

## **Estimation of Soil Loss Rate Using RUSLE Model Integrated with GIS and Remote Sensing Techniques: The Case of Wama Watershed, Western Ethiopia**

Dawit Girma Burayu<sup>1</sup>

1, Wolkite University, Wolkite, Ethiopia

cetwku@wku.edu.et

**ABSTRACT-** One of Ethiopia's most problematic issues is soil loss due to degradation and erosion. Estimating the quantity of soil loss at the watershed level is required to solve this problem. However, in many catchments (watersheds) in Ethiopia, specific up-to-date information is still lacking. The goal of this study was to use model estimates and GIS to investigate the nature, extent, and rate of soil loss in the watershed. The Revised Universal Soil Loss Equation (RUSLE) was used in conjunction with satellite remote sensing and geographic information systems (GIS) as a useful tool for conservation planning. Mean annual precipitation, digital soil map, digital elevation model, LULC map, and slope steepness were used to determine the RUSLE parameters. The result showed that the potential annual soil loss of the watershed ranges from 0 to 53200.7t/ha/year and the mean annual soil loss rate is 357ton/ha/year. The study area was classified into five

severity classes as, Low ( $0 - 15 \text{ t h}^{-1} \text{ yr}^{-1}$ ), Moderate ( $15.1 - 35 \text{ t h}^{-1} \text{ yr}^{-1}$ ), High ( $35.1 - 50 \text{ t h}^{-1} \text{ yr}^{-1}$ ), Very High ( $50.1 - 75 \text{ t h}^{-1} \text{ yr}^{-1}$ ) and Severe ( $>75 \text{ t h}^{-1} \text{ yr}^{-1}$ ). Moreover, the total annual soil loss in the study area was 13400000 tons from 3344.Km<sup>2</sup>. According to the study result, an area that covers 62% (2074.82 sq. km) of the watershed have low soil loss which indicated more than half of the area has low soil loss while 38% (1269.58 sq. km) of the watershed has severe to moderate soil loss. As a result, governments, non-governmental organizations, and communities in the watershed should concentrate on implementing soil and water conservation measures that will assist to alleviate the situation. The integration of the RUSLE model and geographic information systems platforms are also presented in this study as a strong and relevant strategy for estimating and monitoring the geographical rate of soil loss distribution for sustainable soil resource management.

Keywords: GIS, Soil loss, RUSLE, Remote Sensing

### **INTRODUCTION**

Soil degradation in the form of soil erosion is a serious and continuous environmental problem all over the world especially in developing countries like Ethiopia (1). According to studies, soil erosion is caused by cultivation without the use of particular control techniques and unplanned land use, such as uncontrolled urban development, deforestation, and bad agricultural practices. (1). The effects of soil loss are visible in developing countries because of the incapacity of their farming population to replace lost soils and nutrients (2). To alleviate this problem Ethiopia started to plan on a watershed basis starting from the 1980s. But it was mostly unsatisfactory due to a lack of effective community participation, unmanageable planning units, and a lack of deep study about the watershed (3). Extension of agriculture to

marginal lands in the Ethiopian highlands, such as steeper slopes and swampy plains, and traditionally unexploited parts of the environment, may indicate the presence of strain on land vegetation and water resources (4).

Due to overpopulation, 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 highlands of Ethiopian are severely affected by watershed management problems (5) Thus Understanding Watershed characteristics and Watershed management is a very important part to maintaining healthy productive rivers.

