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A S Shobary, A S Elsharkawy, H E M El-Hanafy & O M Moussa

ABSTRACT

Soil erosion is a severe and uninterrupted problem that threatens the environment all over the world. Sedimentation has a great effect on basins with large surface areas. Lake Tana basin is one of these lake basins with a surface area of about 15935 km2. The main objective of this study was to assess soil erosion and concentration of sediment yield of lake Tana basin and map their spatial distribution. The study was conducted by integrating Geographic Information System (GIS), remote sensing, and the Revised Universal Soil Loss equation (RUSLE). Data sets of rainfall, soil, topography, cover management, and conservation practices were integrated and modeled in GIS. Soil loss, sediment delivery ratio (SDR), and sediment yield were estimated. The results showed that the computed mean annual soil loss was 79.3 t.ha-1.y-1. Six classes of soil erosion were classified: very low (0-5), low (5-10), moderate (10-15), moderately high (15-20), high (20-40) and very high (>40) t.ha-1.y-1. About 57.5% of the study area is under low erosion risk (0-10 t.ha-1.y-1), whereas about 40.3% of the study area is under high and very high erosion risk. SDR was estimated, based on the mainstream slope, and found to be 0.281. The findings of the study also showed that the average annual sediment yield of the lake Tana basin is approximately 22.28 t.ha-1.y-1. The results of this study can benefit policymakers to investigate erosional risk areas and take the best appropriate decisions to control soil erosion risk in these regions.

Keywords: soil erosion, sediment yield, RUSLE, SDR, GIS, lake tana basin.

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The study was conducted by integrating Geographic Information System (GIS), remote sensing, and the Revised Universal Soil Loss equation (RUSLE). Data sets of rainfall, soil, topography, cover management, and conservation practices were integrated and modeled in GIS. Soil loss, sediment delivery ratio (SDR), and sediment yield were estimated. The results showed that the computed mean annual soil loss was 79.3 $t.ha^{-1}.y^{-1}$. Six classes of soil erosion were classified: very low (0-5), low (5-10), moderate (10-15), moderately high (15-20), high (20-40) and very high (>40) $t.ha^{-1}.y^{-1}$. About 57.5% of the study area is under low erosion risk (0-10 $t.ha^{-1}.y^{-1}$), whereas about 40.3% of the study area is under high and very high erosion risk. SDR was estimated, based on the mainstream slope, and found to be 0.281. The findings of the study also showed that the average annual sediment yield of the lake Tana basin is approximately 22.28 $t.ha^{-1}.y^{-1}$. The results of this study can benefit policymakers to investigate erosional risk areas and take the best appropriate decisions to control soil erosion risk in these regions.

Keywords: soil erosion, sediment yield, RUSLE, SDR, GIS, lake tana basin.

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I. INTRODUCTION

Soil erosion is the biggest economic challenge that threatens developing countries as it is a dangerous issue in agriculture [1]. Runoff affects soil erosion severely as it is considered a world land dissolution problem [2]. The runoff is an essential factor for soil erosion as it controls the acceleration of erosion rates from high land regions to low ones [3]. Furthermore, human also causes erosion in regions by construction works, dense agriculture production, mining, and intensive population density [4]. Soil erosion accelerated severely in the 20th century over the world [5]. The world mean annual soil erosion varies from 12 to 15 $t.ha^{-1}$ [6]. The annual soil loss was estimated approximately between 0.9-0.95 mm by FAO [7]. FAO also demonstrated that the world annual soil loss by water effect ranges from 20 to 30 gigatonnes [7]. Suppression of erosion and sedimentation is important as they affect the richness of land and water goodness [8]. Soil erosion has a negative effect on agriculture aspect, ecosystems and results in sedimentation boost [9]. Soil erosion causes spoiling crops production and decreases fertile lands, which results in food insecurity [7, 10]. Soil erosion and sedimentation have a direct effect on the cycle of soil nutrients [11]. Therefore , it is obligatory to find solutions to reduce the calamitous effects of soil erosion [12].

