002). However, low productivity characterizes the country's agriculture.

Soil erosion has accelerated on most of the world, especially in developing countries including Ethiopia, due to different socio-economic, demographic factors and limited resources (Bayramin *et.al*, 2003). To effectively estimate soil erosion the Revised Universal Soil Loss Equation (RUSLE) has been used in many countries including Ethiopia. The rate of soil erosion is severe in the highlands of Ethiopia. Accelerated soil erosion by water has been a major threat to crop production in Ethiopia (Hurni, 1993; Sutcliffe, 1993 and Tamene, 2005). In the Ethiopian highlands only, an annual soil loss reaches 200-300 tons $ha^{-1}yr^{-1}$(FAO, 1984 and Hurni, 1993). The impact of soil erosion can be most problematical in the developing countries and unable to improve soil fertility through application of purchased inputs (Lulseged and Vlek, 2008). In the Ethiopian highlands only, an annual soil loss reaches 200-300 tons $ha^{-1}yr^{-1}$, and can be as much as 23.4x109 metric tons per year (FAO, 1984 and Hurni, 1993). Hurni (1988), and Hurni, Herweg, Portner and Liniger (2008) estimates that soil loss due to erosion of cultivated fields in Ethiopia amounts to about 42 metric tons $ha^{-1}yr^{-1}$.Therefore, it becomes a destructive process when it is exacerbated by a number of anthropogenic factors such as deforestation, overgrazing, incorrect methods of tillage and unscientific agricultural practices (Lal, 2003; Zhou and Wu, 2008). Despite the severity of soil erosion and its consequences in the study watershed, there have been few studies at watershed level to quantify erosion rates at watershed scale. In addition, study watershed, Gerdi is one of the most erosion-prone watersheds in the highlands of Ethiopia which received little attention. It was, therefore, essential to assess rates of soil loss and develop a soil loss intensity map of the study watershed using RUSLE within a GIS environment and identify severity areas for specific soil conservation plans.

2. MATERIALS AND METHODS

2.1 Description of the study watershed

Gerdi watershed is located in Awi Zone at about 450 km northwestern of Addis Ababa. The watershed lies within 1213313 to 1217144 m north and 245870 to 251285 m East in UTM coordinates with altitude ranges of 1920 up to 2291 m.a.s.l. (figure 1) with the total area of 1225.56 ha. Agro-ecologically, 51% and 49% of the watershed is found to be warm and hot zone, respectively. Rainfall is ranging from 720 mm to 1253.2 mm. Temperature extends from $12.8^0{}_C$ to $30.15^0{}_C$. The elevation ranges from 1920 up to 2291 m.a.s.l. The mean annual precipitation ranges from 1800-2000 mm.

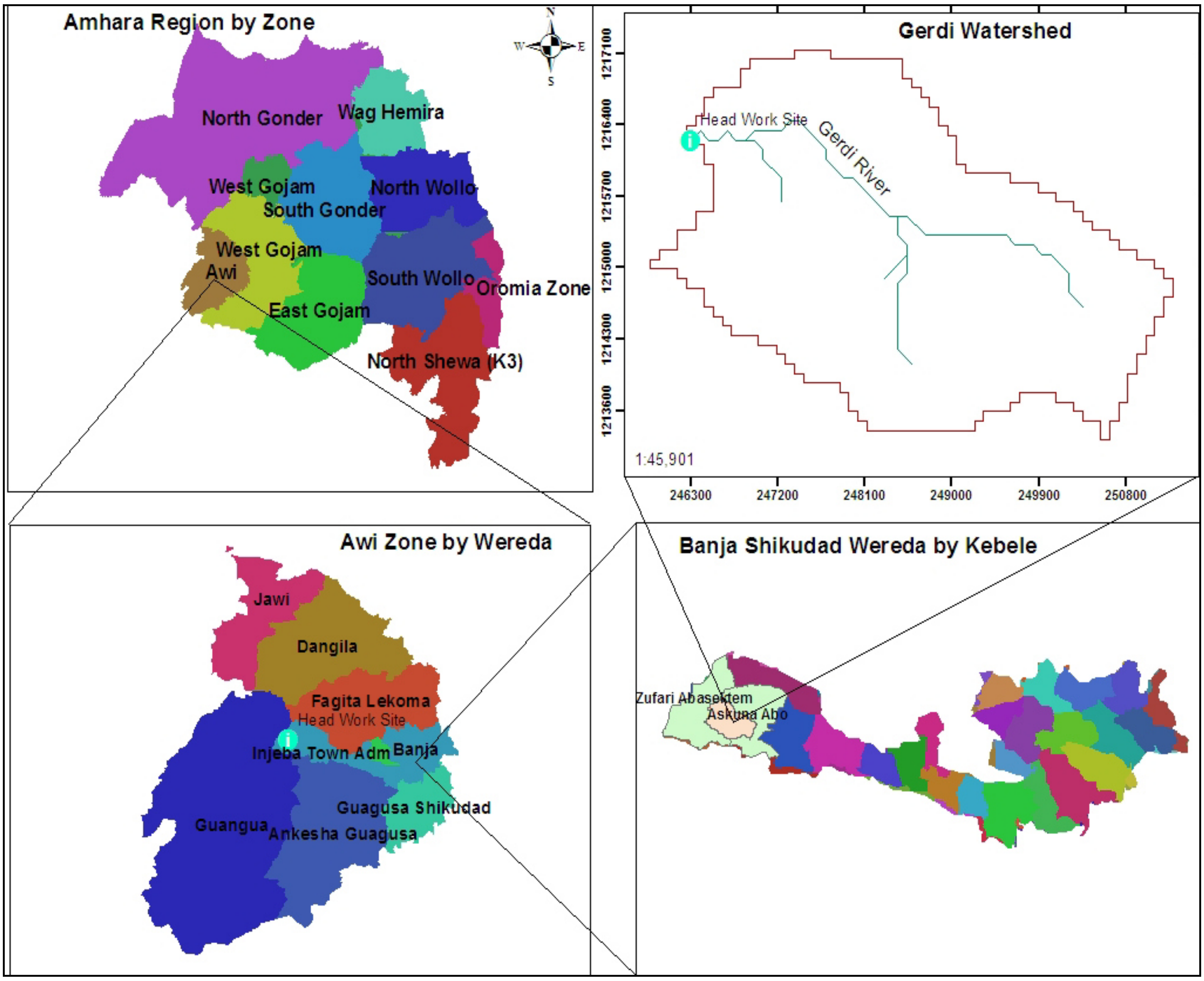

Figure 4: Location Map of Gerdi Watershed

2.2 Methods

The input thematic data included rainfall, soil units, slopes and land use/cover and determined as follow.