In Ethiopia, where agriculture is the mainstay of the economy, soil loss is one of the most serious and

persistent kinds of land degradation, posing a threat to the country's agricultural production's long-term viability. Due to the high erosive strength of rainfall, intense agricultural techniques, and high human density, the problem is particularly acute in the country's highlands. (6)

Blue Nile Basin is one of the largest basins found in the highlands of Ethiopia characterized by high population pressure, degradation of land, and is highly dependent on the agricultural economy (7). Wama watershed is found in Didessa Sub basin which has a major contribution to the Nile River basin. Due to the rapid growth of population, deforestation, and overgrazing, soil erosion, sediment deposition, storage capacity reduction, drainage and waterlogging, flooding, pollutant transport, overexploitation of specific fish species, the land and water resources of the sub-basin and its ecosystem are in high risk. Water erosion moves almost 1.9 billion tons of nutrient-rich soil from the highlands of Ethiopia annually (8). This amount is found to be equivalent to an annual soil loss from cultivated lands of 130 tons per hectare (8). As one part of the watershed in the highlands of Ethiopia, Wama Watershed is highly affected by soil erosion problems (9). Besides this, Soil acidity is a common problem in Western Ethiopia including the study area. Agricultural expansion, which promotes soil erosion, continues despite the Ethiopian government's application of soil and water conservation techniques in various parts of the nation due to population growth. Soil erosion is still a big hazard to the country, and experts need to pay attention to it. In Ethiopia, more than 200 studies on soil erosion, soil loss, and water conservation have been done (10). However, the majority of them were concentrated in the Ethiopian highlands, particularly in the northern highlands. (10). The eastern, western, and southern parts of the country need the focus of researchers. Wama Watershed is