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Various processes of soil erosion are the cause of the problems related to on-site and off-site [13]. On-site problems are represented inland decay and reducing agriculture production, while off-site problems are related to reducing the lifespan of reservoirs [14]. Soil erosion causes loss in dams and reservoirs storing tendency [15]. Reports have indicated that the global annual loss in storage capacity of reservoirs, related to sedimentation, is about 0.5-1.0 %, and it is expected that, through the coming 20-30 years, the majority of the world's reservoirs capacity would be lost [13]. Findings of studies have shown that the range of sediment deposition of rivers and reservoirs in Africa is between 0.002 and 157 $t.ha^{-1}.y^{-1}$ [16]. Siltation due to water erosion threatens about 19% of Africa reservoirs [7]. Soil erosion has a great impact on the environment as it is resulted in landslides in valleys [17]. Therefore, the determination of soil erosion is an important solution for conservation soil as its spatial distribution assessment can help in advancing protecting policy framework [13].

There are many methods for assessing soil erosion and sediment yield [18]. In the few recent decades, among these methods, the RUSLE model is the most commonly acceptable method around the world [19, 20]. The RUSLE model is the most convenient method for developing countries that suffer from lack of data [21]. The use of the RUSLE model has been advanced from small watersheds to large watersheds to assess mean annual soil loss at the long term [22]. The RUSLE method depends on various factors: rainfall erosivity, slope length-steepness, soil erodibility, crop management factor, and conservation support practice factor [23]. RUSLE can be integrated with GIS and remote sensing techniques to assess sediment yield in a watershed [24]. GIS helps the RUSLE to get more precise outputs [25]. Lewoy Tsegaye and Rishikesh Bharti used the RUSLE and GIS-based approach to assess soil erosion and sediment yield in the Anjeb watershed, northwest Ethiopia [13]. RUSLE, integrated with GIS, model was used by Meena Kumari et al. to determine the concentration of soil loss and sediment yield in the Kolleru lake basin [22].

This research aims to assess soil loss and sediment yield and spatial distribution to investigate the erosional risk zones. The objectives of this study were obtained by: (1) applying integration between the RUSLE model and techniques of GIS and remote sensing to assess soil erosion, (2) recognizing the spatial distribution of soil loss across lake Tana basin, (3) computing SDR factor, (4) determining the concentration of sediment yield and its spatial distribution through the study area.

II. STUDY AREA

Lake Tana is considered the largest freshwater lake in Ethiopia, an with area of about 3000 km^2. It is 78 km long, 67 km wide and 14 km in depth. However, the Nile Basin has many lakes; Lake Tana is the third biggest one. In the northwestern part of Ethiopia, the Lake Tana Basin is situated. Gilgel Abbay, which flows into Lake Tana, is the main source of the Blue Nile (Abbay). Gumera, Ribb, and Megech are also the main rivers that flow into Lake Tana. Lake Tana Basin, which contains lake Tana, lies at latitude 10° 57' 0" and 12° 46' 48" and longitude 36 53' 24" and 38 15' 0". In northeastern of the Abbay Basin, Lake Tana Basin lies with a drainage area of about 15935 km^2. It rises at elevations ranging from 1701 m up to 4108 m above mean sea level as shown in **Figure 1**. The area surrounding the lake is flat, unlike highlands in the north and the east. Its average annual precipitation is 1634 mm, with a higher amount in the south, unlike the north which has a lower amount of rainfall. The area around the lake has a maximum temperature with a range from 14° C to 27° C. The more you get away from the lake, the temperature gets cooler and varies from 1° C to 12° C. It has an average annual potential evapotranspiration of about 1288 mm. Lake Tana has various soil types such Luvisols, Vertisols, Alisols and Cambisols, but the most common soil type is Haplic Luvisols. Chromic Luvisols is considered the second dominant soil type, after Haplic Luvisols, in lake Tana. The geology of lake Tana is prevails Basalt. In the eastern and northeastern part of the basin, Marsh soil is found. In the center of the basin and around the lake, Alluvial deposits are spread.

