

Soil Erosion Risk Assessment Using GIS Based USLE Model for Soil and Water Conservation Planning in Somodo Watershed, South West Ethiopia

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Abstract— Soil erosion is natural phenomena and is modified by biophysical environment comprising soil, climate, terrain, ground cover and their interactions. Due to different factors, it is difficult to make watershed management successful in all areas at one time. Because of this, prioritization of sub watershed is very important for soil conservation planning and implementation. In Somodo watershed more than five years different soil and water conservation technologies were implemented and satisfactory result was not recorded. In this aspect, it is important to consider further watershed management planning. This study therefore investigated soil erosion risk assessment using GIS and USLE model for soil and water conservation in Somodo watershed southwestern Ethiopia with the aim of estimating soil erosion rate and identify soil erosion hot spot areas through prioritization of sub watershed in Somodo watershed by the help of GIS based USLE model. Both primary and secondary data sources were used for model input. These data were computed at a grid level with 30*30m resolution and then overlaid to generate mean annual soil loss by the help of raster calculator in Arc GIS tool. Results of the study showed that, the mean annual soil loss of the watershed was 18.69 ton ha⁻¹ year⁻¹ ranging from 0 to 131.21. More than 75% of the watershed have soil loss greater than 20 ton ha⁻¹ year⁻¹ and only 25% of the area have soil loss less than 10 ton ha⁻¹ year⁻¹. On the bases of mean annual soil loss SW-4, SW-6 and SW-7 were under slight (0-10 ton ha⁻¹ year⁻¹) erosion severity level, while the remaining SW-2, SW-3 and SW-8 were under moderate (10-20 ton ha⁻¹ year⁻¹) level. And SW-1 was in high (20-30 ton ha⁻¹ year⁻¹) erosion severity level, where as SW-5 and SW-9 were found in very high (>30 ton ha⁻¹ year⁻¹) erosion severity level. Since large area of the watershed has soil loss more than tolerable level (11 ton ha⁻¹ year⁻¹) attention should be given to identify erosion hot spot areas to minimize the on-site and off-site problems. Therefore, the study suggested that for effective watershed management and soil conservation planning, these sub-watershed priorities should be used in the watershed.

Keywords— Soil loss, GIS, USLE, Hot spot and prioritization.

I. INTRODUCTION

Soil erosion is a major cause of land degradation that affects the physical and chemical properties of soils and resulting in on-site nutrient loss and off-site sedimentation of hydraulic structures in Ethiopia [1]. Lack of effective watershed management system and poor land use practices played significant role in land degradation in Ethiopian highlands [2]. According to the Ethiopian highland reclamation study [3], in the mid 1980's, 27 million hectare or almost 50% of the high land area was significantly eroded, 14 million hectare seriously eroded and over 2 million hectare were beyond reclamation.

Soil erosion is also a natural phenomena and modified by biophysical environment comprising soil, climate, terrain, ground cover and interactions between them. Important terrain characteristics influencing the mechanism of soil erosion are slope, length, aspect and shape. Impact of slope and aspect would play a major role in runoff mechanism. More the slope, more the runoff and thus infiltration reduces. The runoff generated from slope will find a path nearby and this would lead to erosion of soil as the velocity of the runoff increases [4]

Soil erosion models are useful to estimate soil loss and runoff rates from agricultural land, to plan land use strategies, to provide relative soil loss indices and to guide government policy and strategy on soil and water conservation. The universal soil loss equation (USLE), is one of the most popular empirical models [5] to estimate the long-term average annual rate of soil loss from small field having an average length of 22 m, a field slope of 9% based on rainfall pattern, soil type, topography, cropping system and management practices.

Most of the earlier models, such as the well-known Universal Soil Loss Equation (USLE) [5], were empirically derived. This is relatively simple technique to predict erosion, subsequently led to the application of empirical models in many parts of the world, including Ethiopia. Empirical models could be expected to be used mainly as screening tools in integrated studies,

land resource assessments would demand increased accuracy in quantification of erosion rates in a spatial and temporal context when integrated with Geographical Information System (GIS). They all consider slope steepness, slope length, vegetative cover, rainfall, soil properties and erosion control methods as parameters which influence erosion.