## **MATERIALS AND METHODS**

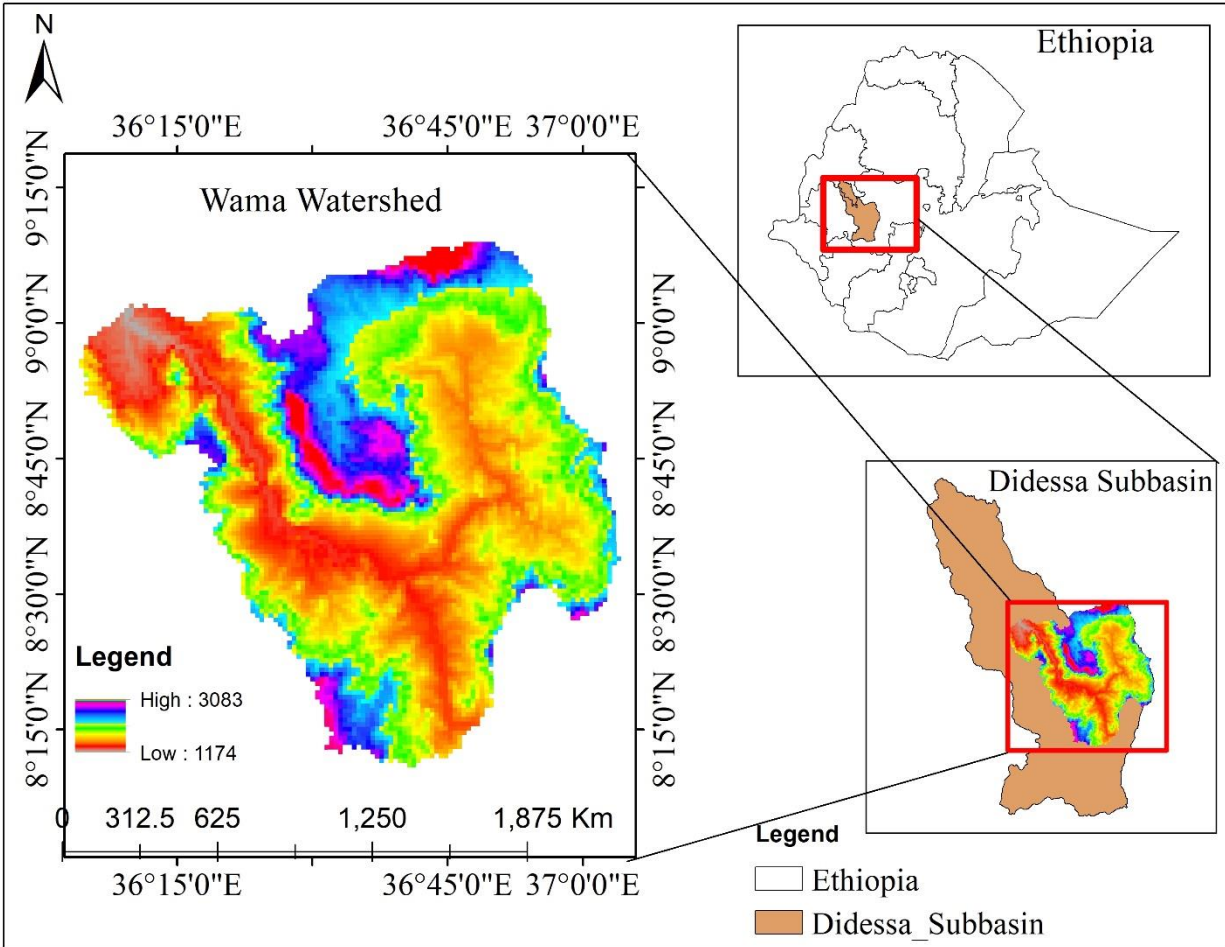
### **Description of the Study Area**

Wama is among the top important watersheds in terms of share in Didessa Sub-basin's annual runoff volume. Geographically the sub-basin is located between  $08^{\circ} 10' 00''$ -  $9^{\circ} 10' 00''$  N and  $36^{\circ} 05' 00''$ - $36^{\circ} 05' 00''$  E latitude and longitude respectively in the western part of Ethiopia. The general elevation in the basin ranges between 1174m a.m.s.l. and 3083m a.m.s.l. It drains

located in the southwestern part of the country which is a less studied area. However various small-scale, medium-scale, and large-scale water resource projects are constructed and is under construction.

Geographic Information System (GIS) and remote sensing technologies have become an important tool in the spatial analysis of factors such as topography (11), DEM, soil, land use/land cover, and Rainfall GIS-based RUSLE method was used in Wama Watershed to predict soil loss (2). GIS provides a digital representation of the catchment, which can be used in hydrologic modeling (12). The land surface slope, land use and soil characteristics can be extracted using this technique. In the current study, the parameters of soil erosion were generated by GIS (6). The Universal Soil Loss Equation (USLE) (13) is designed to predict soil loss from sheet and rill erosion in specific conditions from agriculture fields and later improved to Revised Universal Soil Loss Equation (RUSLE). (14) Runoff factor (R), which accounts erosive potential of rainfall droplets, and runoff has been incorporated in RUSLE for soil loss rate estimation (15). The models can be successfully used to estimate soil loss because they consider climate, topography, soil, and management practices. There are some studies conducted in Ethiopia to estimate soil loss problems using RUSLE (6) (16) (3) (17) (7) (5) (4) (1) (2) (12) (18) (19) (15) (11) (9), but no specific study is done to determine the amount of soil loss for the current study area. This study aimed to determine the spatial distribution of soil loss in Wama Watershed and to estimate the annual soil loss rate from the subbasin by using Remote sensing and GIS-based RUSLE is very important for decision-makers.

a catchment area of about 3,344.4 km<sup>2</sup>. It receives a mean annual rainfall of 1,934.64 mm (the highest among Didessa Sub-watersheds) and the mean annual runoff is about 448 mm. The river basin is classified under a humid tropical climate with heavy rainfall with an annual amount that is mainly received when the weather is wet. The highest and lowest temperature ranges between 21–31<sup>o</sup>C and 10–15 <sup>o</sup>C, respectively.



**Fig 1 Study area map**

**Data collection and Analysis**

For this study, soil loss modeling was employed by using RUSLE empirical equation integrated with the GIS environment. The Existing Soil map recorded rainfall of eleven (11) stations LANDSAT Image, Digital Elevation Model (DEM of 30mX30m resolution), were used to develop the important factors for the RUSLE model. Grid-based (cell by cell) soil loss rate of the watershed was predicted by using the revised universal soil loss equation (RUSLE) in the GIS environment (7). Thus, grid cells were devoted before the estimation of the physical properties of these cells such as slope, land use, and soil type, all of which affect the soil loss process in different grids of the watershed.

