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Full Length Research Paper

Landscape–scale Soil Erosion Modeling and Risk Mapping of Mountainous areas in Eastern Escarpment of Wondo Genet Watershed, Ethiopia

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Abstract

Soil erosion is a common phenomenon in Ethiopia, causing severe land degradation and/or desertification, especially in the dryland areas of the country. It is more acute in the highland areas, and is often associated with heavy loss in agricultural productivity. Cognizant of the severity of soil erosion and its impact, it is necessary to undertake appropriate management measures before it is too late. The *Abaro–medeo* area, a mountainous landscape in Wondo Genet Watershed, is among the highland erosion–prone areas in Ethiopia which received little conservation attention while soil loss from erosion is expectedly higher. A study was, thus, initiated to develop a landscape–based soil erosion model and show the risk level of the area, which could be an input for further sustainable management measures. The study employed RUSLE model together with GIS to develop soil erosion model. Based on the level of soil erosion rates, seven different priority categories were identified for further conservation interventions. The results show that nearly 39% of the study area suffer from a severe or very severe to extremely severe erosion risk (contributing to about 81% of the annual soil loss), mainly in the steeper slope banks of drainage areas where inappropriate cultivation practices occur, and in areas that are covered with sparse vegetation. The total annual soil loss potential of the study area was estimated at 64,014 tons from an area of 2,472 hectares. This urges for timely and integrated conservation endeavors from all stakeholders by taking the priority areas into the forefront.

Keywords: GIS, RUSLE, Soil Erosion, Soil Conservation

INTRODUCTION

Soil erosion is one of the biggest global environmental hazards causing severe land degradation. Population explosion, deforestation, unsustainable agricultural cultivation, and overgrazing are among the main factors causing soil erosion hazards (FAO, 1990; Reusing *et al.*, 2000). Soil erosion is more acute in tropical areas where rainfall is more intense and soils are highly erodible due to the relatively shallow depth and low structural stability of the soil (Eaton, 1996). Through its effect on soil fertility and productivity, soil erosion is often associated with heavy loss in agricultural productivity (Morgan, 2005). According to FAO's (2000) prediction, if soil losses continue unchecked in Africa, the potential rain-fed crop production will decline by about 15% in the next two decades.

In Ethiopia, soil erosion, its severity being pronounced in the highland areas of the country, has long been a serious problem in Ethiopia; often associated with widespread ecological and socio-economic damage (Abate, 2011). It has been estimated that out of the estimated 60 million ha of agriculturally productive land, about 27 million ha are significantly eroded, 14 million ha are seriously eroded and 2 million ha have reached the point of no return, with an estimated total loss of 2 billion cubic meters of top soil per annum (Fikru, 1990). Soil erosion affects about 50% of the agricultural area and 88% of the total population of Ethiopia (Sonneveld, 1999). The average crop yield from a piece of land in Ethiopia is very low according to international standards mainly due to soil fertility decline associated with removal of topsoil by erosion (Sertu, 2000). This upper part of the soil removal always implies nutrient loss, loss of water by runoff, reduction of rooting depth, and water and nutrient storage capacity and sooner or later reduced crop production (Abate, 2011). As per to Taddese's (2001) report, Ethiopia loses over 1.5 million metric tons of soil each year from the highlands by erosion resulting in the reduction of about 1.5 million metric tons of grain from the country's annual harvest.

Cognizant of the severity of soil erosion and its impact, it is necessary to undertake appropriate management measures before it is too late. Prior to applying conservation measures, assessment and delineation of erosion–prone areas is vital for conservation prioritization. Modeling of soil erosion potential provides several insights such as which area is first conserved based on the severity level of soil loss with the interactions among erosion factors. The *Abaro–medeo* area, a mountainous landscape in Wondo Genet watershed, is among the highland erosion–prone areas in Ethiopia, which received little conservation attention while soil loss from erosion is expectedly higher. As a result, the study was initiated to assess soil erosion potential of the area, which could serve as an input for further sustainable management endeavors.

Various models, including the Revised Universal Soil Loss Equations (RUSLE), the Water Erosion Prediction Project (WEPP) and the European Soil Erosion Model (EUROSEM) can be used to predict soil erosion of a given area. However, the RUSLE is the most widely accepted and used model as it consists of relatively simpler response functions calibrated to fit limited numbers of statistical observations, unlike to the other models which require complex field measurements and applied only for geographically limited areas. The RUSLE model integrated with geographic information system (GIS) is reported as an important tool to estimate soil loss and facilitate sustainable land management through conservation planning (Abate, 2011). The same author has recommended this method of soil erosion modeling to be applied in various parts of Ethiopia as it ensures an efficient use of limited resources. Therefore, the study employed RUSLE model together with GIS to develop soil erosion model for the *Abaro–medeo* landscape. The objective of the study was to develop a landscape–based soil erosion model and show the risk level of *Abaro -medo* area, and thereby pointing out priority areas for further conservation measures.