2.2.1 Determination of Soil Loss factors

Rainfall Erosivity Factor

The monthly amounts of precipitation for the watershed were collected over 15 years by the Amhara Regional Meteorological Agency. Monthly rainfall records from these meteorological stations covering the period 1998-2012 were used to calculate the rainfall erosivity Factor (R-value). The mean annual rainfall was first interpolated to generate continuous rainfall data for each grid cell by "3D Analyst Tools Raster Kriging Interpolation" in ArcGIS environment. Then, the R-value corresponds to the mean annual rainfall of the watershed was found using the R-correlation established in Hurni (1985) to Ethiopia condition.

$R= -8.12 + 0.562P$…………………………………..…………………………… Equation (1)

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

Soil Erodibility Factor

"Spatial Analyst Tool Extract by Mask" in GIS environment was used to obtain soil units map of the study watershed from Amhara Regional digital soil map at 1:50,000 scale developed by DSA and SCI (2006).The soil erodibility (K) factor for the watershed was estimated based on soil unit types referred from FAO (1989) soil database adapted to Ethiopia by Hurni (1985) and Hellden (1987). Finally, the resulting shape file was changed to raster with a cell size of 30x30 m. The raster map was then reclassified based on their erodibility value as shown in table 1.

Table 2: Soil Types and their Areas

Soil types	Area	
	Hectare (ha)	Percent (%)
Dystric Fluvisols	729.9	59.6
Dystric Gleysols	65.0	5.3
Dystric Nitosols	145.5	11.9
Orthic Acrisols	285.2	23.3
Total	1225.6	100

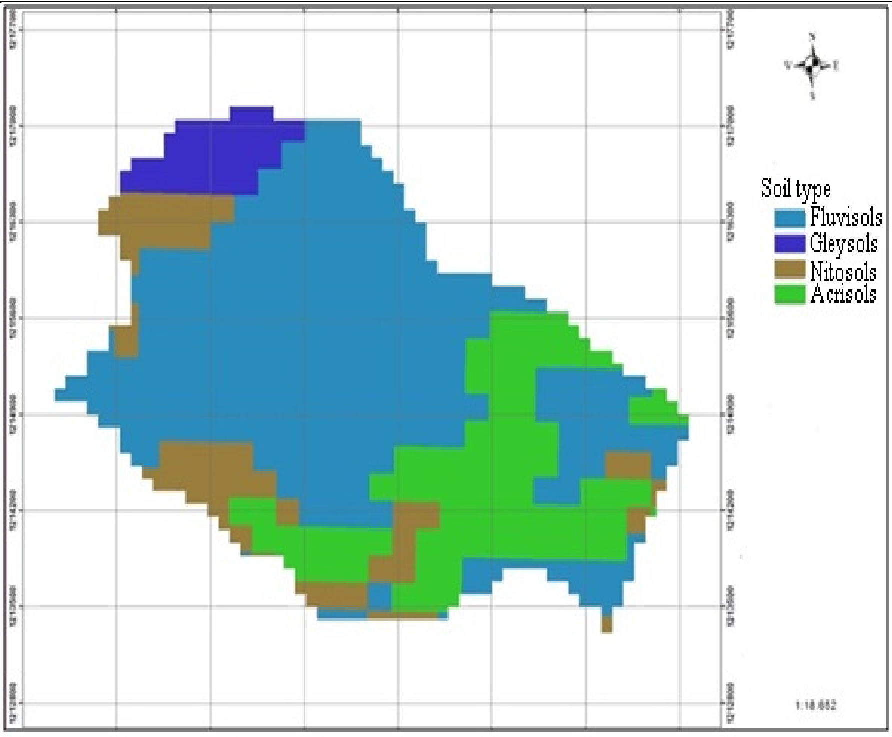

Figure 5: Soil Map

Slope Length and Slope Steepness

The 30 m spatial resolution DEM (Digital Elevation Model) was used to generate slope as shown figure 6 by using "Spatial Analyst Tool Surface Slope" in ArcGIS 10.1 environment. The flow accumulation and slope steepness were computed from the DEM using ArcGIS.

Flow accumulation and slope maps were multiplied by using "Spatial Analyst Tool Map Algebra Raster Calculator" in Arc GIS 10.1 environment to calculate and map the slope length (LS factor) as shown in equation (2) and defined by (Wischmeier and Smith 1978).

LS = (Flow Accumulation*Cell size/22.13)$^{0.4}$ *(Sin slope/0.896)$^{1.3}$…………………....Equation (2)