The Rainfall data were collected from the National Metrological Agency (NMA) located nearby the watershed and the Kriging method of Interpolation was applied to estimate rainfall erosive factor Value for the study area using ArcGIS Spatial Analysis Tool. Soil data of the study area were obtained and extracted from the FAO soil Map of Ethiopia (8) and used, to

analyze the soil erodible factor (K). The soil map has a polygon shape format. The soil feature map of the study area is obtained by clipping the FAO soil map of Ethiopia with the study watershed and then the erodible value (K factor) was assigned for each of the soil types based on their colors as indicated by (14). Digital elevation model (DEM) is a digital file consisting of elevation for ground positions at regularly spaced horizontal intervals. In other words, digital elevation model (DEM) data are digital representations of cartographic information. Digital elevation models (DEM) with 30-meter resolution developed by NASA were used in analyzing the flow accumulation and slope gradient of the watershed. Multi-temporal satellite imageries of the watershed have been imported to EDRISI image processing software. Image pre-processing, enhancement, classification were applied to the raw image. The classified images have been used in the extraction of information on land cover conditions and quantification of C- factor value over the last three decades using multi-temporal GIS analysis. The

dominant LULC classes were selected and different LULC classes, such as Forest, Woodland, Shrubs/Bush, Cropland, Grassland, Bare land, Wetland, Waterbody, and Settlements were identified.

**Determination of RUSLE parameters**

**Rainfall Erosive (R) factor**

The rainfall erosive factor estimates the effect of rainfall impact and also reflects the amount and rate of runoff that are most likely to be linked with  $R = -8.12 + (0.562 * P)$

Where R is the rainfall erosive factor, P is the mean annual rainfall in mm.

**Soil Erodibility (K) factor**

The soil Erodibility factor expresses the soil susceptibility to the detachment and transportation of soil particles. It's the ratio of soil loss from the field's slope length and steepness to a standard slope length of 22.1 m and steepness of 9%. According to (21), soils that have different characteristics have different resistance to erosion. Hence, erodible varies with the

precipitation events. The mean annual rainfall data of 12 stations were interpolated by Kriging and used to calculate the rainfall erosive factor (R). The most appropriate expression of rainfall erosive is an index based on the rain's kinetic energy (20; 20). Different approaches can be used to derive the Rainfall Erosive factor. The empirical equation developed for Ethiopia and Egypt was employed in this investigation (14).

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physical and biochemical properties of soil such as soil texture and structure, aggregate stability, shear strength, infiltration capacity of organic matter, and chemical content (18). However, in Ethiopia, soil data frequently lacks specific information regarding such soil properties. The K-factor values for each type of soil were assigned based on the existing soil types in the study area. Then, as one factor, a K-factor map was created to account for the effects of soil type on soil erosion Table1

Table1. Soil Types and corresponding Erodibility Factor (K-values)

Types of Soil	Humic Nitisols	Humic Alisols	Lithic Leptosols	Eutric Vertosols
K-Value	0.2	0.25	0.225	0.25

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

LS-factor is the ratio of soil loss per unit area from a field slope to that of the standard field slope (22.1 m long and 9% slope). This factor is a combined factor of slope length (L) and slope steepness (S) (18). The distance between the site of origin of overland flow to the point where deposition begins or runoff water enters a well-defined channel is referred to as a slope length (19). Slope steepness is the gradient from point of origin of flow to the point where either the slope

$$LS = Power \left[ (Facc) * \left( \frac{resolution}{22.1} \right), 0.6 \right] * Power \left[ \left( \frac{\sin(slope) * 0.01745}{0.09} \right), 1.6 \right] \quad (2)$$

where, FA (flow accumulation) is the raster-based total of the accumulated flow to each cell, and (Resolution) is cell size or length and width of the pixel size.

