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Assessment of Soil Erosion Using RUSLE and GIS Techniques: A Case of Fincha'a Watershed, Western Ethiopia

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Abstract: The study integrated the Revised Universal Soil Loss Equation (RUSLE) with Geographic Information System (GIS) to quantify the potential soil erosion risk in the Fincha'a watershed. Rainfall, soil, digital elevation model (DEM) and satellite image data sets were used as inputs in order to generate RUSLE factor values. The potential annual soil loss of the study area ranged from nil at plain surfaces to 223.12 t ha^{-1} yr^{-1} at steep slopes of the farmland. The mean annual soil loss rate of the study area was 33.66 t ha^{-1} yr^{-1}. We obtained the highest mean annual soil loss of 38.8 t ha^{-1} yr^{-1} for farmland. However, the smallest annual soil loss of 4.3 t ha^{-1} yr^{-1} was obtained from the forestland. Nearly 36.2% of the total farmland was classified under high soil erosion risk while only 2.4 and 11.7% were categorized under high soil erosion risk for the forestland and grassland, respectively. The study revealed that the farmland was highly vulnerable to erosion than other land use and land cover types. In conclusion, information on average annual soil loss is important for selecting appropriate conservation measures to reduce on-site soil loss and their off-site effects.

Key words: Fincha'a Watershed · Soil Erosion · RUSLE · GIS · Soil Conservation

INTRODUCTION

Soil erosion is one of the global threats that causes land degradation and negative impact on the environment by threatening the natural environment, agriculture and the economy [1, 2]. Specially, its effects are more visible in developing countries due to their incapability to replace lost soils and nutrients of farming area [3, 4]. In Ethiopia, soil erosion is a serious problem, which threatens the agricultural sector [5, 6] and causes increased sedimentation of reservoirs and lakes [7, 8]. According to Ethiopian Highland Reclamation Study [9] 60 million hectares of Ethiopian land are estimated to be used for agricultural productive. Out of these lands that used for agricultural purpose, about 27 million hectares are significantly eroded, 14 million hectares are seriously eroded and 2 million hectares have reached the point of no return with an estimated total loss of 2 billion m^3 of topsoil per year [10, 11] estimated that soil loss due to erosion of cultivated fields in Ethiopia amounts to about 42 t ha^{-1} yr^{-1}. According to Kebede *et al*. [12] over population, poor cultivation and land use practices, deforestation and overgrazing, loss of soil fertility, rapid degradation of natural systems, significant sediment depositions in the lakes and reservoirs and sedimentation of irrigation infrastructures in the highlands of Ethiopian are the main causes that triggers problems of soil erosion. The study area-Fincha'a watershed is located in the highlands of Ethiopia suffering from soil erosion hazard due to the aforementioned human and natural causes.

Different researchers used Remote Sensing and GIS with Revised Universal Soil Loss Equation (RUSLE) and showed its efficiency and capacity for assessing erosion hazard and identifying highly affected areas [13-15]. Therefore, this study was designed mainly to estimate amount of soil loss from Fincha'a watershed by integrating RUSLE model with GIS and Remote Sensing techniques. These techniques are highly important for identifying highly eroded areas and planning and implementation of watershed management strategies and policies by giving attention for more erosion prone areas of the watershed.

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MATERIALS AND METHODS

Study Area: The Fincha'a watershed is situated between 9°10'30? and 9°46'45? N and 37°03'00? and 37°28'30? E in Abay Choman district, Ethiopia (Fig. 1) with elevation ranging from 2196 to 2438 m a.s.l. The area is characterized by having tropical highland monsoon with an average annual rainfall of 1479 mm and the mean monthly temperature that varies between 14.6 to 17.7°C [16]. The study area covers about 8090 ha and its major landforms fall in undulating terrain class (2-10%) which covered about 46%, rolling terrain about 27% and hilly terrain about 23%. Only small pockets of land which accounts about 1% from total area was covered by flat plain and 1% also characterized by highly rugged, mountainous and rolled topography with steep slopes. The soils of the area was dominated by Haplic vertisols (2913 ha), Ferralic Cambisols (2522 ha) and Ferralic Nitisols (1839 ha). Only small portion of Fincha'a watershed (31 ha) characterized by Ferralic Luvisols. The rest part of the study area was covered by wetland.