The efficient and optimum management and conservation of soil, land and water resources is best approached on a watershed basis. Normally, the amelioration processes are developed and applied following prioritization and landscape planning. Prioritization plays a key role in identifying areas that require attention [6]. In a watershed management program due to time and financial limitation, it is difficult to make rehabilitation, and soil and water conservation work at one time in all places. Thus it is important to study the watersheds of the area and make ordering by their risk of erosion [7]. Estimation of soil loss and identification of critical area for implementation of best management practice in watershed is central to success of a soil and water conservation program.

In Somodo watershed soil and water conservation measures was implemented to minimize soil erosion without identification of erosion hot spot areas. However, satisfactory result was not observed in the watershed for past five years through implementation of soil and water conservation technologies to the whole watershed at a time. Because of this the study was aimed to estimate erosion rate of the watershed and identify erosion hot spot areas through prioritization of the sub-watersheds for further soil conservation, and watershed management planning by the help of GIS based USLE model in the study area.

II. METHODOLOGY

2.1 Description of the study area

2.1.1 Location

The study was conducted in the upper part of Abay (Nile) river basin at Somodo watershed, Oromia regional state in the South West part of Ethiopia. It is located about about 369 kilometers to the South West of Addis Ababa, Capital City of the country. The watershed covers about 300 ha and found in between $7^{\circ}46'00''$ - $7^{\circ}47'00''$ N latitude and $36^{\circ}47'00''$ - $36^{\circ}48'00''$ E longitude with the altitude ranging from 1900 to 2075m.a.s.l

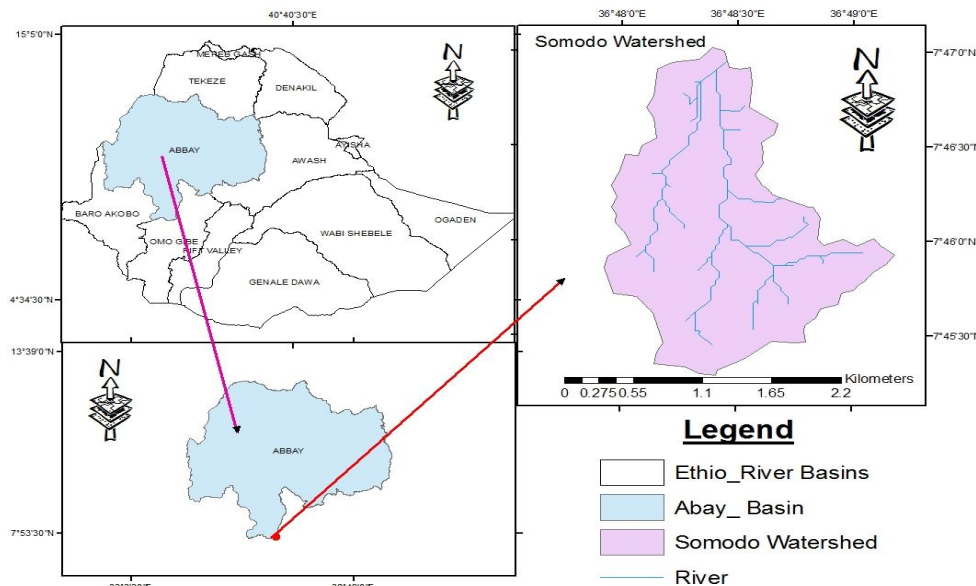


FIGURE 1. MAP OF THE STUDY AREA

2.1.2 Soil and Climate

Somodo watershed is dominated by Humic Nitosols, and percent of organic matter distribution is high at the middle part of the watershed and low near to the outlet of the watershed. The watershed found in between Jimma, Somodo, Agaro and Limu Genet meteorological stations having the mean annual rainfall of 1449.87, 1940.94, 1421.23 and 1460.92 at Jimma, Somodo, Agaro and Limu Genet respectively. The mean annual rainfall of the watershed is then 1523 mm with the mean temperature of 18.9°C ranging from 13.0°C and 24.8°C . Fig.2. below shows that 30 years annual rainfall of all stations around the watershed [8].