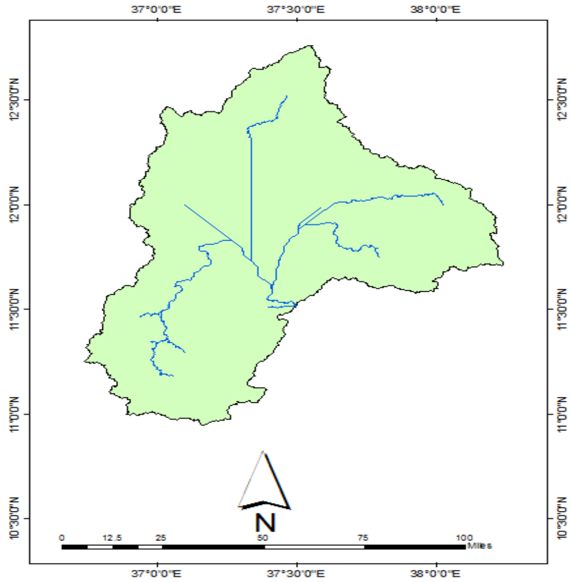

Figure 1: Map of the study area

III. METHODOLOGY

3.1 Soil erosion model – RUSLE

Renard et al. advanced an empirical model, Revised Universal Soil Loss (RUSLE), to assess the mean annual soil loss of watersheds [26]. Soil loss is considered a huge problem in many regions on earth. Laflen and Molden studied and inherited all likely applications of RUSLE to deal with soil loss problems [27]. RUSLE application was investigated in Tigray Region, situated in the highlands of Ethiopia, after adaptation USLE by Hurni [28]. The RUSLE equation estimates mean annual soil loss, which depends on various factors, and is expressed as **equation (1)**

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

Where A is the average annual soil loss (tons per hectare per year), R is the rainfall-runoff erosivity factor (MJ mm h^{-1} ha^{-1} $year^{-1}$), K is the soil erodibility factor (tons ha^{-1} MJ^{-1} mm^{-1}), LS is the slope length-steepness factor (dimensionless), C is the cover and cropping-management factor (dimensionless), P is the support practice factor (dimensionless). **Figure 2** shows the model integrated by GIS and remote sensing to estimate soil loss.

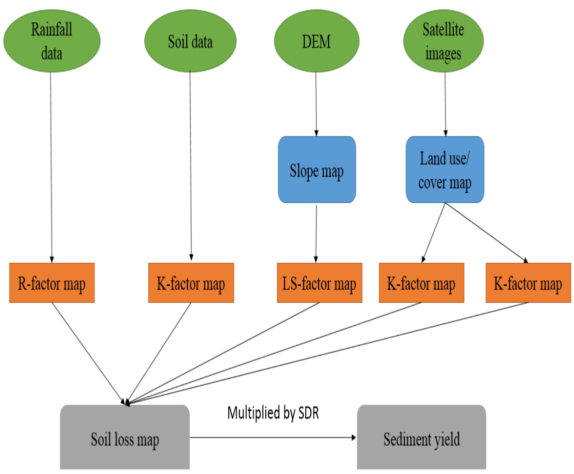

Figure 2: Methodology diagram of soil loss

3.1.1 Rainfall erosivity factor (R)

The rainfall erosivity factor (R) determines the impact of precipitation events and quantifies the amount of possible runoff [29]. In the case of rare rainfall data, a regression equation can be applied to assess the value of the rainfall erosivity factor [30]. Hurni used spatial regression analysis, depending on Ethiopian conditions, to develop a model determining rainfall erosivity factor due to lack of rainfall data [28]. Hurni depended, in his model, on mean annual rainfall data [28]. The equation of the model, derived by Hurni, is expressed as [28]:

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

Where R is the rainfall-runoff erosivity factor and P is the mean annual rainfall.

Average annual rainfall data was collected from four rainfall stations as shown in

No	Station name	location		Mean annual rainfall (mm)
		longitude	latitude	
1	Addiet Canna	37° 29′	11° 16′	1494.2
2	Bahir Dar	37° 24′	11° 36′	1430
3	Debre Tabor	38° 01′	11° 51′	1270.1
4	Werota	37° 42′	11° 55′	1203.5

Table 1 and was processed through ArcGIS 10.3 by the Inverse Distance Weighted method (IDW) to produce continuous rainfall data. The R-value was estimated for each grid cell from the uninterrupted rainfall data using equation (2) with the help of the raster calculator tool.