Modelling Techniques: In order to determine the annual soil loss of the study area, RUSLE equation adapted to Ethiopian condition by Hurni [17] was used. Mathematically the equation is denoted as:

$$A = R * K * LS * C * P \quad (1)$$

where, A = predicted annual soil loss per unit area (t $ha^{-1}yr^{-1}$), R = rainfall erosivity factor (MJ mm h^{-1} ha^{-1} yr^{-1}), K = soil erodibility factor (t ha^{-1} MJ^{-1} mm^{-1}), LS = slope length and steepness factor, C = land cover and management factor and P = conservation practice factor.The parameters used to estimate potential soil loss and processes to generate each parameter was shown in flow chart (Fig. 2).

Model Parameters

Rainfall Erosivity (R): The erosivity factor R was calculated using the equation derived from a spatial regression analysis adapted by Hurni [17] for Ethiopian conditions. It is based on the available mean annual rainfall data of 25 years (1991-2016) recorded at six relevant meteorological stations (Fincha'a, Neshe, Shambu, Homi, Sibu Sire and Alibo) correlation using the raster calculator in ArcGIS environment as follows.

$$R = -8.12 + (0.562 * P) \quad (2)$$

where R= rainfall erosivity factor and P = mean annual rainfall in mm

Soil Erodability (K): The soil erodibility (K) factor for study area was estimated depending on soil colour. According to Hurni [17] and Hellden [18]Ethiopian soils having black, brown, red, yellow, grey and white colour were assigned K value of 0.15, 0.20, 0.25, 0.30, 0.35and 0.40, respectively. The major portion of the study area was covered by Haplic vertisols (2923 ha) with grey colour (k = 0.35), Ferralic Cambisols (2600 ha) with yellow colour (k = 0.3) and Ferralic Nitisols (1886 ha) with red colour (k = 0.25). Only small portion of the study area covered by Ferralic Luvisols (35 ha) has yellow colour (k = 0.3). The remaining 646 ha was covered by wetland that has no significant characteristic of erodibility. So, after K values were assigned for each soil type, the grid data set was reclassified based on K-value for each soil class in ArcGIS 10.3 software.

Topographic Factor (LS): Topographic factor was generated from Digital Elevation Model (30 m * 30 m resolution). Both slope (%) and flow accumulation were calculated using the spatial analyst tool of ArcGIS after correcting the DEM by using fill and flow direction. Thetopographic factor was calculated as a single index using the formula suggested by Simms *et al.* [19] as follows:

$$LS = P\,(FA.*cell\ size / 22.1, 0.6) * P\,(\sin(slope * 0.01745) / 0.09, 1.3 \quad (3)$$

where P = power and FA = flow accumulation

Cover Management Factor (C): This parameter was generated from land use and land cover map prepared from Landsat ETM^+ satellite image of 30 m resolution. Accordingly, the land use and land cover of the study area and their C value was indicated in Table 1.

Support Practice (P): The conservation practice factor (P) is the ratio of soil loss for a given practice to that for up and down the slope farming. According to Hurni [17] values assigned for local management practices is varies between 0 to 1 depending on a range of practices applied on the farmland such as contouring, strip cropping and terracing (Table 2).