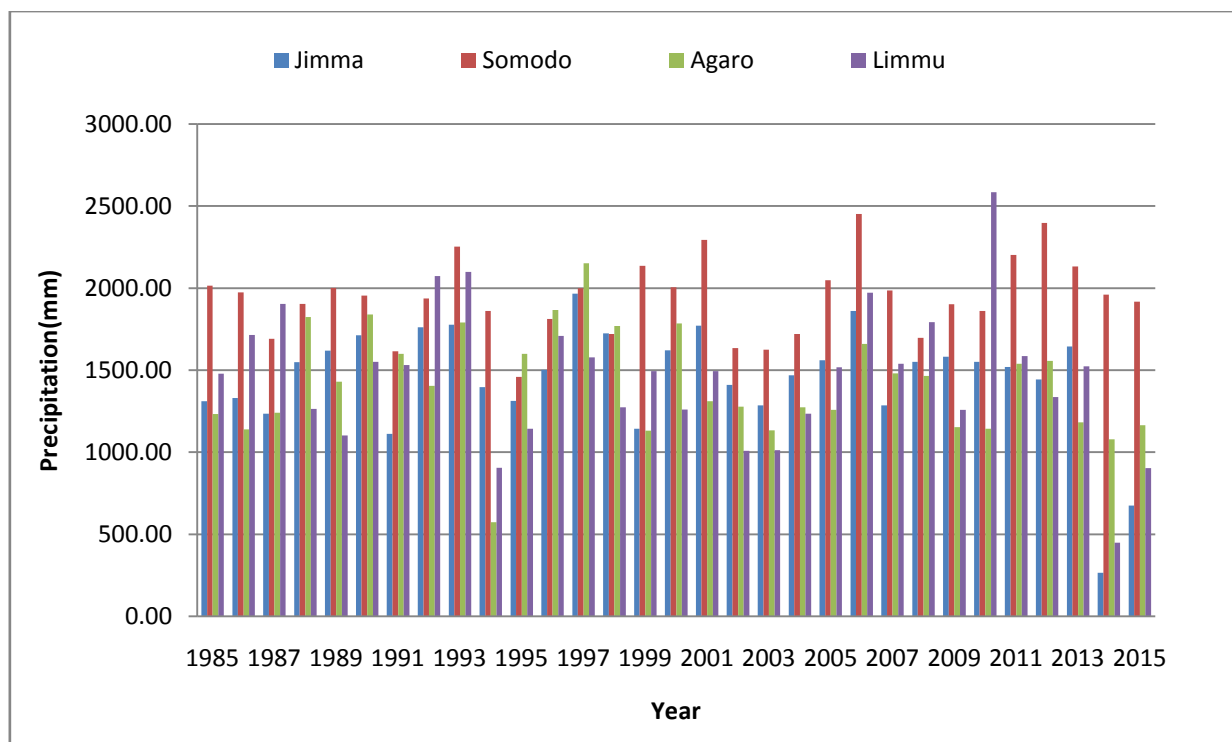


FIGURE 2. RAINFALL DATA OF STATIONS AROUND THE WATERSHED

2.1.3 Land Use of the Watershed

Coffee based farming system and agro forestry is a common practice in the watershed. Cultivation land, Forest, grazing and agro forestry are major land uses in somodo watershed. In case of this study cultivation land is used to represent for areas covered by annual crops while agro forestry stands for areas covered by perennial crops including coffee and home gardens. Agro forestry covers large area of the watershed followed by cultivation land which is about 46.97% and 21.26% respectively. About 18.51% of the watershed is covered by forest land (natural forest and plantation) while grazing land covers only 13.26% of the watershed.