Table 1: Rainfall stations around Lake Tana basin

No	Station name	location		Mean annual rainfall (mm)
		longitude	latitude	
1	Addiet Canna	37° 29′	11° 16′	1494.2
2	Bahir Dar	37° 24′	11° 36′	1430
3	Debre Tabor	38° 01′	11° 51′	1270.1
4	Werota	37° 42′	11° 55′	1203.5

3.1.2 Slope length-steepness factor (LS)

LS factor is the topographic factor that demonstrates the percentage of soil loss per unit area in a field with given standard conditions of slope length of 22.13 m and slope steepness of 9% [19]. Slope length factor (L) represents the impact of slope length on erosion. Slope length is defined as the distance from the start point of overland flow to the point that its slope decreases to the range that deposition begins. There is a positive relation between slope length and soil loss, as when slope length increases, soil loss also increases [31].

Slope steepness factor (S) represents the impact of slope steepness on soil erosion. Soil loss is greatly affected more by slope steepness than by slope length. Soil loss increases as soil steepness increases.

Robert PS et al. linked soil loss with slope length only as when they calculated the topographic sub-factor of slope length; they did not consider the three-dimensional complex terrains in that calculation [32]. Some other researchers observed flow converges and diverges, so they pretended that soil loss is independent on slope length for the three-dimensional complex nature of the terrain. Zhang et al. developed an algorithm to compute LS as they denounced the USLE and RUSLE methods for estimating slope length-steepness factor [33]. Furthermore, limits of estimating slope length in USLE were reanalyzed by calculating accumulated uphill length from cells that interpret convergence of flow paths and area of deposition [34]. Then, the upslope contributing area replaced slope length. In this study, LS factor estimation equation (3) (developed by Desmet and Groves [35], Moore and Bruch [36, 37], Mitasova and Mitas [38], and Simms et al. [39]) was used equation (3).

$$LS=As/22.130.6*\sin B /0.08961.3 \tag{3}$$

Where LS is the slope length-steepness factor, A is the basin area, and B is the slope angle.
LS factor was estimated through ArcGIS with the help of raster calculator tool by using equation (4) supposed by Mitasova and Mits [40] and Simms et al. [39]

POW flow accumulation*cell size/22.13. 0.6*POWsin slope*0.01745/0.0896. 1.3 (4)

A 30-m resolution DEM was used to prepare the LS factor map through ArcGIS. Arc Hydro tool was used to extract flow accumulation after filling gaps and flow direction were conducted in ArcGIS. Grid cells number is demonstrated by flow accumulation, and 30*30 contributing area is represented by cell size.

3.1.3 Soil erodibility factor (K)

Soil erodibility factor has a great effect on soil erosion through the properties and characteristics of soil. It depends on percentages of silt, sand, and clay as well soil texture. Distribution of particle size and permeability of soil affect soil erodibility factor [41]. In this study, the soil data was derived from global soil raster data downloaded from Harmonized World Soil Database-Food and Agriculture, HWSD FAO, soil web browser. The soil properties data was analyzed by the method depending on the percentages of sand, silt, clay, and organic carbon fraction as shown in equations (5)-(8). Then, the soil erodibility factor was estimated by equation (9).

$$f_{csand} = \left\{0.2 + .3 \exp exp\left[-0.25m_s\left(1-\frac{m_{silt}}{100}\right)\right]\right\} \tag{5}$$

$$f_{cl-si} = \left(\frac{m_{silt}}{m_c+m_{silt}}\right)^2 \tag{6}$$

$$f_{orgC} = \left\{1 - \frac{0.25orgC}{orgC+exp[3.72-2.95orgC]}\right\} \tag{7}$$

$$f_{hisand} = \left\{1 - \frac{0.7\left(1-\frac{m_s}{100}\right)}{\left(1-\frac{m_s}{100}\right)+exp\left[-5.51+22.9\left(1-\frac{m_s}{100}\right)\right]}\right\} \tag{8}$$

$$K = f_{csand} * f_{cl-si} * f_{orgC} * f_{hisand} \tag{9}$$

Where K is the soil erodibility factor, f_{csand} is the high-coarse sand content in soil, f_{cl-si} is the clay and silt in content soil, f_{orgC} is the organic carbon content in soil, f_{hisand} is the high sand content in soil, m_s is the percentage of sand fraction content (%), m_{silt} is the percentage of silt fraction content (%), mc is the percentage of clay fraction content (%), and orgC is the percentage of the organic carbon content of the layer (%).