MATERIALS AND METHODS

Description of the study area

The study was conducted in eastern escarpment of Wondo Genet catchment, in *Abaro-Medeo* mountainous area (7^{o}7'30" N to 7^{o}10'30" N and 38^{o}35'0" E to 38^{o}39'30" E) (Figure 1) in southern Oromiya Region, where severe land degradation incidences resulted mainly from soil erosion are evident. The study area covers a total surface area of 2,472 hectare. There are about three different sub districts in the study area, namely *Dida Boke, Medo* and *Ebecha*. Luvisols, nitosols, phaeozems, and vertisols are the major soil types.

The agro-climatic zone of the area is characterized by a 'tropical highland monsoon'. The area has a bimodal rainfall pattern (June to September), with a total rainfall ranging between 860.19mm and 167.6mm. On average 80% of the total annual precipitation occurs between June and September, with the highest mean totals in July (449mm.), and the rest during autumn (Figure 2). Temperature of the area shows large diurnal but small seasonal changes with an annual average of 20 ℃.

Undulating topography dominates most of the study area except to the south east where hilly mountain chains are apparent. The elevation (as derived from digital elevation model) ranges between 1830 m.a.s.l (far west) and 2531m.a.s.l (Far East). Most of the plain areas are dominantly agricultural lands, where some *ficus sp*, *acacia sp* and *eucalyptus* are scattered along the farm plots. Alongside *Abaro* Mountain, the hillside areas are covered dominantly with *Cupresus lustanica* and *Eucalyptus* plantations. The livelihood of the local people is mainly based on subsistence mixed agriculture.

Data Source

To come up with suitable landscape-level soil erosion model and thereby suggest possible conservation interventions, various bio-physical and climatic data types were subjected to quantitative assessments and brought to the GIS environment. Data collection considered precipitation data, topography, remote sensing data, vegetation cover and soil types using field sample plots measurements. The field inventory was conducted using strata-delineated sampling with the aid of GPS. Digital Elevation Model (DEM) was used to analyze slope length and slope gradient (LS), whereas the Land sat ETM+ was used to analyze and obtain the cover management factor (C). After analysis, each data was interpolated using IDW (Inverse Distance Weighting). IDW was used for it showed no significant variation between the actual processed result and the result after being interpolated.