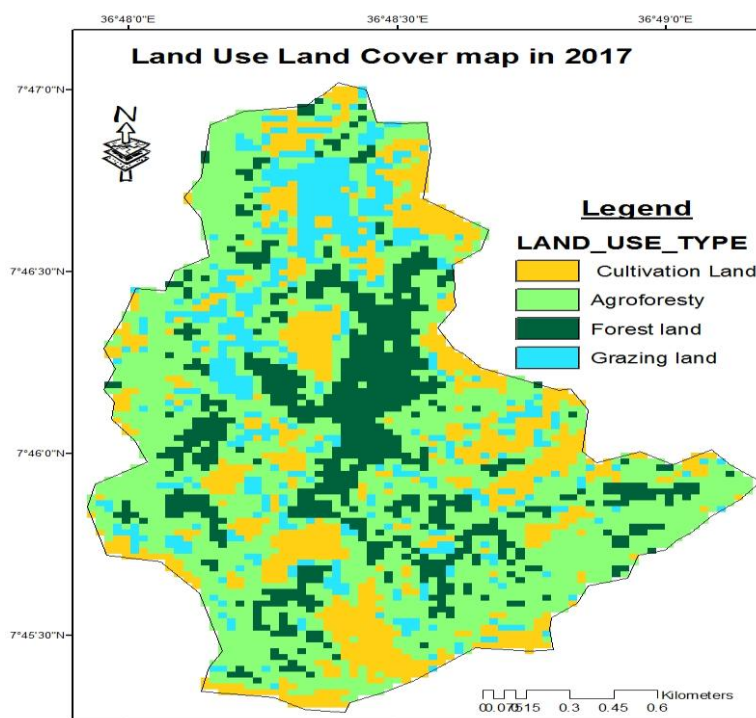


FIGURE 3. LAND USE LAND COVER MAP OF SOMODO WATERSHED IN 2017
(Source: Own data, 2017).

2.2 Determination of USLE Factors

USLE is an empirically based model, which has been developed for both natural and simulated runoff plots. Its simplicity and statistical relationships between input and output variables make it adaptable to other environments [9], [10]. The general equation of USLE is [11]:

$$A = R * K * LS * C * P$$

Where A is the average soil loss (Mg/ha/year), R is the rainfall erosivity factor (MJ mm/ha/h/year), K is the soil erodibility factor (Mg h/MJ/mm), L is the slope length factor, S is the slope steepness factor C is the cover and management practice factor and P is the support practice factor.

The erosivity factor of rainfall (R) is the product of kinetic energy of the raindrop and the 30-minute maximum rainfall intensity. In Somodo watershed, 30-minute rainfall intensity data was not available and therefore, the erosivity factor R that was adapted by [12] for Ethiopian conditions based on the easily available mean annual rainfall P was used in this study.

$$R = -8.12 + 0.562 * P$$

30 year (1985-2015) rainfall data for four stations (Jimma, Somodo, Limmu Genet and Agaro) around the watershed were taken from National Meteorological Agency and checked for missing data, homogeneity and consistency before using it for further analysis. R-factor value was calculated for each station and spatial distribution of Rainfall runoff factor (R) was interpolated using 'Kriging' method in spatial analysis tool in Arc GIS environment.

The soil erodibility factor is based on the soil texture, structure, organic matter and permeability. Accordingly, soil survey was conducted in the watershed on the bases of slope steepness, slope aspect and soil color, and a total of 106 soil samples were collected randomly and composited into 82 composite soil samples. These soil samples were analyzed for soil textural class (*hydrometer method*) and organic matter (*walkley black method*) in Jimma Agricultural Research Center, Soil and plant tissue analysis laboratory. Therefore using the equation developed by [13] soil erodibility factor (K-value) for each soil sample was calculated and soil erodibility map was generated as a raster data through interpolation by 'Kriging' method.

$$K = [2.1 M^{1.14} \times 10^{-4} (12 - a) + 3.25(b - 2) + 2.5(c - 3)] / 100$$

where, M = particle size parameter; (percent silt + percent very fine sand) (100–percent clay), a = percent organic matter, b = soil structure code used in soil classification; (very fine granular= 1, fine granular= 2, medium or coarse granular =3, blocky, platy or massive= 4) and c = soil permeability class; (rapid= 1, moderate to rapid =2, moderate =3, slow to moderate =4, slow =5, very slow =6). Soil permeability code in relation to textural class and structural code is presented in Appendix Table.1 and 2 respectively.

The L and S factors represent the effects of slope length (L) and slope steepness (S) on soil erosion. LS -factor was calculated by Unit Stream Power Erosion and Deposition (USPED) method, which uses the raster calculation between flow accumulation and slope of watershed, [14]. The following equation was used:

$$LS = Power ("flow accumulation" * [cell resolution] / 22.1, 0.4) * Power (Sin ("slope in degree" * 0.01745) / 0.09, 1.4) * 1.4.$$

Landsat image taken in 2017 was pre-processed and classified for land use land cover by the help of both ArcGIS 10.1 and ERDAS IMAGINE 2013 through supervised classification system. The watershed was classified into four major land use classes namely, cultivation land, grazing land, forest land and agro-forestry. C-values given by different scholars for different land use classes given in Appendix Table 3 were used to map and estimate the weighted C-values of the catchment, which was used in the USLE model.