Where: -Cell size- represents the field slope length

-22.13 is the length of the research field plot

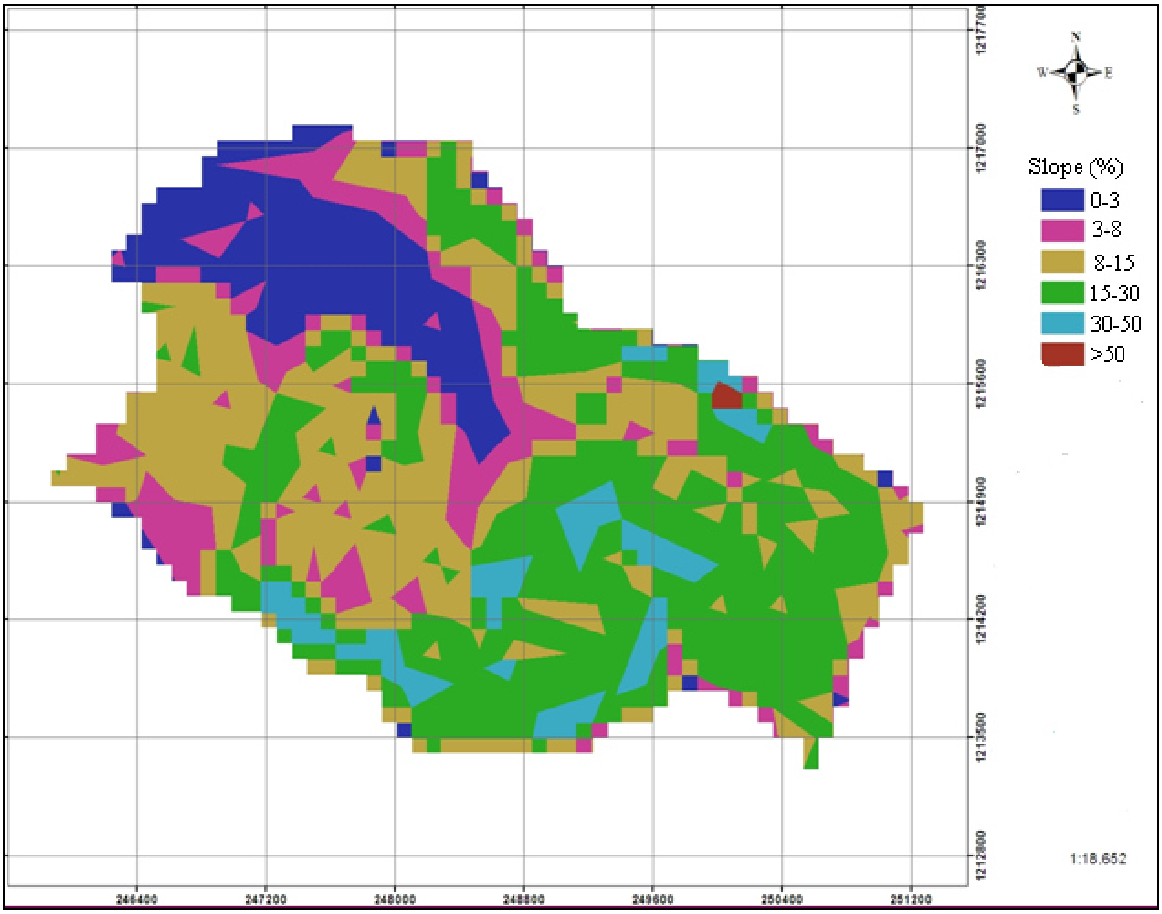

Figure 6: Slope Map of Gerdi Watershed

Land Use/Cover Data and Crop Management Factor

A land-use and land-cover map of the study area was prepared from LANDSAT satellite image acquired on 2013 and supervised digital image classification technique was employed using ENVI 5.0 software. A field checking effort also was made in order to collect ground truth information. The LAND SAT satellite image was used to classify the current land use and land cover map. Digital image processing operations were carried out using ENVI 5.0 software. In addition, ground truth data were used as a vital reference for supervised classification, accuracy assessment and validation of the result. In supervised image classifications technique, land use and land cover types were classified so as to use the classified images as inputs for generating crop management (C) factor and support practice (P) factor. Based on the land cover classification map, a corresponding C value obtained from Hurni (1985) was assigned in a GIS environment (Table 3).

Table 3: Land cover types and their areas

		Area	
Major land cover	Slope (%)	ha	%
Cultivated Land	0-3	126.38	10.31
	3-8	99.28	8.1
	8-15	176.62	14.41
	15-30	70.76	5.77
	30-50	7.4	0.6
Sub-total		480.44	39.2
Forest Land	0-3	2.5	0.2
	3-8	13.14	1.07
	8-15	80.62	6.58
	15-30	294.94	24.07
	30-50	62.9	5.13
	>50	2.43	0.2
Sub-total		456.53	37.25
Grass Land	0-3	35.15	2.87
	3-8	22.04	1.8
	8-15	87.19	7.11
	15-30	47.03	3.84
	30-50	1.05	0.09
Sub-total		192.46	15.7
Shrub and Bush Land	0-3	5.15	0.42
	3-8	17.95	1.46
	8-15	34.67	2.83
	15-30	32.41	2.64
	30-50	5.96	0.49
Sub-total		96.13	7.84
Grand total		1225.56	100

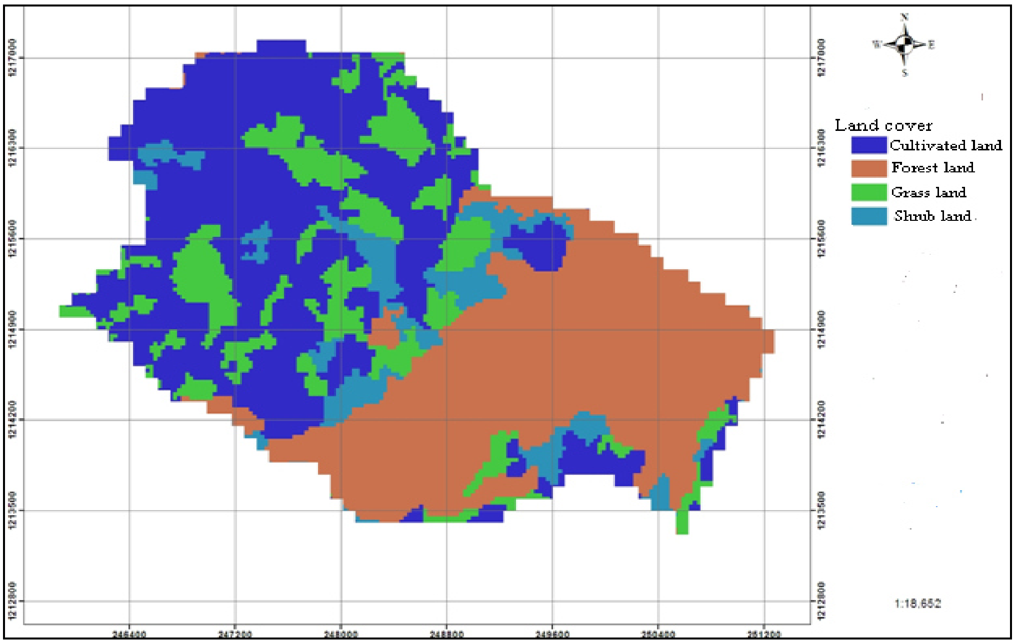

Figure 7: Land Use/Cover Map of the Watershed

Erosion Management Practice Factor
The P-factor was assessed using major land cover and slope interaction adopted by Wischmeier and Smith (1978) for Ethiopia condition. The data related to management or support practices of the watershed were collected during the field work. Therefore, values for erosion management practice factor (P- factor) were assigned

considering local management practices and it was taken the weighed value for similar land use types. The corresponding P values were assigned to each land use/land cover classes and slope classes and the P factor map was produced.