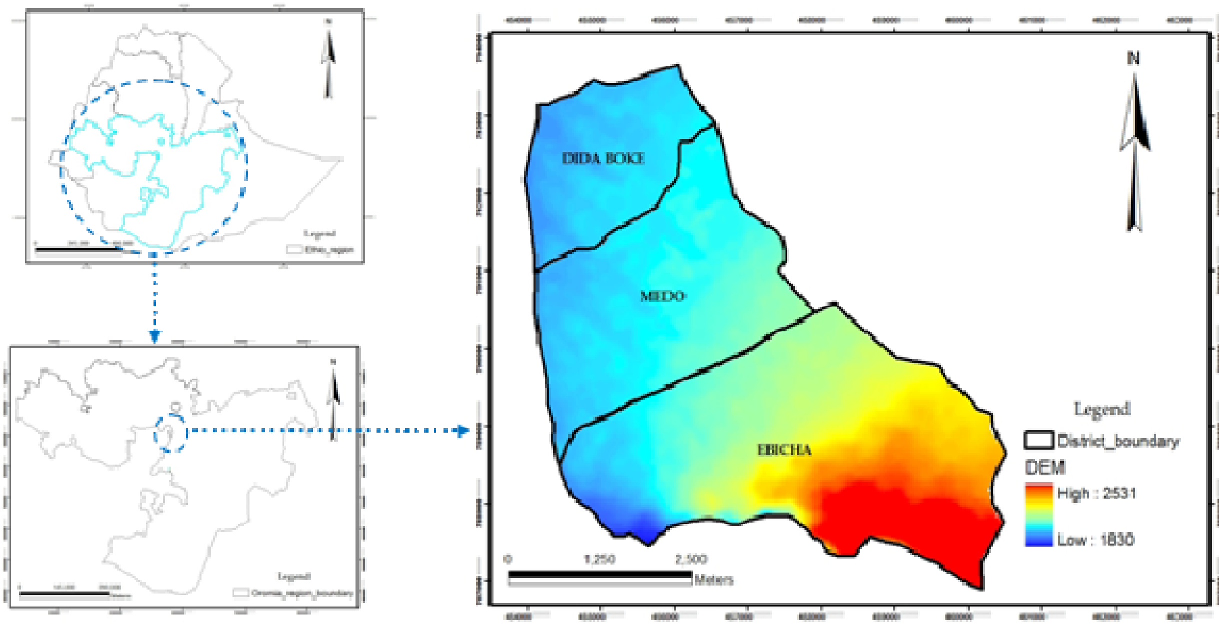

Figure 1. Location of the study area

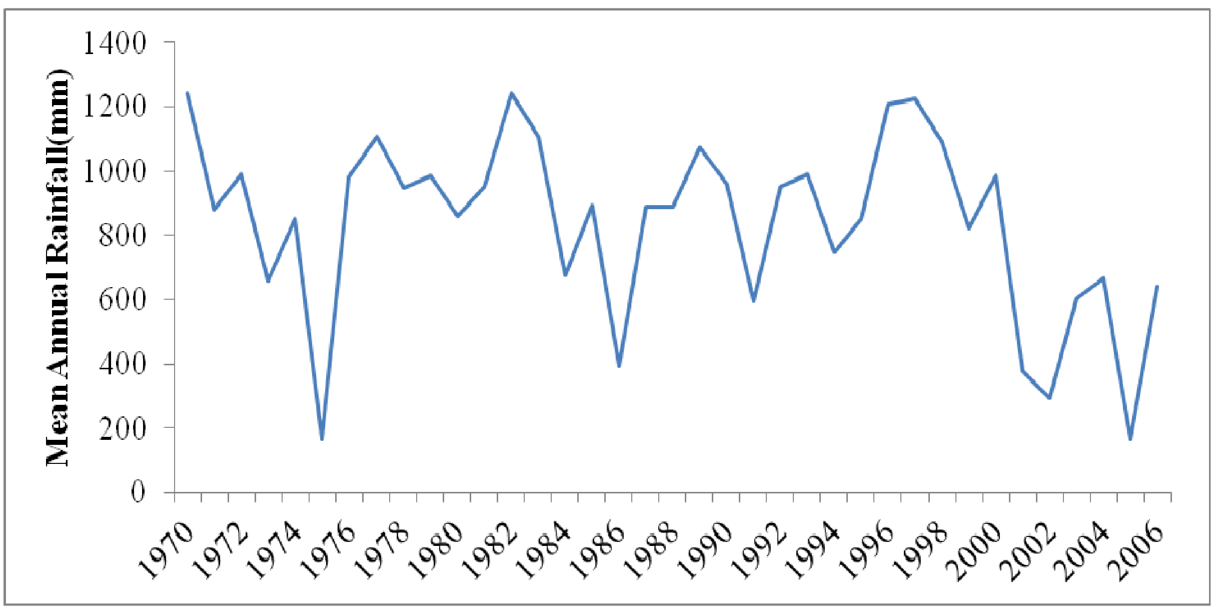

Figure 2. Mean annual rainfall distribution (1970 – 2006)

Methods of data collection and analysis

RUSLE developed by Morgan (2005) was applied to determine soil loss in the study area. The equation is given as:

E = R*K*L*S *C*P …………………………………. eq. (i)

Where: **E** is the mean annual soil loss; **R** is the rainfall erosivity factor; **K** is the soil erodibility factor; **L** is the slope length factor; **S** is the slope steepness factor; **C** is the crop management factor; and **P** is the erosion-control practice factor. Figure 3 shows the flow chart of the processes employed to develop the model.