The support practice affects erosion primarily by modifying the flow pattern, grade and direction of surface runoff and by reducing runoff amount and rate [15]. The P-factor values adapted for Ethiopian condition by [16] was used for this study to

determine P-value as described in Appendix Table.4. Based on the estimated P-values given for different land uses support practice factor map was generated by reclassifying land use type map by the help of spatial analysis tools in ArcGIS.

The watersheds was divided into nine sub-watersheds on the bases of hydrological response unit generated and prioritized 1 to 9 on the bases of mean annual soil loss rate of each sub-watershed, and first priority was given for sub-watershed having high mean soil loss rate while last priority was given for sub-watershed with low soil loss rate. Erosion severity class was also done using mean annual soil loss recorded in sub-watersheds. Tolerable soil loss rate is known as $11 \text{ ton ha}^{-1} \text{ year}^{-1}$ [17]. On the bases of this the sub-watersheds of Somodo was categorized under four classes as mean annual soil loss ranging from $0\text{-}10 \text{ ton ha}^{-1} \text{ year}^{-1}$ slight, $10\text{-}20 \text{ ton ha}^{-1} \text{ year}^{-1}$ moderate, $20\text{-}30 \text{ ton ha}^{-1} \text{ year}^{-1}$ high and $> 30 \text{ ton ha}^{-1} \text{ year}^{-1}$ very high.

III. RESULT AND DISCUSSION

3.1 Estimated Universal Soil Loss Equation (USLE) Factors

The rainfall erosivity factor (R), soil erodibility factor (K), topographic factor(LS), land cover factor(C) and land management factor (P) were resulted ranging from 990.98 to 1082.1, 0.28 to 0.42, 0 to 121.84, 0.001 to 0.15 and 0.27 to 1, with a mean weighted value of 1042.426, 0.349, 2.173, 0.036 and 0.657 respectively. Spatial distribution map of each parameters were shown in Fig. 4 below.