**Vegetative cover (C) factor**

The land use and land cover (LULC) factor expresses the effect of land use and land cover on soil erosion rate (22). It's the ratio of soil loss from a field with a specific vegetation cover to the equivalent soil loss from a continuous fallow with the same rainfall. (13). Therefore, for this study, the land use and land cover classification map of 2016 was used. It shows detailed classification of LULC in the specified year for the study area. Using the classified map, the

decreases enough that deposition begins or runoff water enters a well-defined channel

A flow direction and flow accumulation map were processed and generated from digital elevation model data after fill operation in Hydrology tools of the GIS extension to use as an input for the calculation of the LS-factor. To generate the map of the LS-factor, Equation (2) was used in the raster calculator of the GIS database. The equation was developed by (13)

corresponding recommended C-factor values for different LU LC classes were assigned (23). These values were collected from previous studies and assigned for corresponding LULC types. Finally, the gis database generated the c factor map.

**Soil and water conservation practice (P) factor**

In the RUSLE model, the P-factor is considered as the ratio of soil loss with a specific conservation practice to the corresponding loss with up and downslope cultivation (zero management), which has a value of one (13). The values of the P-factor for the current condition and the suggested management condition with the respective classified slope in percent are given in table 2

Table2. cover and Management (C) and Support Practice (P) Factors

LULC	C-factor	P-factor
Forest	0.05	1
Woodland	0.25	0.27
Shrub/Bush	0.37	68
Cropland	0.68	0.48
Grassland	0.45	0.87
Bare land	0.65	0.57
Wetland	0.75	0.91
Waterbody	0.66	0.69
Settlement	0.47	0.67

**Soil Loss modeling approach**

The integration of RUSLE (equation (3)) with GIS and remote sensing was used to estimate the soil loss of the Subbasin. RUSLE requires five Spatial data layers including R factor, K factor, LS factor, C factor, and P factor these are obtained from the metrological station,  $A=R*K*LS*C*P$  (3)

Where, A = annual soil loss, R = runoff erosivity, K = soil erodibility, L = slope length, S = slope steepness, C = cover-management, P = support practice factor.

soil map, and remote sensing data. Using the "spatial analyst tool map algebra raster calculator" in ArcGIS10.7environment, the annual soil loss rate was calculated by multiplying the relevant RUSLE factor values interactively as shown in equation (3)

The RUSLE model analysis in the GIS database from the data source to the result is given in Figure 2. It shows the detailed process of the methodology.