2.2.3 Soil Loss Analysis

The overall methodology involved the use of the RUSLE in a GIS environment with factors obtained from meteorological stations, soil map, topographic map, Satellite Images and DEM as shown in equation 4 and figure 5. 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 ArcGIS 10.1 environment as shown equation 3 adopted from the recommendations of Hurni (1985) and Gebreselassie (1996). For the purpose of identifying priority areas for conservation planning, soil loss potential of the watershed was then categorized into different severity classes following FAO & UEP (1984) guide line.

A= LS* R* K* C* P…..………. ………………………………………………… Equation (3)

Where A is the annual soil loss (metric tons $ha^{-1}yr^{-1}$); R is the rainfall erosivity factor [MJ mm h^{-1} ha^{-1} yr^{-1}]; K is soil erodibility factor [metric tons ha^{-1} MJ $^{-1}$ mm^{-1}]; LS = slope length factor (dimensionless); C is land cover and management factor (dimensionless); and P is conservation practice factor (dimensionless). Ground truth data collected by GPS were used for checking and validation of results.

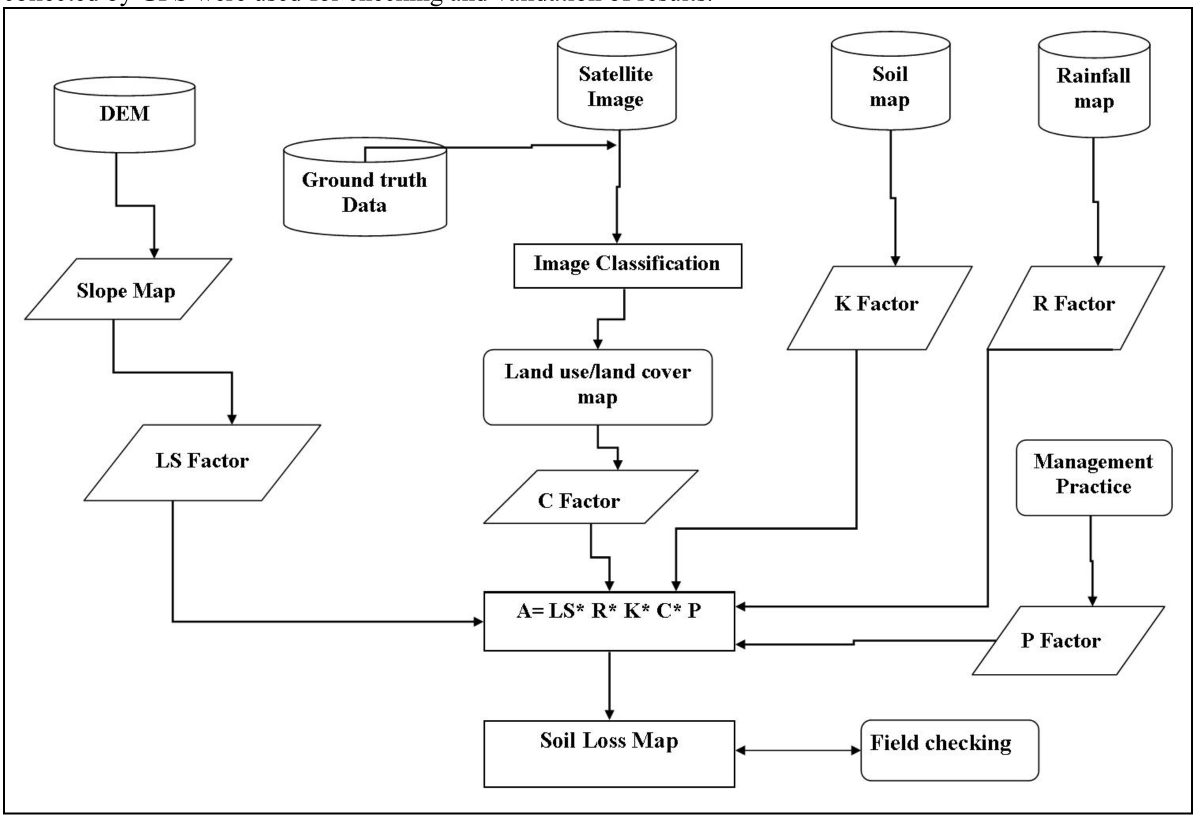

Figure 8: Flow Chart showing the GIS based Soil Loss Estimation

2.2.4 Sediment Yield

The sediment delivery ratio (SDR) denotes the ratio of the sediment yield at a given stream cross section to the gross erosion from the watershed upstream from the measuring point (Julien, 1998). To generate the sediment yield at the outlet, empirical equations were carried out.

SDR = $A^{-0.2}$……………………………………………………………………...Equation (4)

Where, SDR denotes the sediment delivery ratio and area of the watershed. The SDR physically means the ratio of the sediment routed to the outlet over the watershed, both overland and channel.

Sediment yield is commonly estimated by the following empirical formula:

Sy=E*(1/$A^{0.2}$) ....Equation (5)

Where, S_y= Sediment yield (ton) at the watershed out let; E = total erosion (ton); A = watershed area (ha)

3. RESULTS AND DISCUSSION

3.1 Rainfall Erosivity Factor

Soil loss is closely related to rainfall partly through the detaching power of raindrops striking the soil surface and partly through the contribution of rain to runoff (Morgan, 1994). 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 average annual rainfall of the watershed is approximately 1900 mm. The result showed that rainfall erosivity factor (R-factor) value in the watershed ranged between 1059.68 MJmm $ha^{-1}yr^{-1}$.