3.1.4 Crop cover and management factor (C)

The crop cover and management factor is defined as the proportion of soil loss from land with particular vegetation and uninterrupted heath [19]. C factor is the only parameter that can be changed over time in most conditions and has a great role in keeping strategy development. C factor map was derived based on the land use and land cover of the lake Tana basin. Six land cover classes were targeted, namely, urban, barren, water, forest, crops, and grass [42]. A supervised maximum likelihood classification method was used. Then, a raster map of land use and land cover was converted into a vector, values of the C factor were assigned and the C factor map was generated.

3.1.5 Conservation support practice factor (P)

Conservation support practice factor is defined as the ratio of soil loss by particular support practice to the correspondent loss of up and downslope farming [19]. The P factor considers the control practices which minimize the rainfall and runoff power of erosion by their effect on runoff velocity, runoff concentration, and drainage patterns [43]. **Table 2** Shows values of the P factor based on slope and cultivation method.

Table 2: P value [44]

Slope (%)	P factor value
0-7	0.55
7-11.3	0.6
11.3-17.6	0.8
17.6-26.8	0.9
>26.5	1

3.2 Sediment Yield Model

3.2.1 Sediment Delivery Ratio (SDR)

Sediment delivery ratio is defined as the fraction of overall soil loss from a specific area in a specific period. It measures the sediment amount that is imparted from sources of erosion to the basin outlet in comparison with the gross amount of discrete soil from the same area. Many physical factors affect the SDR such as land use and land cover, slope, sediment particle size, drainage area, and relief length. Many relationships of SDR have been advanced on the basis of integration between different physical characteristics of the basin [45], but these relationships are applicable for small watersheds only [46]. The average slope of mainstream was found more important than other parameters in the assessment of SDR [47]. Williams and Berndt developed an empirical expression equation to estimate SDR based on a percentage of the main stream slope [47].

$$SDR=0.627*slp0.403 \qquad (10)$$

Where slp is the percentage of mainstream slope. Method of Williams and Berndt [47] for estimating SDR was affirmed by Onyando et al. [48]. Empirical equation (10) was applied in this study.

3.2.2 Sediment yield estimation

Sediment yield estimation is the sediment load computed at the outlet of the basin (end of main stream channel). It can also be defined as smoothed sediment load in the drainage area and the gross outcome of deposition and erosion operations through a basin. Factors, which affect erosion and sediment delivery, are the same ones that affect sediment yield, such vegetation cover, climate, basin morphology, soil characteristics, and drainage network properties [49]. Due to lack of basin-appropriate sediment system, sediment yield cannot be measured directly [46]. Therefore, precise assessment of sediment delivery ratio is an essential tactic for estimating sediment yield. In this study, sediment yield was estimated by overlapping the soil loss raster layer acquired from the RUSLE model and sediment delivery ratio based on the slope of mainstream channel as expressed in the following equation:

$$SY= i=1nSDR*A \qquad (11)$$

Where SY is the sediment yield, SDR is the sediment delivery ratio, and A is the annual soil loss.

IV. RESULTS AND DISCUSSION

4.1 Soil loss factors evaluation

4.1.1 Rainfall erosivity factor (R)

Rainfall erosivity values were analyzed and computed through ArcGIS using equation (2) with the help of the raster calculator tool. The R value ranges from 505.4 $MJ.mm.ha^{-1}.h^{-1}.y^{-1}$ to 647.4 $MJ.mm.ha^{-1}.h^{-1}.y^{-1}$ with a mean of 568.3 $MJ.mm.ha^{-1}.h^{-1}.y^{-1}$ and standard deviation of 42.1. R factor values are spatially distributed over the lake Tana basin as shown in **Figure 3**. The northern part of the basin has the lowest values of R factor, unlike the southern part which has maximum values.