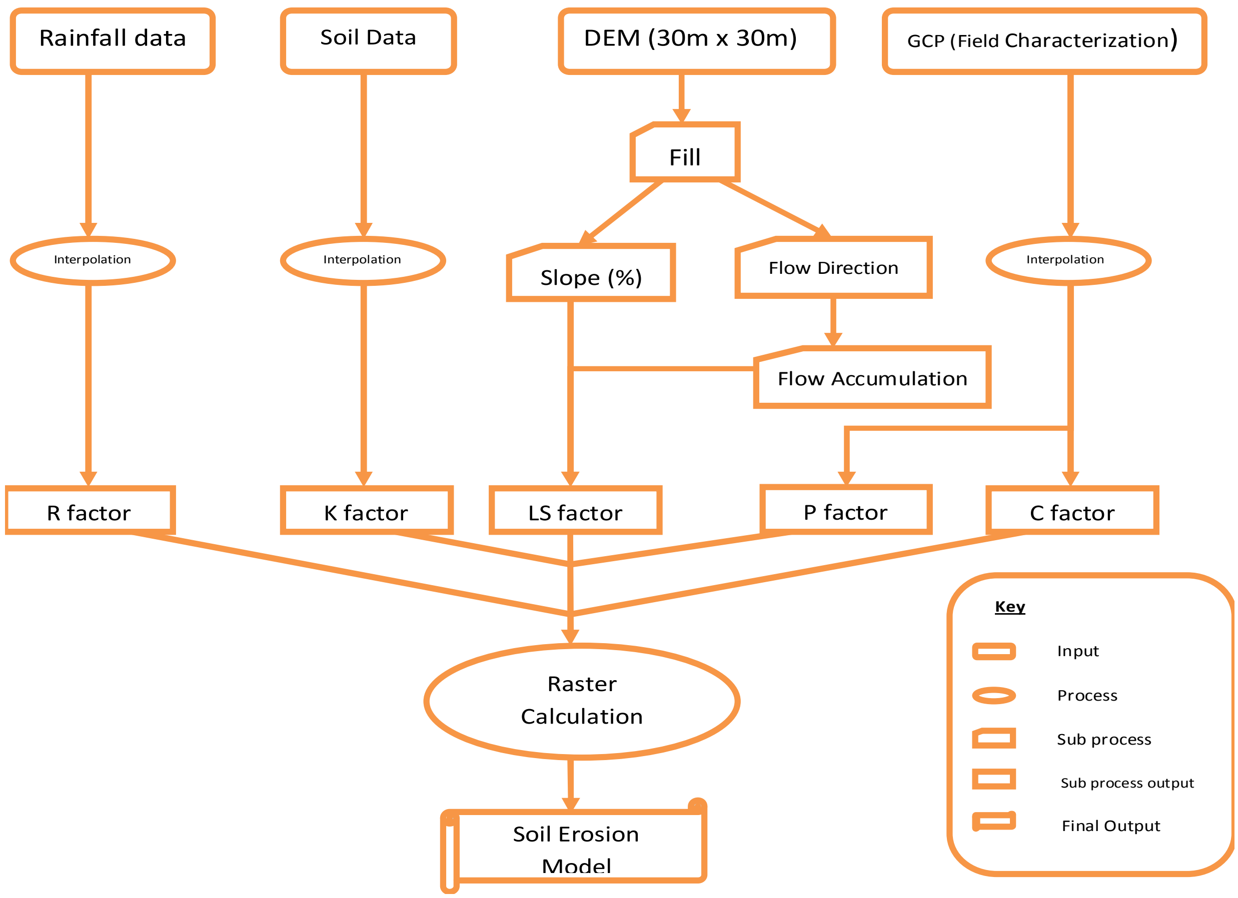

Figure 3. Flow chart showing the GIS based processes to get the final Soil erosion model

(a) Erosivity Factor(R)

Erosivety, which is expressed as the ability of the rainfall to cause soil erosion is calculated by multiplying the total kinetic energy of a rainfall event with its maximum 30-minute intensity (Brown and Foster, 1987). However, one of the problems of developing R-factor values using this method is that it is difficult to calculate the maximum 30 minute intensity because it may not always be available. To overcome such difficulties, Renard and Freimund (1993) developed the following equations:

$R = 0.0048P^{1.61}$……………………………………eq. (ii)

$R = 0.074F^{1.85}$……………………………………..eq. (iii)

Where: R = rainfall and runoff factor ($10^{-2}Nh^{1}yr^{-1}$) (N is Newton force)

P = annual precipitation (mm)

F = Fournier (1960) index (mm) which expressed as $= \sum_{i=1}^{12} {p_i}^2/p$

P_i = Monthly precipitation (mm)

Since these authors didn't make any specification about the geographic areas for which these relations might best be applied; equation (iii) was randomly selected and used to determine the R-factor. Rainfall data from Shashemene town was used to derive the R for the study area (Figure 4). This is due to the fact that the study area is found in a great proximity to the metrological station and availability of a complete 36 years rainfall data record. The 36 years annual average rainfall record was used to estimate Fournier index, from which the Erosivity (R) factor was derived, and was estimated to be **264.68.**

(b) Erodibility Factor (K)

Erodibility, described as resistance of soil to both detachment and transport, is known to vary with soil texture, aggregate stability, shear strength, infiltration capacity, and organic and chemical content (Morgan, 2005). K could be predicted using regression equations, describing relationships between K and soil chemical and physical properties. An equation (eq. iv), which describes the relationship between K and soil physical properties,