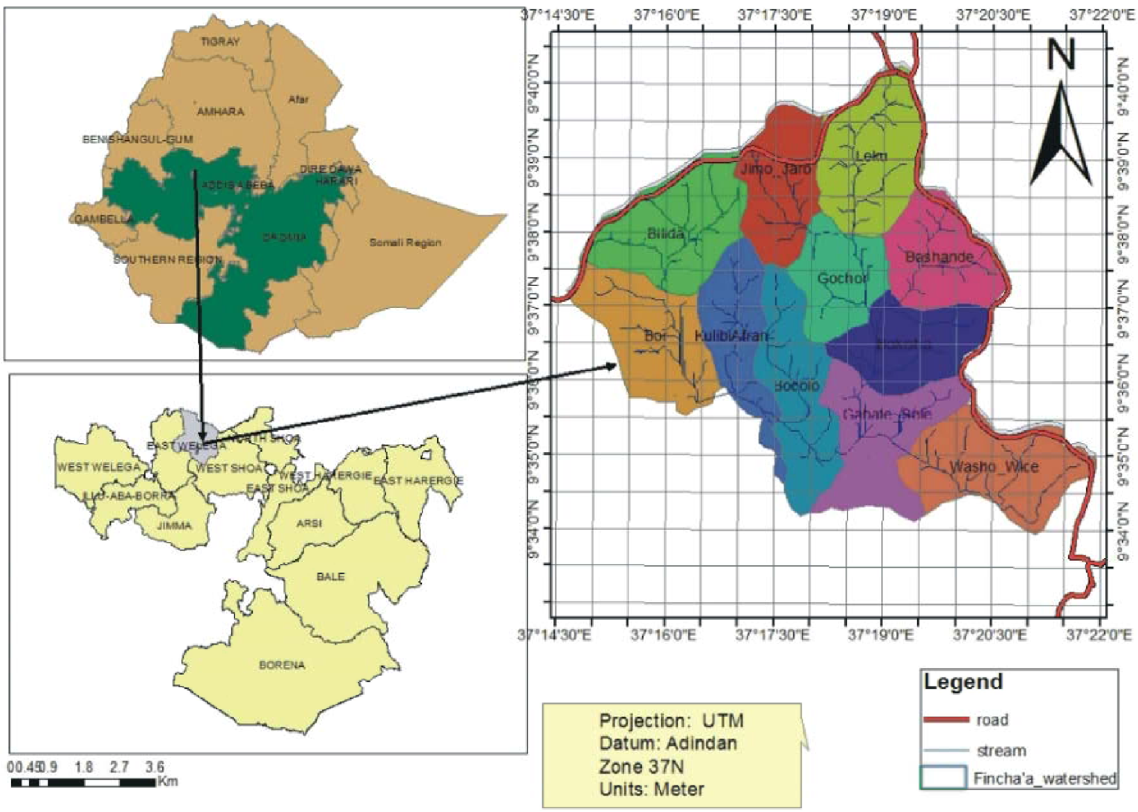

Fig. 1: Location map of Fincha'a watershed

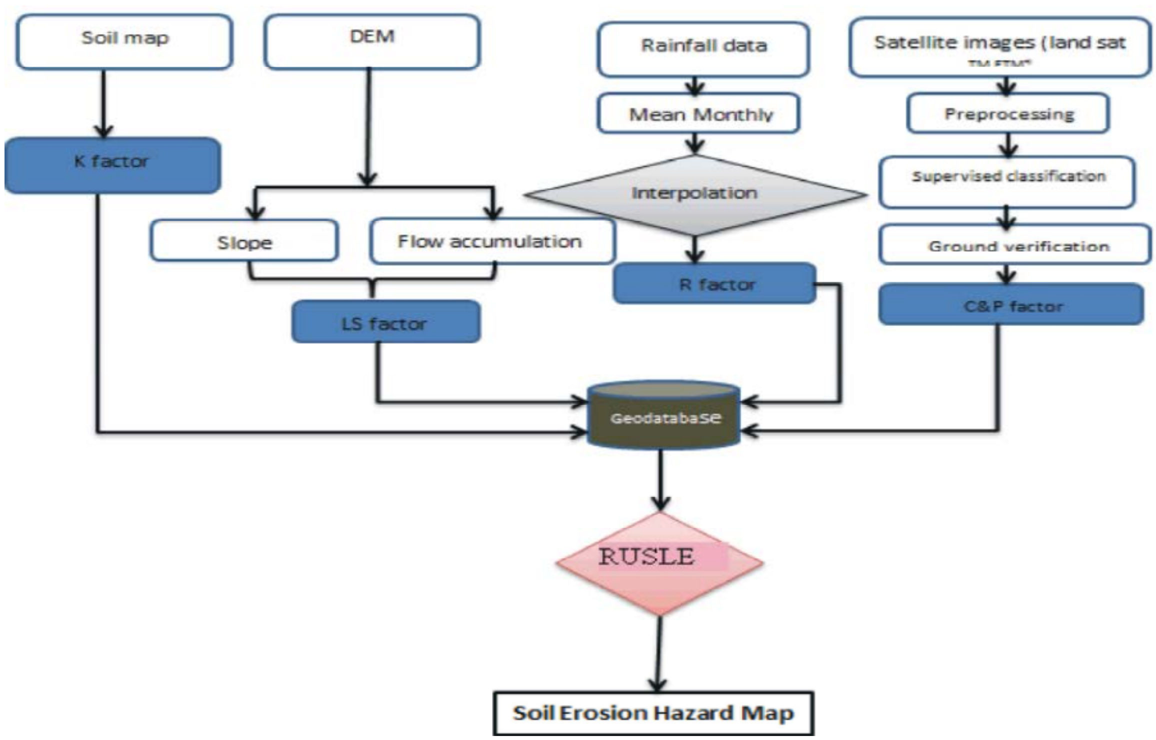

Fig. 2: Modeling flow chart showing analysis of soil loss based on GIS application