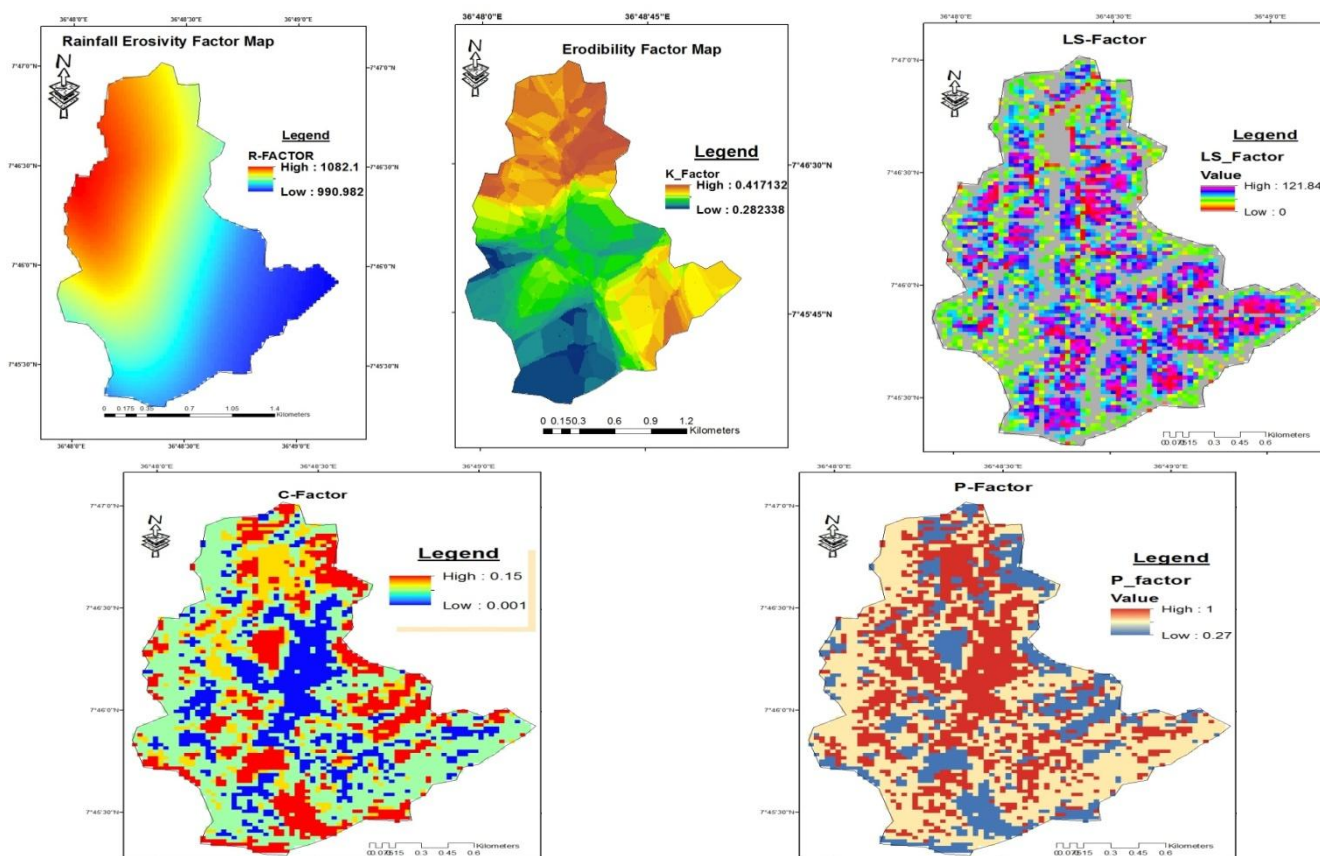


FIGURE 4. SPATIAL DISTRIBUTION OF USLE PARAMETERS

3.2 Estimated Mean Annual Soil Loss

Mean annual soil loss of Somodo watershed was resulted to be $18.699 \text{ ton ha}^{-1} \text{ year}^{-1}$ ranging from 0 to 131.21 with a standard deviation of 51.05. The maximum soil loss was recorded only in one pixel area with a dimension of $30\text{m} \times 30\text{m}$ (0.09 ha). Spatial distribution of the result was shown in Fig.5. below and high soil loss value was recorded at the right side of the watershed specially nearby the outlet and upper part of the watershed at steep slopes. This may be due to high land slope and cultivation land with annual crops was the dominating land use type in these areas.

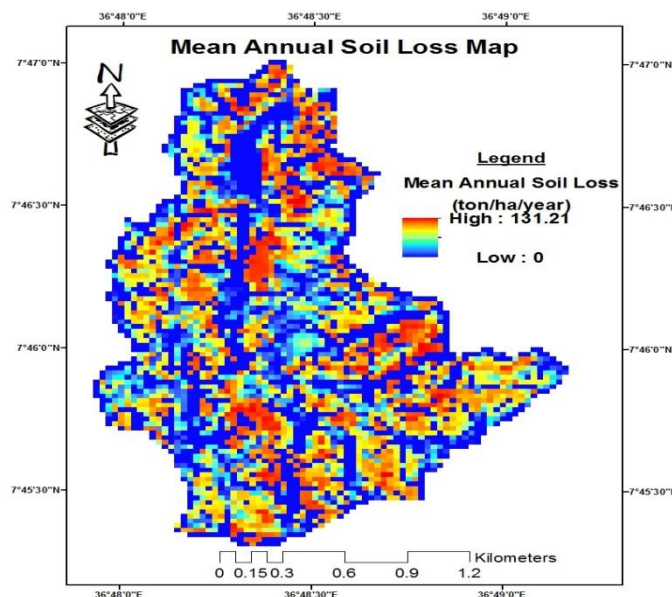


FIGURE 5. SPATIAL DISTRIBUTION OF MEAN ANNUAL SOIL LOSS IN SOMODO

The result of this study is in agreement with the findings of previous studies done in the country and around the study area on erosion rate. [18] found 16-300 ton ha⁻¹ year⁻¹ mean annual soil loss in Ethiopia and [1] reported 3.4-84.5 ton ha⁻¹ year⁻¹ mean soil loss in Ethiopian highlands. Similarly, [19] found soil loss rate ranging from 2.6 - 116.94 ton ha⁻¹ year⁻¹ in Eastern Ethiopia by the help of USLE model.

In Blue Nile basin [20] reported mean annual soil loss ranging from 7 - 243 ton ha⁻¹ year⁻¹. Since Somodo watershed is also part of upper part of the Blue Nile basin, the result of the study for Somodo watershed which is 18.69 ton ha⁻¹ year⁻¹ is in between the range. [21] conducted a study in Jimma zone using USLE model and reported mean annual Mana Woreda, where Somodo watershed is located, had low mean soil loss rate when compared to other woredas.