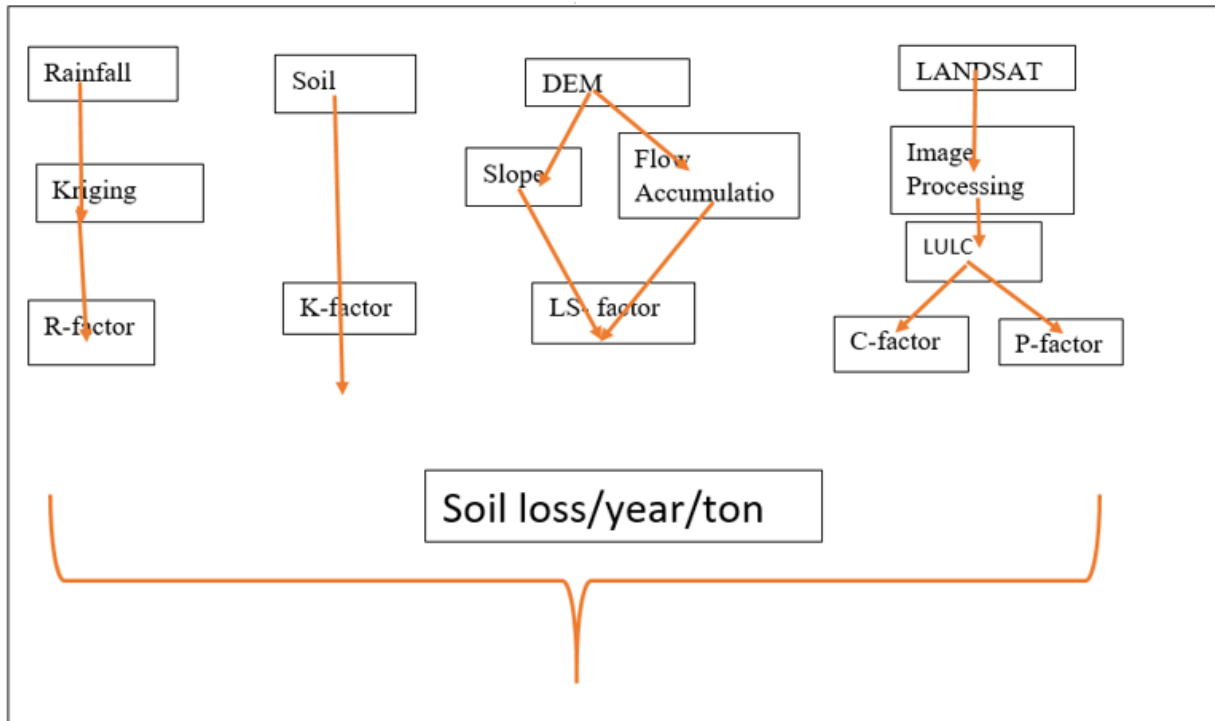


Fig 2. Frameworks to determine soil loss using RUSLE

**RESULT AND DISCUSSION**

Geographic information system (GIS) and Remote sensing techniques integrated with the RUSLE model to conducted cell by cell calculation of mean annual

soil loss rate and to identify and map soil erosion risk area. Each RUSLE parameter is represented by a raster map, which was compiled from multiple data sources and explained as follows.

**Rainfall erosive (R) factor**

Rainfall erosive is determined by the amount and pattern of rainfall. The erosive factor of rainfall (R) is a function of the falling raindrop and the rainfall intensity and is the product of the kinetic energy of the raindrop and the 30-minute maximum rainfall intensity (4). However, in Ethiopia, the R-value correlates to the watershed's mean annual rainfall, as determined by the r correlation established by (14). The result of Kriging interpolation using precipitation data of 12 meteorology stations indicated that the mean annual rainfall of the watershed is ranged from 1681.88 to 2118.56 mm with the highest value in the

Central part and lower value in the northeastern part of the watershed (Figure 3a).

The rainfall erosive (R) factor map was calculated by applying equation (2) in Raster Calculator of Spatial Analyst Extension in ArcGIS 10.7 software from the interpolated rainfall map, and the result indicated that the R-factor value of the watershed ranged from 937.5 to 1182.79 MJ mm ha<sup>-1</sup> year<sup>-1</sup> (Figure 3b) with higher values occurring in the Central part of the watershed, and the potential of rainfall to erode soil gradually decreases toward the north, south and southeast part of the watershed.

Table3 Mean annual rainfall and erosivity factor(R)result

Station Nama	Long	Lat	Mean Annual Rainfall	R_Value
Arjo	36.5	8.75	2120.7	1183.7134
Atinago	36.333	8.45	1857	1035.514
Bedele	36.1	9.3833	1548	861.856
Dedessa	35.783	9.1667	1870	1042.82
GidaAyana	36.783	8.6833	1853	1033.266
Gimbi	36.463	9.0833	2101	1172.642
Haro	37	8.76	2081.6	1161.7392
Kone	36.872	9.0397	1675.6	933.5672
Nekemte	36.61	9.87	1768	985.496
Nunu	36.31	9.84	1757.7	979.7074
Shambu	37.12	9.57	1827.1	1018.7102
Sibusire	36.98	8.3	1933.2	1078.3384