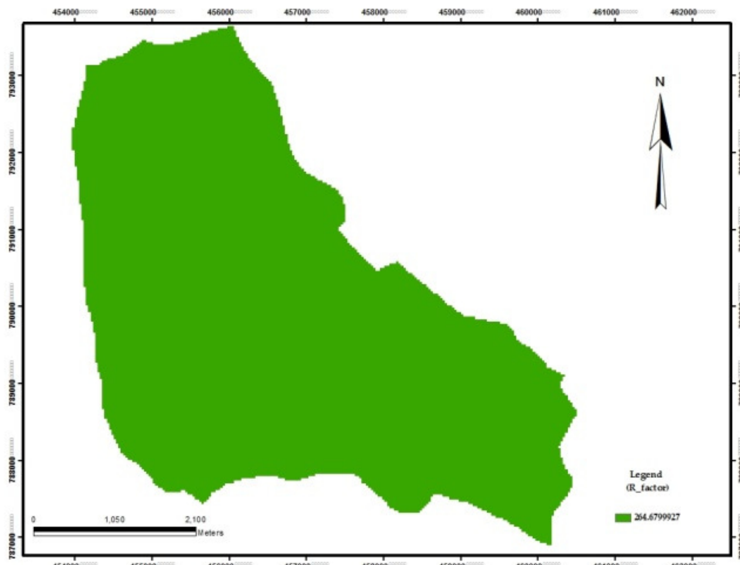

Figure 4. R_factor

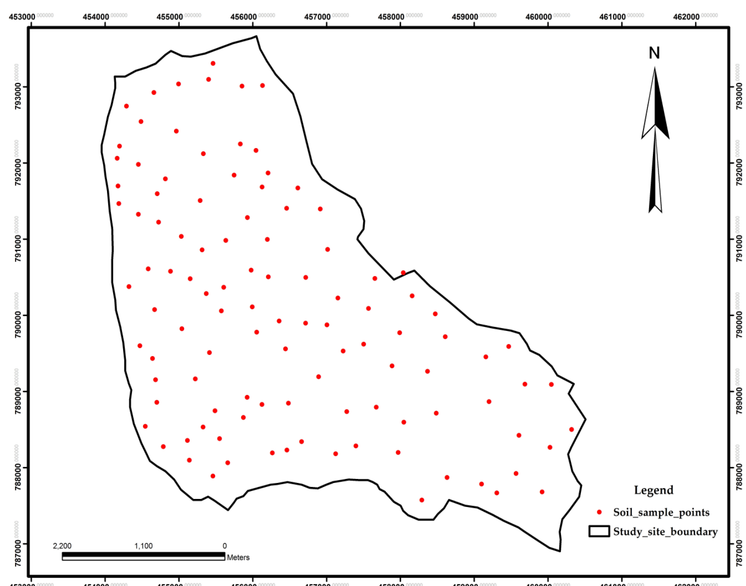

Figure 5. Soil sampling points

has been developed by Wischmeier *et. al.* (1978), and is shown below:

$K = 2.1*10^{(-6)*}M^{1.14}*(12\text{-}OM) + 0.025(s-3) + 0.0325(p-2)$ …………………eq. (iv)

Where: k = Soil Erodibility (t.h/MJ.m)

M = (%very fine sand +%silt)*(100-%clay)

OM = Organic Mater

S = Soil structure Cod

P = Permeability Cod

Soil samples (from a depth of 30cm) were taken from 107 distributed pits (Figure 5) and analyzed in laboratory to estimate the percentage of very fine, sandy, silt, clay and organic matter. Then, both soil structure cod and permeability cod were indentified based on the textural classes. Accordingly, the K_factor was developed (Figure 6).