3.2 Soil Erodibility Factor

The erodibility of a soil is an expression of its inherent resistance to particle detachment and transport by rainfall. It is determined by the cohesive force between the soil particles, and may vary depending on the presence or absence of plant cover, the soil's water content and the development of its structure (Wischmeier and Smith, 1978). The soil erodibility factor (K) represents the effect of soil properties and soil profile characteristics on soil loss (Renard *et al*., 1997). Erodibility depends essentially on the amount of organic matter in the soil, the texture of the soil, the structure of the surface horizon and permeability (Robert & Hilborn, 2000). The results indicated that soil erodibility value in the study watershed ranged from 0.10 Mgh MJ^{-1} mm^{-1} to 0.15 Mgh MJ^{-1} mm^{-1} (table 3 and figure 6).

Table 4: Soil Erodibility Factor

Soil type	K-value	Area	
		ha	%
Dystric Fluvisols	0.1	729.9	59.6
Dystric Gleysols	0.15	65.0	5.3
Dystric Nitosols	0.15	145.5	11.9
Orthic Acrisols	0.15	285.2	23.3
Total		1225.6	100

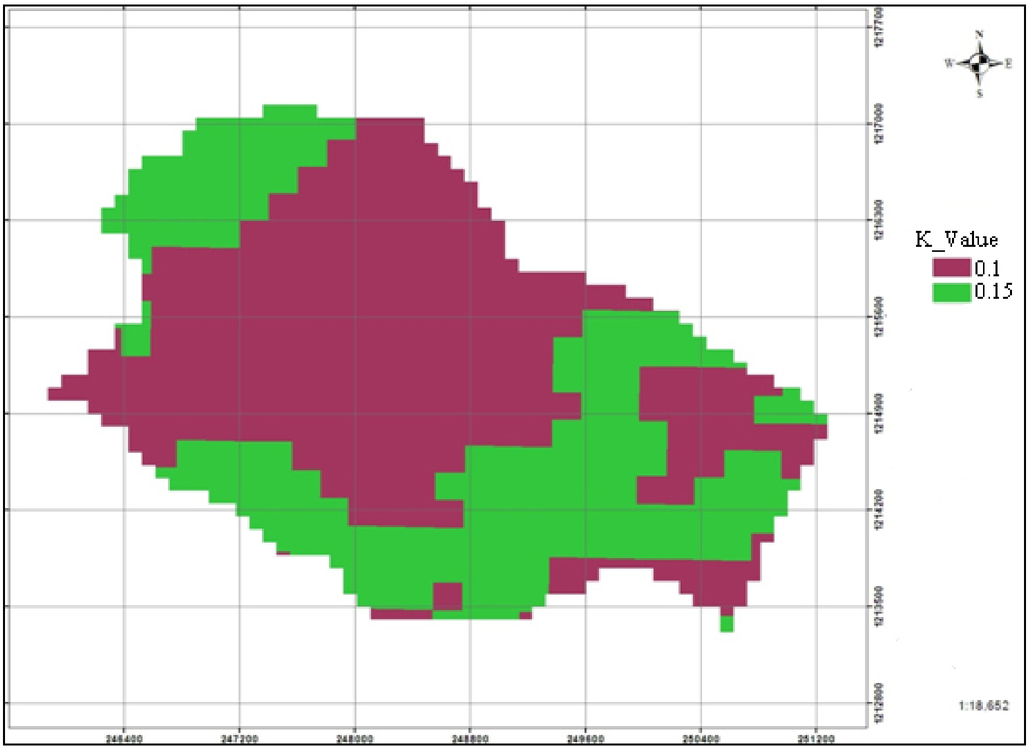

Figure 9: Soil Erodibility Factor Map

3.3 Slope Length and Slope Steepness Factor

The influence of topography on erosion is complex. The local slope gradient (S sub-factor) influences flow velocity and thus the rate of erosion. Slope length (L sub-factor) describes the distance between the origin and termination of inter-rill processes. In RUSLE, the LS factor represents a ratio of soil loss under given conditions to that at a site with the "standard" slope steepness of 9% and slope length of 22 m plot (Robert & Hilborn, 2000). The steeper and longer the slope, the higher is the erosion. Some researchers have argued that upslope drainage area is a better parameter when describing the influence of slope length on erosion, not slope length (Desmet &

Govers, 1996). The upslope drainage area for each cell in a DEM was calculated with multiple flow algorithms. The steepness factor value in the study watershed varies from 0.5 to 4.8 (Figure 7). As slope length increases, total soil erosion and soil erosion per unit area increase due to the progressive accumulation of runoff in the down slope direction. The slope length and slope steepness can be used in a single index, which expresses the ratio of soil loss as defined by (Wischmeier and Smith 1978).