Table 1: Crop management factor value

LULC-type	Area (ha)	% total	C-value	References
Farm land	6299	77.87%	0.15	[17]
Grass land	103	1.27%	0.01	[20]
Forest land	1042	12.85%	0.001	[17]
Water body	216	2.67%	0.00	[17]
Swampy area	430	5.50%	0.00	[21]

Table 2: Support practice factor

Land use/land cover type	P value
Farmland	0.9
Grass land	0.9
Forest land	0.5
Water body	(-)
Swampy area	(-)

RESULTS AND DISCUSSION

Annual Soil Loss Rate of Fincha'a Watershed: The result showed that the annual potential soil loss rate of study area ranged from nil in plain areas to over 50 t ha^{-1} yr^{-1} in much of the steeper slope banks of tributariesand to well over 223.12 t ha^{-1} yr^{-1}in highly hill slopes (Fig. 3). This value is agreed with the annual soil loss of the highlands of Ethiopia (16-300 t ha^{-1} yr^{-1}) reported by FAO [9].

The average annual soil loss rate of the study area was 33.66 t ha^{-1} yr^{-1}. The average annual soil loss rate obtained during the present study was higher than the average annual soil loss rate of 30.2 t ha^{-1} yr^{-1} reported by Tegegne and Biniam [22]. This indicates that the study area was highly affected by soil erosion which leads to land degradation and loss of agricultural production. The high soil erosion in the study area was mainly attributed to poor land management practices. The spatial pattern of the soil erosion risk map (Fig. 3) showed that the study area is potentially prone to soil erosion risk. Except water and swampy areas (7444 ha), nearly 1487ha (20%) of the study area exist under severe soil erosion risk (Table 3). The major portion of the study area which represented about 31.1% (2317 ha) was occurred under high erosion risk. The smallest portion of the study area (14.7% = 1091 ha) had experienced moderate soil erosion risk.

Spatial Variation of Soil Erosion with Land Use and Land Cover: Land use/land cover types greatly affected annual soil loss rate. The results showed that farmland which covered the largest portion of the study area (6299 ha) has the highest mean annual soil loss (38.8 t ha^{-1}yr^{-1}) as presented in Table 4. We found the smallest annual soil