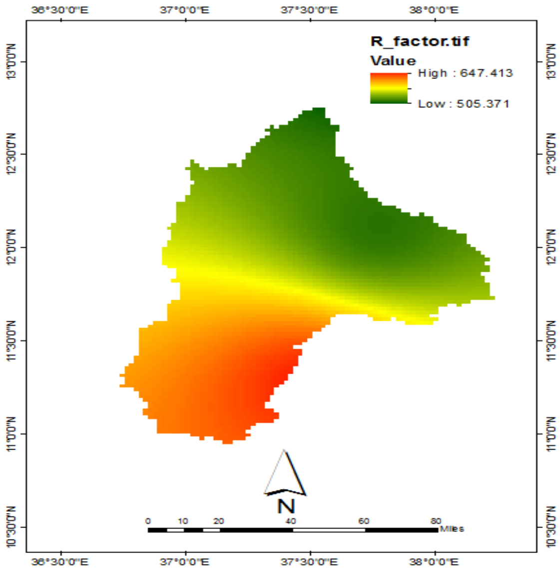

Figure 3: R factor map

4.1.2 Slope length-steepness factor (LS)

The slope length-steepness factor was estimated by using equation (3) and mapped in ArcGIS using the raster calculator tool. LS values range from 0 to 560, representing the steepest part of the basin, as shown in **Figure 4**. The greater the LS factor values, the greater the effect it has on soil erosion for the basin because of the water flows from rainfall and runoff.

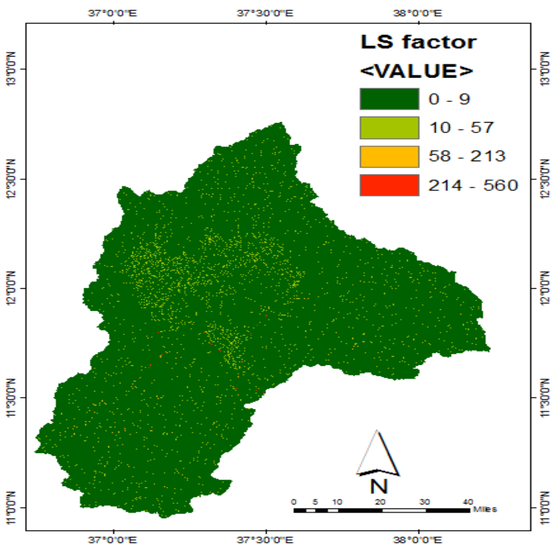

Figure 4: LS factor map

4.1.2 Soil erodibility factor (K)

Hydrologic soil groups for the lake Tana basin were assessed using global soil raster data downloaded from Harmonized World Soil Database-Food and Agriculture, HWSD FAO, soil web browser. Equations (5)-(9) were used to determine the K factor values. In this study, the K factor ranges from 0 to 0.151 with a mean value of 0.11 and standard deviation 0.06. **Figure 5** shows the spatial distribution of K factor as it increases from the lower part to the upper part while it equals 0 for the water body.

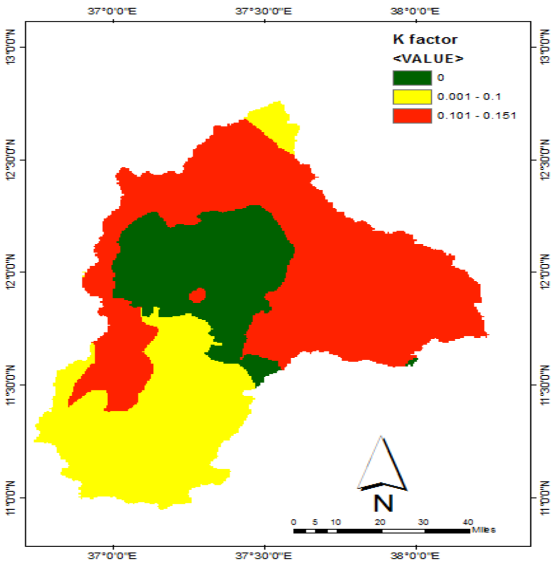

Figure 5: K factor map

4.1.4 Crop cover and management factor (C)

The crop cover and management factor values were assigned as shown in Table 3. the range of the C factor is from 0 to 1 with a mean value of 0.36 and a standard deviation of 0.36. The maximum value of K was assigned to barren land, which represents the most area of Lake Tana basin. Figure 6 shows the spatial distribution of the C factor for the lake Tana basin.