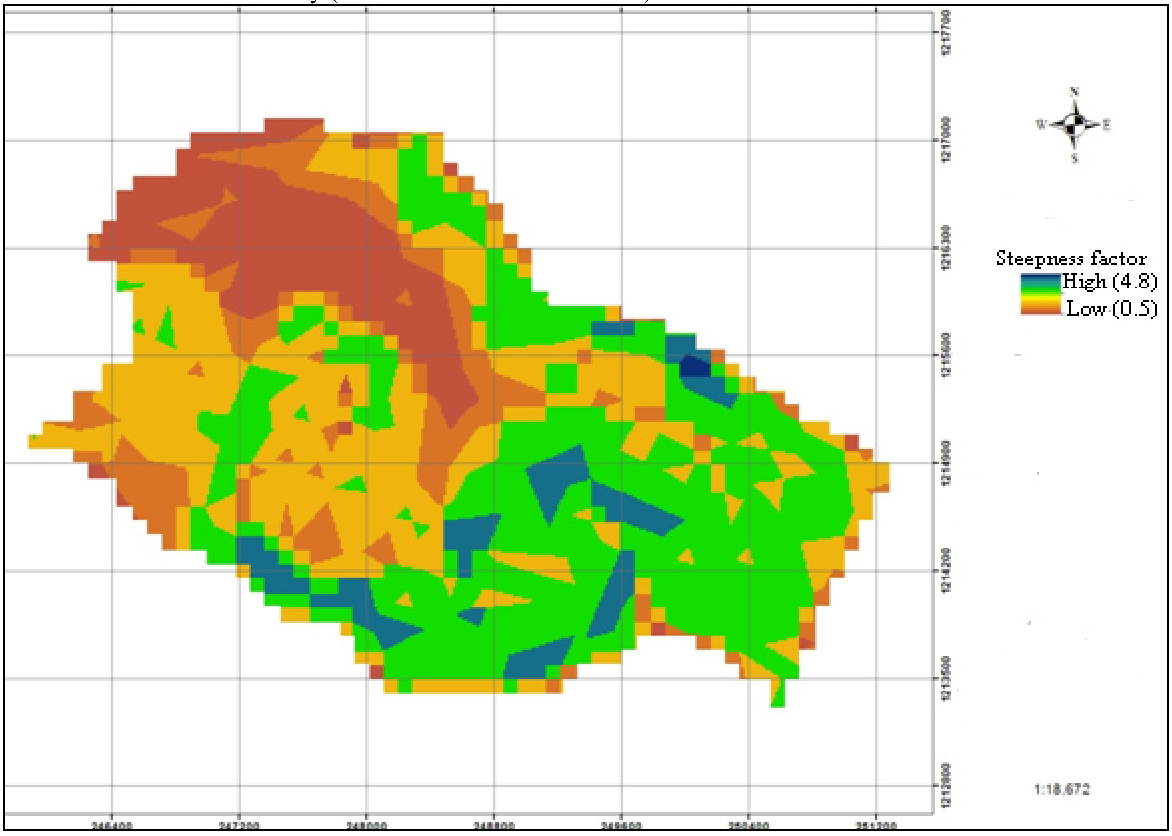

Figure 10: Steepness Factor Map

3.4 Land Use and Land Cover and Crop Factor

The attribute and spatial information on the present status of land use/land cover is a pre-requisite to identify and prioritize areas for soil conservation measures and minimizing further land degradation. The C- value is a ratio comparing the soil loss from land under a specific crop and management system to the corresponding loss from continuously fallow and tilled land. It represents the ratio of soil loss under a given crop to that of the base soil (Morgan, 1994). It measures the combined effect of cropping and management practices in agricultural system and the effect of ground cover, tree canopy and grass covers in reducing soil loss in non-agricultural condition (Wischmeier and Smith, 1978). It also reflects the effect of cropping and management practices on the soil erosion rate (Renard, Foster, Weesies, McCool, and Yoder, 1997). As shown in Table 4 and Figure 8, four land-use and land-cover classes were recognized in the watershed, dominantly by crop cultivation (39.2%). Crop management C factor values of the study watershed were ranging from 0.01 to 0.20 similar with the work of Morgan (2005).

Table 5 : Cover Management (C) Factor values of the study area

Land cover type	C-value	Area	
		ha	%
Cultivated Land	0.15	480.4	39.2
Grass Land	0.05	192.5	15.7
Forest	0.01	456.5	37.3
Shrub Land	0.20	96.1	7.8
Total		1225.6	100.0

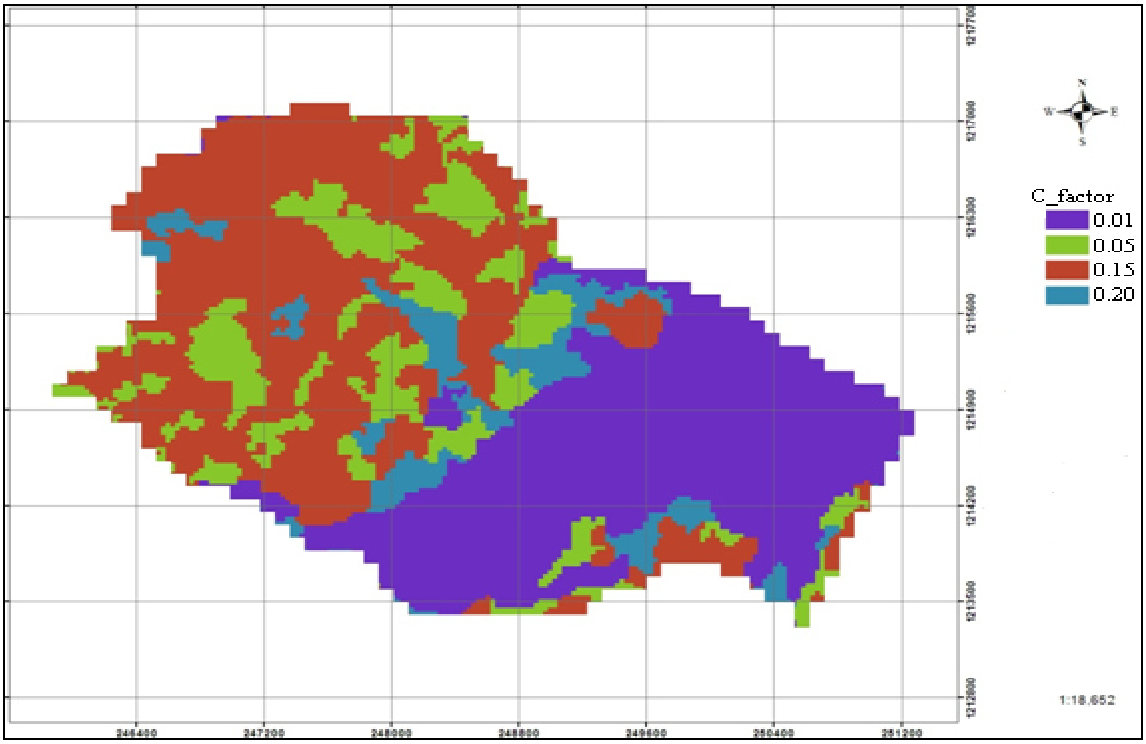

Figure 11: Derivation of Cover Factor from Cover Type

3.5 Management Practice Factor

The conservation practices factor (p-values) reflects the effects of practices that will reduce the amount and rate of the water runoff and thus reduce the amount of erosion. It depends on the type of conservation measures implemented and requires mapping of conserved areas for it to be quantified. In the study area, there is only a small area that has been treated with terracing through the agricultural extension programme of the government. As data were lacking on permanent management factors and there were no management practices, I used the P-values suggested by Bewket and Teferi (2009), Wang and Sun (2002). Thus, the agricultural lands are classified into six slope categories and assigned P-values while all non-agricultural lands are assigned a P-value of 1.00 (Table 5 and Figure 9).