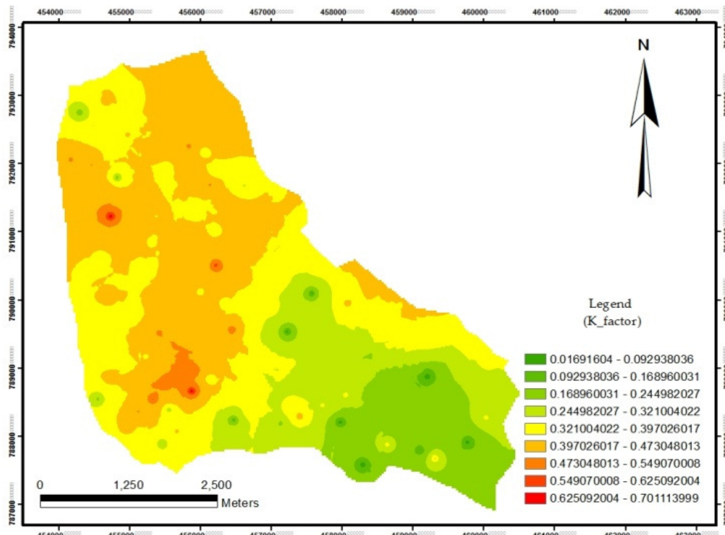

Figure 6. K_factor

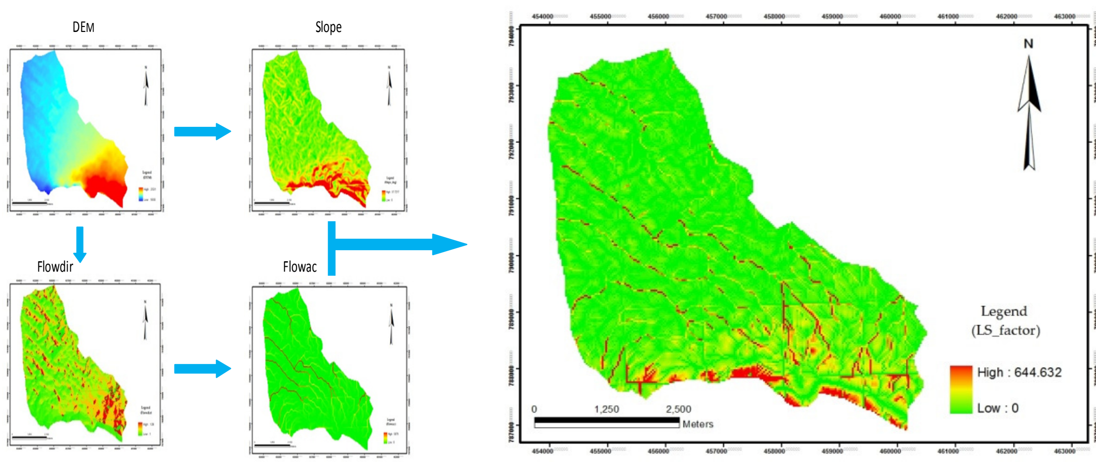

Figure 7. LS_factor

(c) Slope length and slope steepness factor (LS)

LS factor is the combination of slope length and slope steepness and expresses the ratio of soil loss under a given slope steepness and slope length to the soil loss from the standard condition of a 5° slope, 22 m long, for which LS = 1.0 (Morgan, 2005). In executing the RUSLE, the L and S factors are combined into the LS factor. The LS factor can be measured directly in the field or from USGS quadrangle maps, or can be generated from DEM. During the LS-factor derivation, DEM of 30m resolution was masked by the study area and both Slope (in %) and Flow accumulation were calculated using the spatial analyst tool of ArcGIS. Both the calculated slope and Flow accumulation were brought together under Raster calculator function, using the formula below, and used to generate the LS-factor of the study area (Figure 7).

LS=1.6 * Pow(([Flow accumulation] * 30) / 22.1, 0.6) * Pow(Sin([slope_percent] * 0.01745) / 0.09, *1.3)* ………………………………………………………….. eq. (v)

(d) Crop Management factor (C)

The crop management factor represents the ratio of soil loss under a given crop to that from bare soil (Morgan, 2005). The soil loss ratios used to calculate the c-factor (Figure 8) are perhaps the most important terms in RUSLE because they represent conditions that can be managed most easily to reduce erosion.

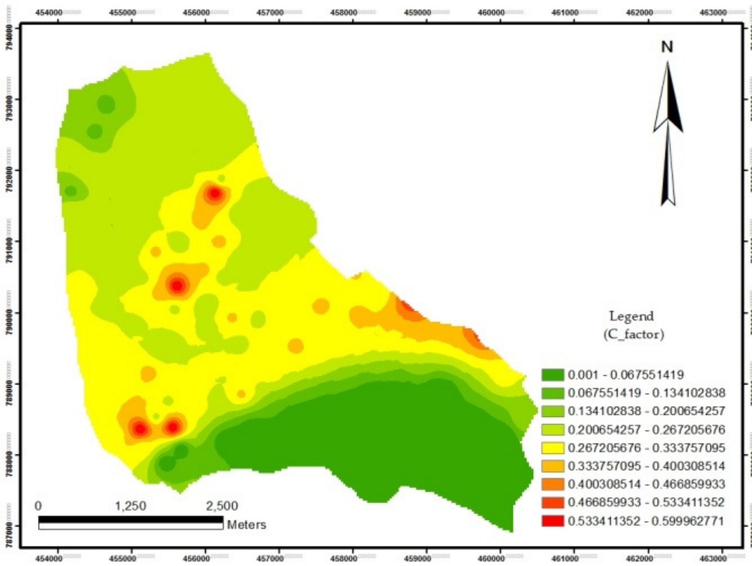

Figure 8. C_factor

Table 1. Major Land cover types of the study area long with their dominant crop and plantation species and their c-values.

Land use	Cover type	C-Value
Agricultural land	Maize	0.2
	Potato	0.25
	Teff	0.25
	Cowpea road side	0.3
	Cultivated land_boloke	0.6
Plantation Forest	Eucalyptus plantation coppice with grass cover	0.001
	Plantation forest_*Cupresus lustanica*	0.001
	Plantation forest_*Eucalyptus*	0.001
	Plantation forest Eucalyptus coppice and shrub land	0.001
Grass land	Grass	0.1
	Road side open land	0.1

C-value (Table 1) has been estimated according to the cover type of the study area and associate values given by Morgan (1986 and 2005). The study area covered three basic land use types: agricultural land, Plantation forest and grass land.

(e) Erosion Management Practice Factor (P-Value)

According to Morgan 2005, P_Values for the erosion-control practice factor are obtained from the ratio of soil loss where the practice is applied to the soil loss where it is not. With no erosion-control practice, P = 1.0. Values may vary based on cover contouring, contour strip-cropping and with the slope steepness. Therefore, based on slope steepness, the following P- values (Figure 9) were identified and mapped.