Table 3: C factor values [50]

Land Use Type	C Factor
Barren land	1
Urban	0.5
Water body	0
Forest	.01
Grass	.015
Crops	0.35

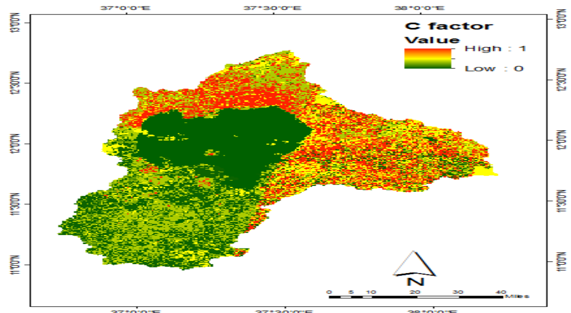

Figure 6: C factor map

4.1.5 Conservation support practice factor (P)

Conservation support practice factor values were computed based on slope and cultivation method as shown in **Table 2**. In this study, the P value varied from 0.55 to 0.6. **Figure 7** shows that P value of most lands in the study area equals 0.6 except the water body which has a value equals 0.55.

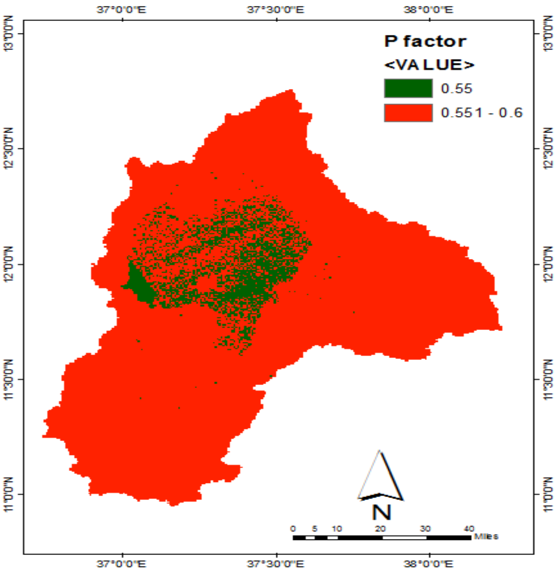

Figure 7: P factor map

4.1.6 Soil loss computation

All layers of RUSLE factors were simulated through ArcGIS using the empirical equation (1) with the help of the raster calculator geoprocessing tool, and the soil map was possessed. The map is represented in a grid format whose cells are 30m*30m. this map accounts for the average annual soil loss per hectare. The range of soil loss computed for the lake Tana basin varies from 0 to 10103 $t.ha^{-1}.y^{-1}$ with a mean value of 79.3 $t.ha^{-1}.y^{-1}$ and a standard deviation of 225.

Six classes of computed soil loss value were targeted on the basis of soil loss spatial distribution and histogram distribution as shown in **Figure 8**. **Table 4** shows that about 57.5% of the lake Tana basin is under low erosion risk (0-10 $t.ha^{-1}.y^{-1}$), and about 40.3% of the study area is under high and very high erosion risk.

Table 4: Soil loss of lake Tana basin

Soil erosion class ($t.ha^{-1}.y^{-1}$)	Area (ha)	Area (%)
Very low (0-5)	884417	56.3
Low (5-10)	19466	1.2
Moderate (10-15)	13667	0.9
Moderately high (15-20)	19610	1.3
High (20-40)	146429	9.3
Very high (>40)	486981	31