Table 6: Land Management Factor (P) values

Land use type	Slope (%)	P-factor	Area	
			ha	%
Cultivated Land	0-5	0.1	167.8	13.7
	5-10	0.12	114.7	9.4
	10-20	0.14	165.2	13.5
	20-30	0.19	25.5	2.1
	30-50	0.25	7.2	0.6
	50-100	0.33	0.1	0.0
Other land use	All	1	745.1	60.8
Total			1225.6	100

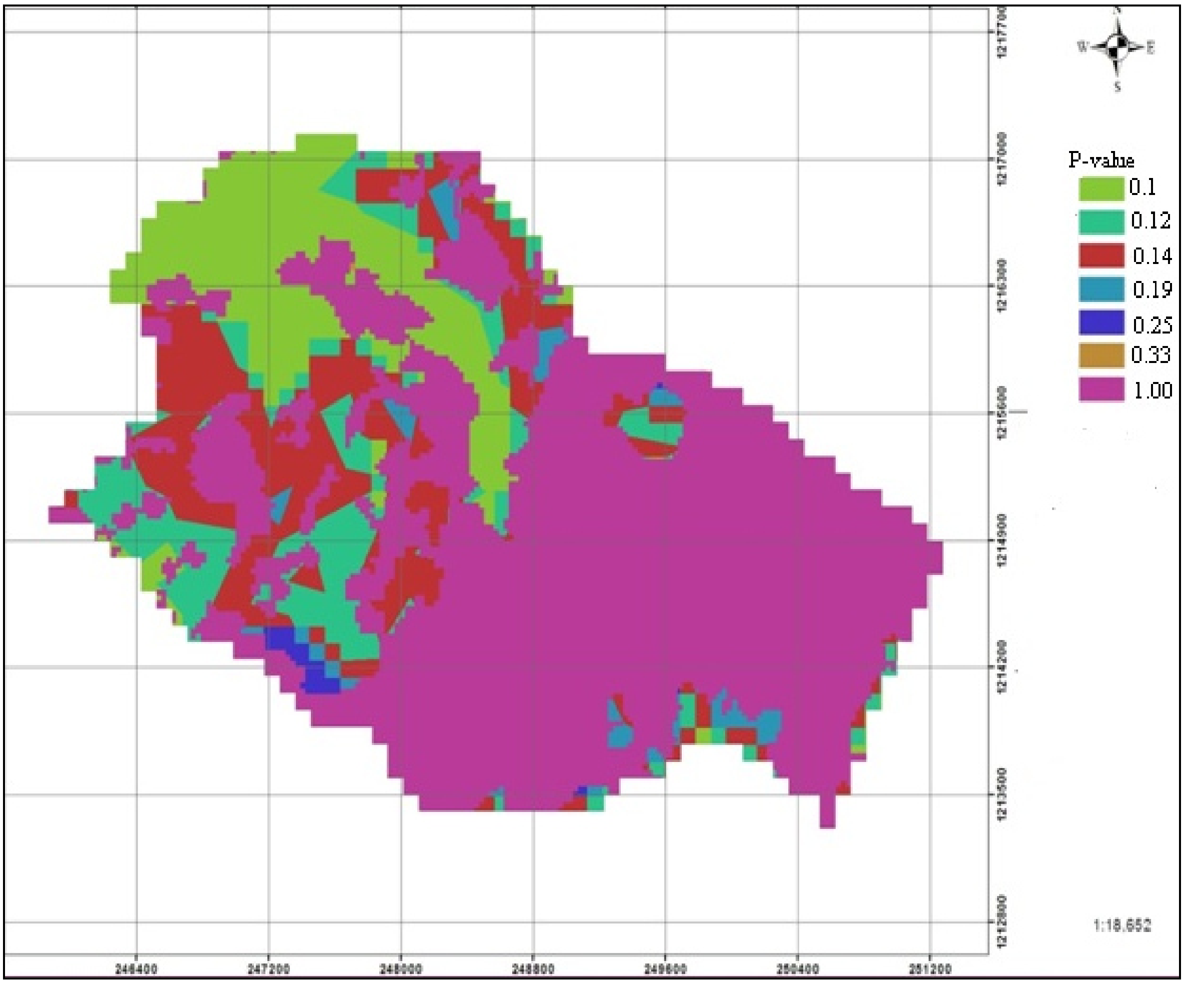

Figure 12: Derivative of Management Factor from Land Cover and Slope

3.6 Soil Loss Estimation and Prioritization for Soil Conservation Planning

The Revised Universal Soil Loss Equation (RUSLE) has been used widely all over the world (Mellerowicz, Ress, Chow and Ghanem, 1994) including Ethiopia (Kaltenrieder, 2007; Bewket and Teferi, 2009) because of its simplicity and limited data requirement. The advent of geographical information system (GIS) technology has allowed the equation to be used in a spatially distributed manner because each cell in a raster image comes to represent a field-level unit. Even though the equation was originally meant for predicting soil erosion at the field scale, its use for large areas in a GIS platform has produced satisfactory results (Mellerowicz, Ress, Chow and Ghanem, 1994; Renard, Foster,Wessies and Porter, 1994). By delineation of watersheds as erosion prone areas according to the severity level of soil loss, priority is given for a targeted and cost-effective conservation planning (Kaltenrieder, 2007; Bewket & Teferi, 2009).