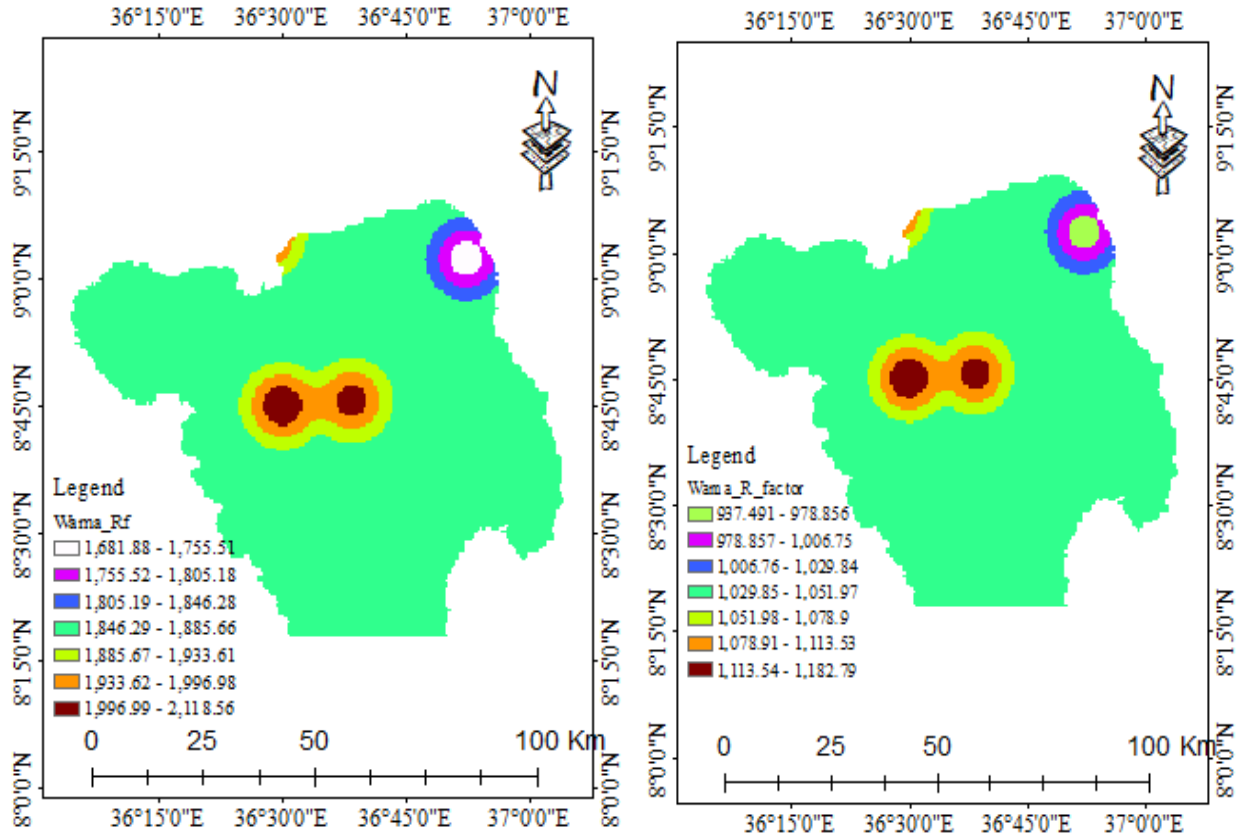


Fig 3 (a) Mean annual Rainfall map

**Soil Erodibility (K) factor**

The Soil Erodibility (K) factor represents both susceptibility of soil to erosion and the amount and rate of runoff. Soil texture, organic matter, structure, and permeability determine the erodibility of a particular soil. Soil erodibility is the manifestation of the inherent resistance of soil particles for the detaching and transporting power of rainfall. This metric measures a soil's cohesiveness and resistance to

(b) Rainfall erosive (R) factor map

dislodging and transport caused by raindrop impact and overland flow shear pressures. The K-factor is a physical and chemical property of soil that contributes to its erodibility potential. It is empirically established for a specific soil type. Based on the color of the soil the value of the k-factor in the study area ranges from 0.15 to 0.25. The high k-factor value indicates a more vulnerable soil type to soil erosion and the smaller value shows a less vulnerable soil type to erosion.