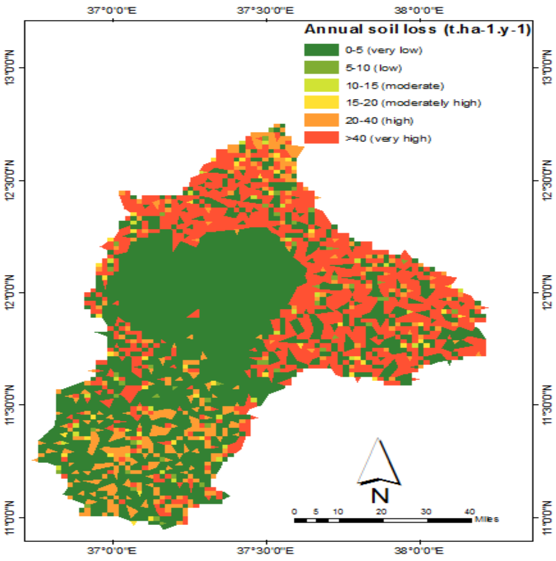

Figure 8: soil loss map of lake Tana basin

4.2 Sediment yield estimation

Sediment delivery ratio was estimated based on the slope of mainstream channel for lake Tana basin through ArcGIS environment. The average channel slope of the study area was found to be 0.136. SDR was computed using equation (10) and was found to be 0.281. sediment yield was calculated using equation (11). Sediment yield map was obtained by using the raster calculator tool through ArcGIS by multiplying the layer of the net soil loss by the average value of SDR. **Figure 9** shows that sediment yield value varies from 0 to 5405 $t.ha^{-1}.y^{-1}$ with an average value of 22.28 $t.ha^{-1}.y^{-1}$. The mean annual sediment yield computed at the outlet of lake Tana basin, in this study, is logic and actual compared to the results of the previous studies. Shimelis Gebriye Setegn used SWAT model to estimate sediment yield delivered to the outlet of the lake Tana basin and found it 24.6 $t.ha^{-1}.y^{-1}$ [51].

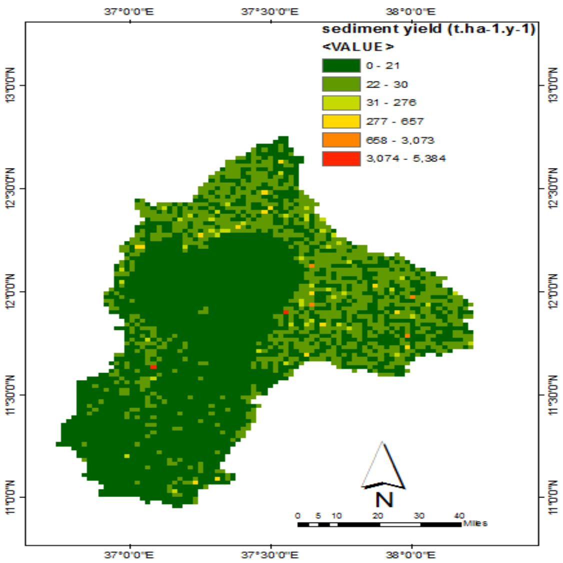

Figure 9: Sediment yield of Tana basin

V. CONCLUSION

Familiar models of investigating erosional hazard zones, even for small watersheds, need enormous data amounts and comprise huge arithmetic works. Integration among the RUSLE model and GIS and remote sensing techniques is efficient in computing soil erosion and sediment yield for basins. It can also be applied to introduce thematic maps of the spatial distribution of soil loss and sediment yield.

In this study, soil loss and sediment yield in the lake Tana basin were simulated using RUSLE model integrated with GIS and remote sensing technologies. The results and analysis show that the average annual soil loss computed at the outlet of lake Tana basin is about 79.3 $t.ha^{-1}.y^{-1}$. This study also investigates zones that exposed erosion risk. The findings indicated that about 40.3 of the study area is under high and very high erosion risk. It is observed that the northern part of lake Tana basin is the most erosional risky zone. Map of annual soil loss is useful to carry out appropriate soil protection practices in areas of high erosion risk.

SDR was estimated through the ArcGIS environment based on the slope of the mainstream channel and found to be 0.281. sediment yield was assessed and found ranges from 0 to 5405 $t.ha^{-1}.y^{-1}$ with a mean value of 22.28 $t.ha^{-1}.y^{-1}$.

RUSLE method based on GIS was successfully used to estimate soil loss and sediment yield and investigate erosion risk zones. This study can be used for other basins other than lake Tana basin. It can help policymakers in making the best appropriate decisions to control soil erosion risk in various regions.

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