[22] also found soil loss rate of 82.3, 11.4, 4.3, 9.8 and 19.4 ton ha⁻¹ year⁻¹ from bare land, coffee, Taro, maize and Teff respectively from erosion experimental plot at Jimma Agricultural Research Center. Somodo watershed also mainly covered by coffee and forest, so the finding of this study favors with this finding.

3.3 Prioritization of Sub Watershe

Two sub watersheds (SW-9 and SW-5) were found under very high soil erosion severity level and one sub watershed (SW-1) was found under high soil erosion severity level. Similarly three sub watersheds (SW-2, SW-3 and SW-8) and the other three sub watersheds (SW-4, SW-6 and SW-7) were felt under moderate and slight soil erosion severity level respectively.

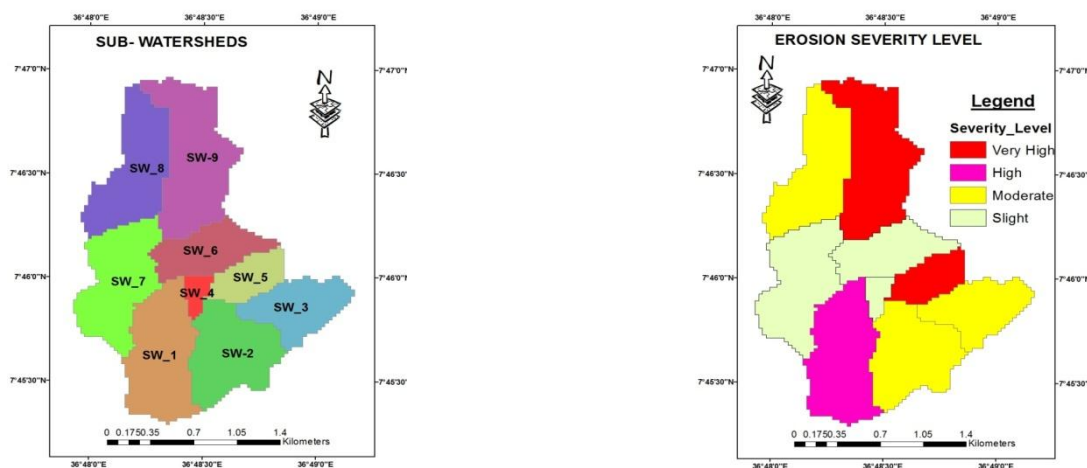


FIGURE 6. SUB-WATERSHEDS AND SOIL EROSION SEVERITY LEVEL

High area of the watershed was covered by moderate (10-20 ton ha⁻¹year⁻¹) soil erosion severity level followed by slight (0-10 ton ha⁻¹year⁻¹) severity level. Less area of the watershed was covered by high(20-30 ton ha⁻¹year⁻¹) erosion severity level. Slight, Moderate, High and Very high soil erosion severity levels covers 24.7%, 36.8%, 15.4% and 23.1% of the watershed respectively.

TABLE 1
AREA COVERAGE, MEAN ANNUAL SOIL LOSS, PRIORITY LEVEL AND EROSION SEVERITY CLASS OF SUB-WATERSHED

Sub Watersheds	Area(%)	Mean Annual Soil Loss	Priority level	Erosion Severity Level
SW_1	15.40	20.10	3	High
SW-2	13.34	17.28	4	Moderate
SW_3	9.19	16.32	5	Moderate
SW_4	1.66	9.07	8	Slight
SW_5	5.28	44.34	1	Very High
SW_6	8.64	7.36	9	Slight
SW_7	14.40	9.61	7	Slight
SW_8	14.28	13.84	6	Moderate
SW-9	17.83	30.26	2	Very High

This result showed that more than 75% of the watershed have soil erosion rate greater than tolerable erosion rate level, 11 ton ha⁻¹year⁻¹. This indicates that further soil conservation and watershed management should be planned to overcome the problem. As shown in Table 1. above SW-5, SW-9, SW-1, SW-2, SW-3, SW-8, SW-7, SW-4 and SW-6 were prioritized from 1 to 9 on the bases mean annual soil loss respectively.