Based on the analysis, the soil loss potential of the study watershed was about 41,424.07 ton per year. Large portion of the watershed (38.5%, 471.6 ha) was categorized none to slight class which under SLT values ranging from 5 to 11 tons $ha^{-1}yr^{-1}$ (Renard, Foster, Weesies, McCool and Yoder, 1996). The remaining 56.2% (689.4 ha) of land was classified under moderate to high class about several times the maximum tolerable soil loss (11 tons ha^{-1} y^{-1}) (Table 6 and Figure 10). Mati, Morgan, Gichuki, Quinton, Brewer and Liniger (2000) estimated average soil loss from croplands in the highlands of Ethiopia as a whole at 100 metric tons $ha^{-1}yr^{-1}$. In the highlands of Ethiopia and Eritrea soil losses are extremely high with an estimated average of 20 metric tons $ha^{-1}yr^{-1}$ (Hurni, 1985) and measured amounts of more than 300 metric tons $ha^{-1}yr^{-1}$on specific plots. Hurni (1993) estimated mean soil loss from cultivated fields as 42 metric tons $ha^{-1}yr^{-1}$. The average annual soil loss estimated by USLE from the entire Gerdi watershed, northwestern Ethiopia was 33.80 ton/ha/yr. Thus, the estimated soil loss rate was generally realistic, compared to results from previous studies.

Table 7: Soil Loss Summary of the Watershed

Soil loss rating and class			Area	
ton/ha/yr	mm/yr*	class	ha	%
0-5	0-0.5	Non to slight	65.1	5.3
5-15	0.5-1	Non to slight	471.6	38.5
16-30	1-2.5	Moderate	409.7	33.4
31-50	2.5-4	Moderate	118.6	9.7
51-100	4-6.5	High	84.4	6.9
101-200	6.5-16.5	High	38.5	3.1
>200	>16.5	Very High	38.2	3.1
Total			1225.56	100

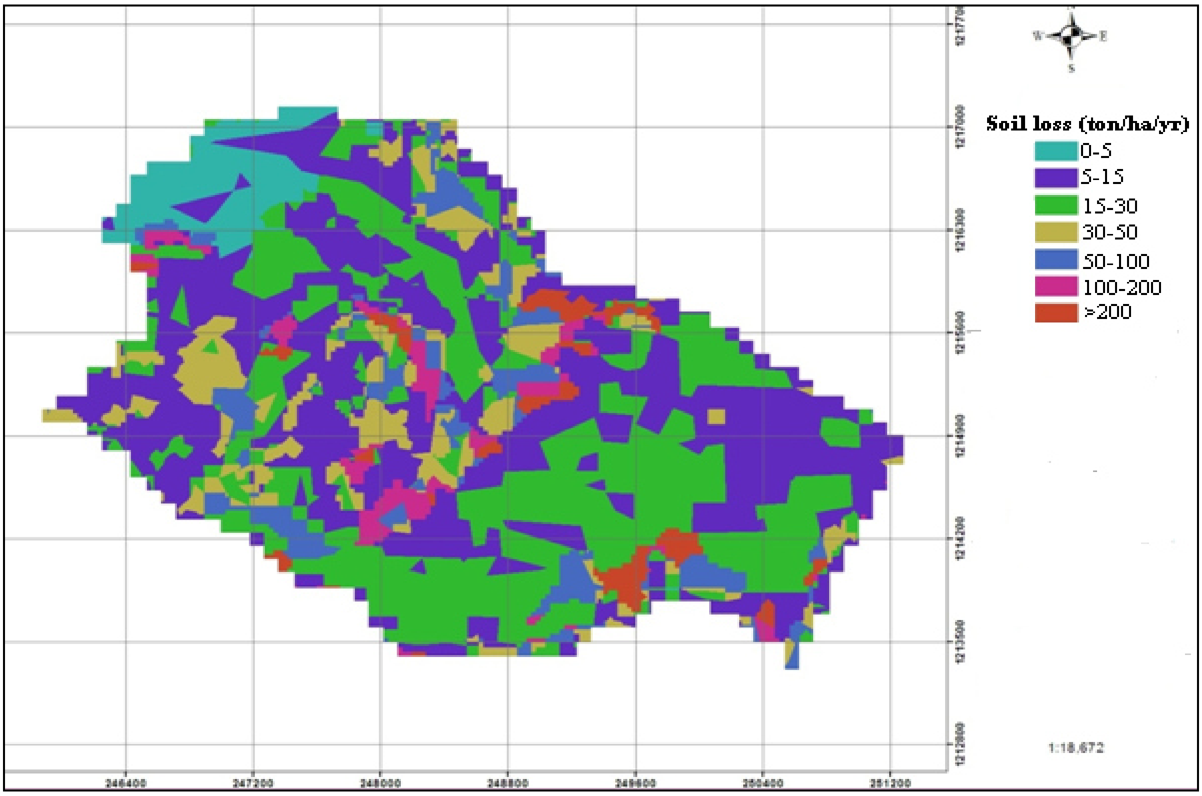

Figure 13 : Soil Loss Map of the Watershed

3.7 Sediment Yield

Similar to the soil losses, sediment yields were also very high at the out let of the watershed. The transporting ability of the runoff to move all the eroded sediments was insufficient. As a result deposition occurs in reservoirs, depressions, at the toe of the hills where changes slope. Thus, the amount of erosion in the watershed was generally more than the amount of sediment leaving the watershed at the outlet point. The most common method for estimating sediment yield is sediment delivery ratio ($1/A^{0.2}$), which is developed from reservoir survey, or measurement of suspended and bed loads at the gauging station and compared with that of erosion in the watershed.

S_y = 9990.46 tons per year

4. CONCLUSIONS AND RECOMMENDATIONS

The predicted amount of soil loss and sediment yield could facilitate comprehensive and sustainable land management through conservation planning for the watershed. Areas characterized by high to very high soil loss should be given special priority to reduce or control the rate of soil erosion by means of conservation planning. The study demonstrates that the RUSLE together with GIS and RS provides great advantage to estimate soil loss rate over areas though the input parameter values need to be calibrated to the specific area.

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