RESULTS

Soil Loss Potential

The RUSLE model (Equation I), created in the Arc-GIS, was used to generate a soil erosion risk map (Figure 10), which shows the spatial distribution of soil loss in the study area.

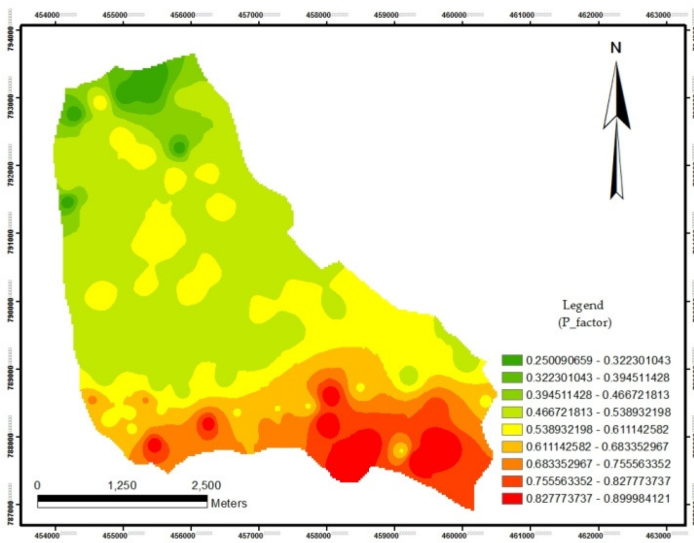

Figure 9. P_factor

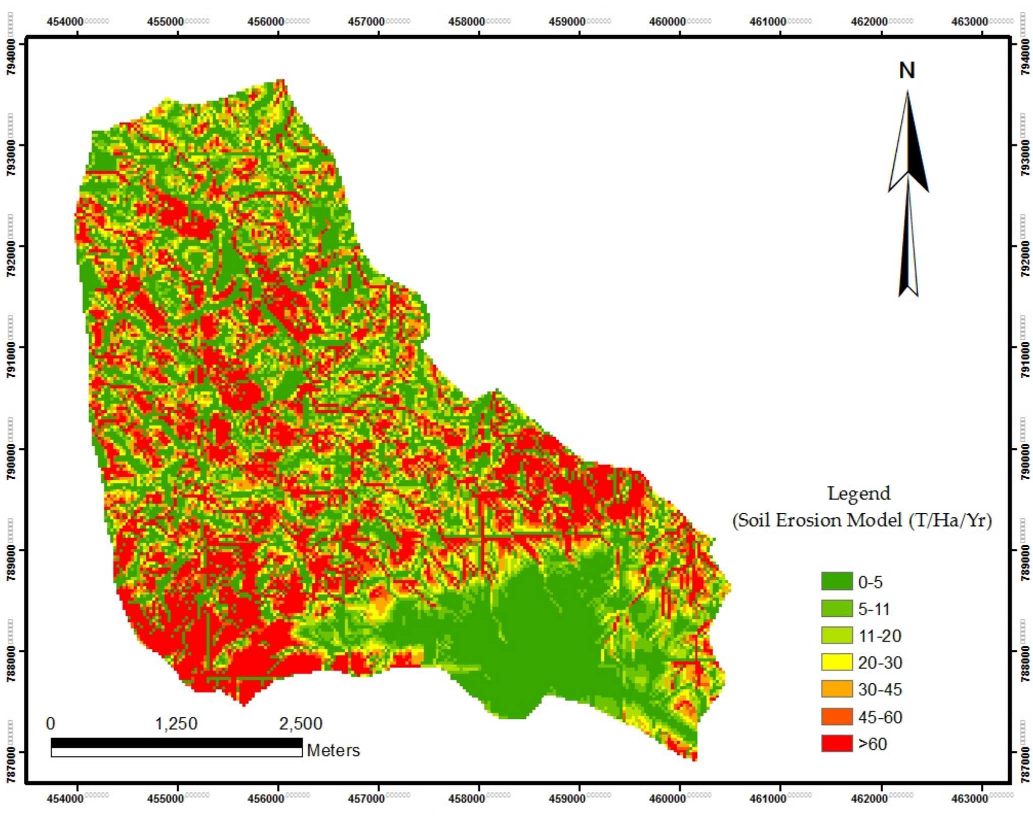

Figure 10. Soil Erosion Risk Map Showing RUSLE Classes Estimated for the Study Area

The soil loss rate map shows various soil erosion rates with an estimated soil loss ranging from 2.5 t/ha/yr in the plain areas and those covered with plantation forests, such as the *Cupressus lustanica* and *Eucalyptus* plantations, to a little over 60 t/ha/yr in the areas of agricultural lands, waterways and drainages. The total annual soil loss in the study area (from an estimated area of 2472 ha) was about 64014.345 tons. The average annual soil loss for the entire district was estimated at 26 t/ha/yr.