IV. CONCLUSION AND RECOMMENDATION

Lack of effective watershed management system and poor land use and land management practices played a significant role in land degradation in Ethiopian highlands. Quantifying the amount of land degradation through soil erosion was difficult at a watershed or basin level for the past many years. Soil erosion models are useful to estimate soil loss and runoff rates at watershed and basin level, to plan land management strategies, to provide relative soil loss indices and guide government policy and strategy on soil and water conservation practices. Estimation of soil loss and identification of critical area for intervention of best management practices in the watershed is central for the success of soil and water conservation program. Somodo watershed also faced similar problems as other watersheds in Nile basin and then this study estimated soil erosion rate of the watershed and prioritized its sub watershed to identify erosion hot spot areas for effective soil and watershed management planning using GIS based USLE model. Accordingly, the watershed mean annual soil loss rate was found 18.69 ton ha⁻¹ year⁻¹ ranging from negligible value to 131.21 ton ha⁻¹ year⁻¹ with a standard deviation of 51.05.

SW-9 and SW-5 were felt in very high (>30) soil erosion level and SW-1 was under high (20-30) soil severity level. SW-2, SW-3 and SW-8 were under moderate (10-20), while the remaining SW-4, SW-6 and SW-7 were found under slight (0-10) soil erosion severity level. Therefore, for effective watershed management and soil conservation planning, these sub-watershed priorities should be used in the watershed. Further study, experimental plots or model based, in the study area are also appreciated by this study.

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APPENDIX TABLES

APPENDIX TABLE 1

SOIL PERMEABILITY CLASS AND RATING IN RELATION TO SOIL TEXTURAL CLASS

Textural class	Permeability class	Saturated hydraulic conductivity (mm/hr)	Permeability rating
Clay, Silty clay	6	<1	Very slow
Silty clay loam, sandy caly	5	1-2	Slow
Sandy clay loam, Clay loam	4	2-5	Slow to moderate
Loam, Silty loam, Silt	3	5-20	Moderate
Loamy sand, Sandy loam	2	20-60	Moderate to rapid
Sand	1	>60	Rapid

(Source: Wischmeir, et al.,1971 in Bobe Bedadi, 2004)

APPENDIX TABLE 2

SOIL STRUCTURAL CODE USED TO DETERMINE SOIL ERODIBILITY

Soil Structure	Soil structural code
Very fine granular	1
Fine granular	2
Medium or coarse granular	3
Platy or massive	4

(Source: Wischmeir, et al.,1971 in Bobe Bedadi, 2004)

APPENDIX TABLE 3**LAND COVER CLASSES AND ASSIGNED COVER (C) FACTOR VALUES BY DIFFERENT SCHOLARS**

Land cover	C- value	References
Cultivated land	0.15	Hurni (1985); Bewket and Teferi (2009); Tadesse and Abebe (2014)
Forest	0.001	Hurni (1985); Reusing et al. (2000); Morgan (2005)
Open Forest	0.006	Bewket and Teferi (2009)
Grass land	0.01	Hurni (1985); Morgan (2005); Bewket and Teferi (2009); Abate (2011); Tadesse and Abebe (2014)
Built-up areas	0.09	Ganasri and Ramesh (2015)
Water body	0	Hurni (1985)

APPENDIX TABLE 4**COMPUTATION OF THE MANAGEMENT (P) FACTOR VALUE ADAPTED FOR ETHIOPIA BY NYSSSEN ET AL., (2009C)**

Ploughing and cropping practices	$P = PC \cdot PN \cdot PM$ (on cropland);			$P = PN$ (on other land)	
	PC	Conservation structures	PN	In situ conservation practices	PM
Ploughing up and down	1	No conservation structures	1	Stubble grazing; no mulching	1
Ploughing along the contour	0.9	bunds (average condition; smaller value for new bunds and larger for older bunds)	0.3	Applying mulch	0.6
Strip cropping	0.8	Grass strip (1 m wide; slope ≤ 0.1)	0.4	Zero grazing	0.8
Intercropping	0.8	Grass strip (1 m wide; slope > 0.2)	0.8		
Dense inter cropping	0.7				

(Source: Hurni (1985), Nyssen (2001), Gebremichael et al. (2005), Nyssen et al. (2007a, b, 2008b) after Nyssen et al. (2009c)).