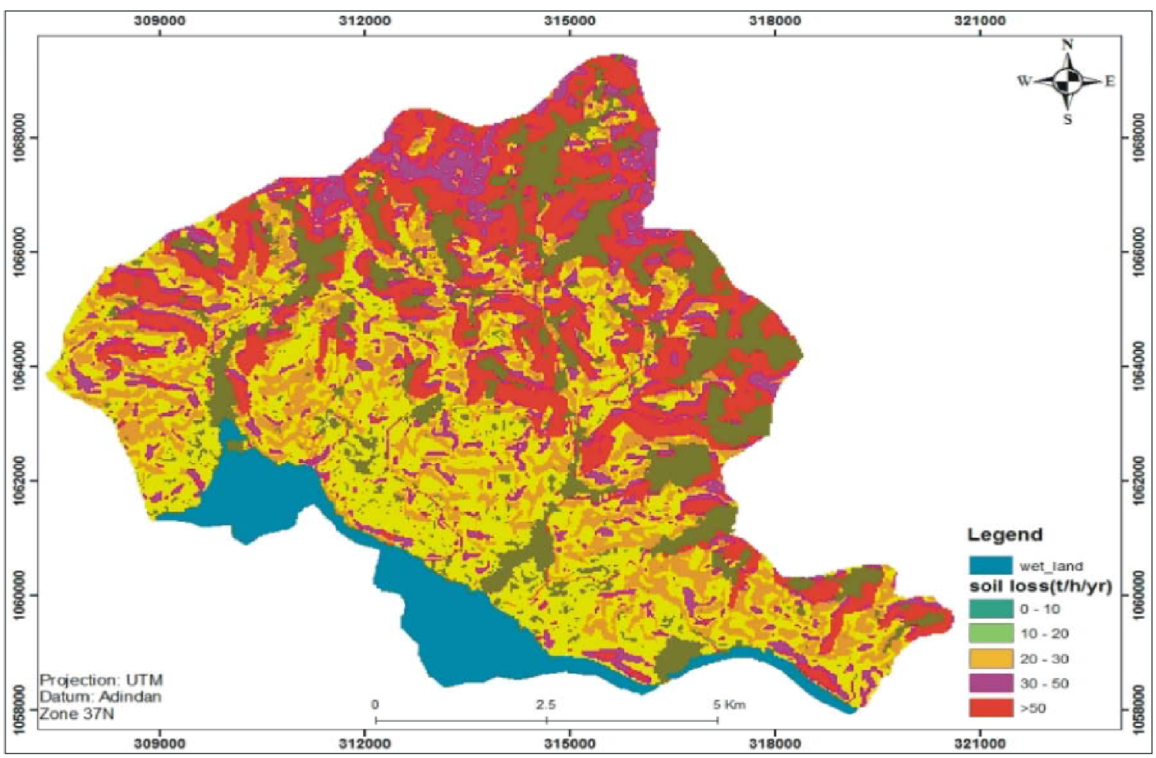

Fig. 3: Map of annual soil loss rate of the study area

Table 3: Soil erosion risk classes and their areal coverage

Soil loss rate (t ha^{-1} yr^{-1})	Severity classes	Area (Ha)	Percent (%)
0-10	Low	1295	17.4
10-20	Moderate	1091	14.7
20-30	High	2317	31.1
30-50	Very High	1254	16.8
>50	Severe	1487	20.0

Table 4: Soil erosion from different land use and land cover types

		Risk class and area (ha)				Area (ha)	
Land use /land cover	Mean soil loss rate (t ha^{-1} yr^{-1})	Low	Moderate	High	Very high	Severe	Total
Grass land	10.4	57	8	12	2	24	103
Forest land	4.3	902	17	25	32	66	1042
Farmland	38.8	336	1066	2280	1220	1397	6299

loss of 4.3 t ha^{-1} yr^{-1} from the forestland. The mean annual soil loss of 4.5 from forest and 65.9 t ha^{-1} yr^{-1} from crop land reported by Adugna *et al.* [23] was higher the mean annual soil loss obtained during the present study for both forestland and farmland, respectively. The major causes for high average soil loss rate from the farmland might be deforestation, continues tillage, inappropriate farming practices, overgrazing of farm residues by livestock and collection and use of crop residues for fuel wood. From the total farmland, nearly 2280 ha (Table 4) or 36.2% was under high soil erosion risk. Compared to this, only 2.4% of the total forestland and 11.7% of the total grassland were under high soil erosion risk. High soil erosion risk on farmland was also reported by Simeneh and Getachew [24]. This indicates that soil and water conservation measures such as mulching and conservation tillage are important to reduce soil erosion from farmlands [25].

Planning Soil Conservation Measures: The tolerable soil loss rate reported for Ethiopian highland conditions range from 2 to 18 t $ha^{-1}yr^{-1}$ [17]. The mean annual soil loss of 38.8 t $ha^{-1}yr^{-1}$ obtained from the farmland during the present study was much higher than the tolerable soil loss rate. This fact shows how much soil erosion is a serious threat and harmful in crop production system of Fincha'a watershed. This clearly shows that cropland should be prioritized to carry out land management practices such as minimum or zero tillage, intercropping, mulchingand planting crops or grasses along contour ridges, use of manure/compost and spreading domestic waste on to cropland land. Specifically on steep slopes of the watershed where soil erosion was severe, soil and water conservation measures such as soil bunds, terraces and micro-basins are mandatory. This was in line with Morgan [26] who suggested that knowing the soil erosion risk of a given area is used for conservation planning.

CONCLUSION

Modeling of annual soil loss rate of Fincha'a watershed provided several insights on erosion hazard. It can be concluded that soil erosion is very severe in the study area. Soil erosion in the farmland was higher than other land use types. The mean soil erosion observed in the farmland was also above the tolerable soil loss rate. As a result, the study area is prone to soil erosion that can put the sustainability of agriculture of the area at risk in a long run if the trend is continued without applying soil erosion control mechanisms. Generally, the study demonstrates that RUSLE together with satellite remote sensing and GIS are useful tools to estimate soil loss over areas and facilitate sustainable land management through conservation planning.

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