Table 2. Annual soil loss rates and severity classes with their conservation priority in the study area

Soil loss (t/ha/y)	Severity classes	Priority classes	Area (ha)	Total area coverage (%)	Total Annual soil loss (tons)	Soil loss (%)
0 – 5	Low	VII	927.27	37.50	2318.175	3.62
5 – 11	Moderate	VI	153.18	6.20	1225.44	1.91
11 – 20	High	V	209.16	8.50	3241.98	5.06
20 – 30	Very high	IV	208.26	8.40	5206.5	8.13
30 – 45	Sever	III	231.75	9.40	8690.625	13.58
45 – 60	Very Sever	II	160.29	6.50	8415.225	13.15
>60	Extremely Sever	I	581.94	23.50	34916.4	54.54
Total			2471.85	100.0	64014.345	100.00

Priority Areas for Conservation Planning

For the purpose of identifying priority areas for conservation planning, soil loss potential of the study area was first categorized into different severity classes following FAO's basis of classification (FAO & UEP, 1984), with some modifications to suit the features of the study area. The Soil Loss Tolerance (SLT) value was used as a basis for the categorization of the severity classes. The SLT denotes the maximum allowable soil loss that will sustain an economic and a high level of productivity (Wischmeier and Smith, 1978; FAO and UNEP, 1984; Gebreyesus and Kirubel, 2009). The normal SLT values range from 5 to 11 t/ha/yr (Renard *et al.,* 1996).

Accordingly, the study area was divided into seven different severity classes (Table 2). As shown in Table 2, about 43.70% of the study area is under SLT level having a total annual soil loss of about 3,543.615 tons. The remaining 1,391.40 ha of land, constituting of 56.3%, is classified under high to extremely severe class, with a total annual soil loss of 60470.73 tons. Nearly 81% of the soil is lost annually from 39.40% of the total area, which is categorized as severe (13.58%), very severe (13.15%) and extremely severe (54.54%).

DISCUSSION

The RUSLE model coupled with field observations revealed that majority of the mountainous landscape of *Abaro-Medeo* area is prone to soil erosion hazards. Results of the annual soil loss rates and the severity classes showed that more than half of the study area (56.3%) is classified under high to extremely severe class. As illustrated in the soil erosion risk map (Figure 10) and Table 2, variations are observed in the soil loss potentials over the entire study area; seven different soil erosion levels were identified. It is evident from the RUSLE model that variations in soil erosion rates are accounted to the interplay of its various components, such as the topography (LS factor), support practices (P factor) and cover parameters (C factor).

Areas under SLT level are found scattered in all over the study area, mainly in the *Dida Boke* and *Ebicha* sub-districts along the plain areas, and areas with better vegetation cover. The possible reasons for lower soil loss values are, thus, related mainly to the protective role of vegetation covers and the shortness of slope length. Others with high soil erosion rates are also found dispersed throughout the study area, but the severity of soil erosion rate is pronounced along with the steeper slope banks of tributaries, and agricultural land uses along steep slopes. Their topographic ruggedness and poor vegetation cover, together with the prevailing poor tillage and management practices contribute to the high rate of soil erosion in these areas. In agreement to our observation, high erosion potential land uses were reported from various cultivated and rugged terrains elsewhere in Ethiopian highlands (e.g. FAO, 1984; Tripathi and Raghuwanshi, 2003; Bewket and Teferi, 2009; Abate, 2011; Rabia, 2012; Bizuwerk et al., 2003).

As shown in Table 2, about 56.3% of the total study area, accounting for 94.46 % of the total soil loss, is highly affected by soil erosion. These areas have ranges of erosion severity classes of severe, very severe and extremely severe, where conservation priorities of the first (I), second (II) and third (III) order are required correspondingly with their order of severity for urgent implementation of different types of soil and water conservation measures. Specially, the extremely severe class was significant (cal.55%), which urges for appropriate conservation measures before the area is turned into level of irreversibility.

CONCLUSION AND RECOMMENDATIONS

Comparison to other studies in mountainous areas elsewhere in Ethiopia, the soil erosion risk map and the erosion severity classes generated using RUSLE mode integrated with the Arc-GIS 93.0 revealed that the *Abaro-Medeo* landscape is under considerable soil erosion potential putting severe challenges to the agricultural productivity. The total annual soil loss from the study area (an area of 2472 ha) was estimated at 64,014 tons. The entire study area was classified under seven different erosion severity classes. About 43.70% of the study area is under SLT level having; while the remaining 56.3% is classified under high to extremely severe classes, contributing about 94% of the total soil loss in the area. Majority of the study area (about 55%) is under extremely severe soil erosion rate which merits urgent conservation measures. In any further soil and water conservation interventions (be it physical or biological conservation), the active involvement of the local community is important and the priority classes identified need to be taken to the forefront. Improvements in the vegetation cover, tillage practices and other related management practices are also proposed.

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