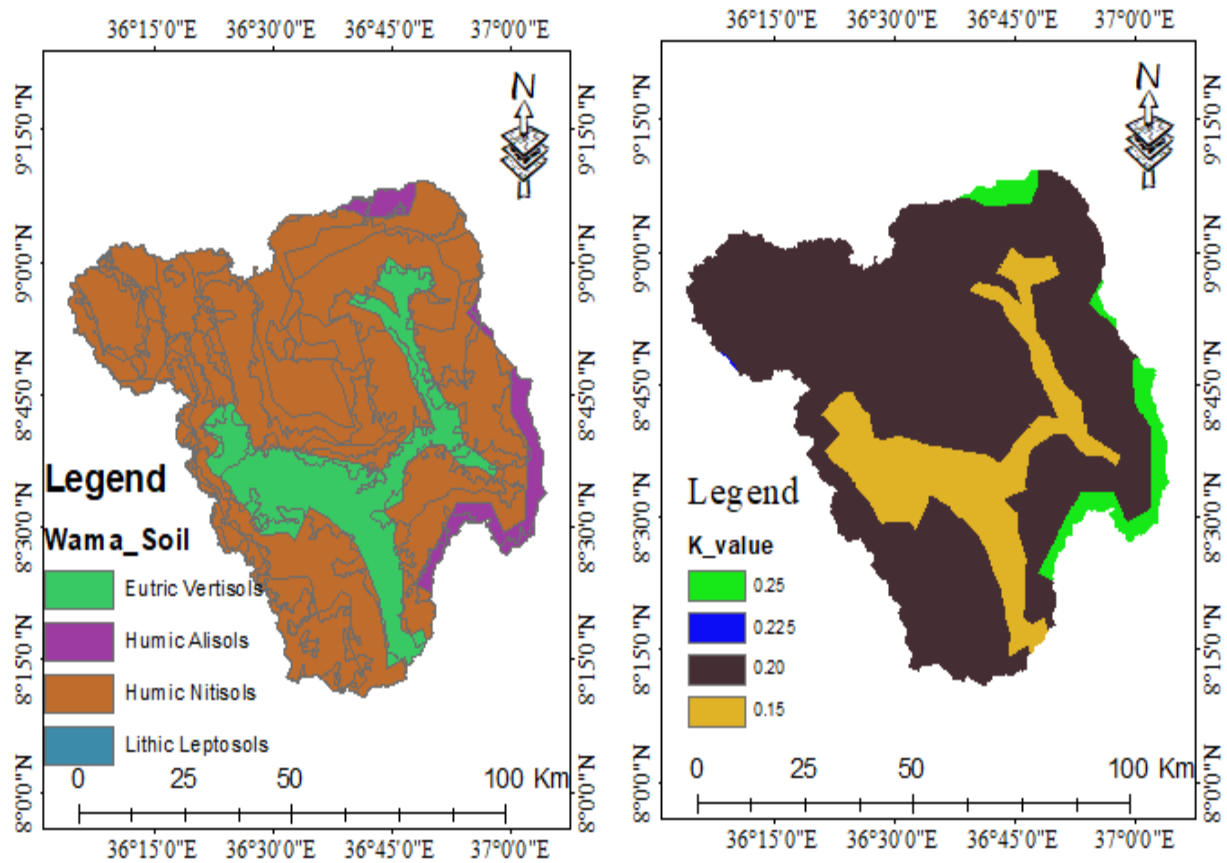


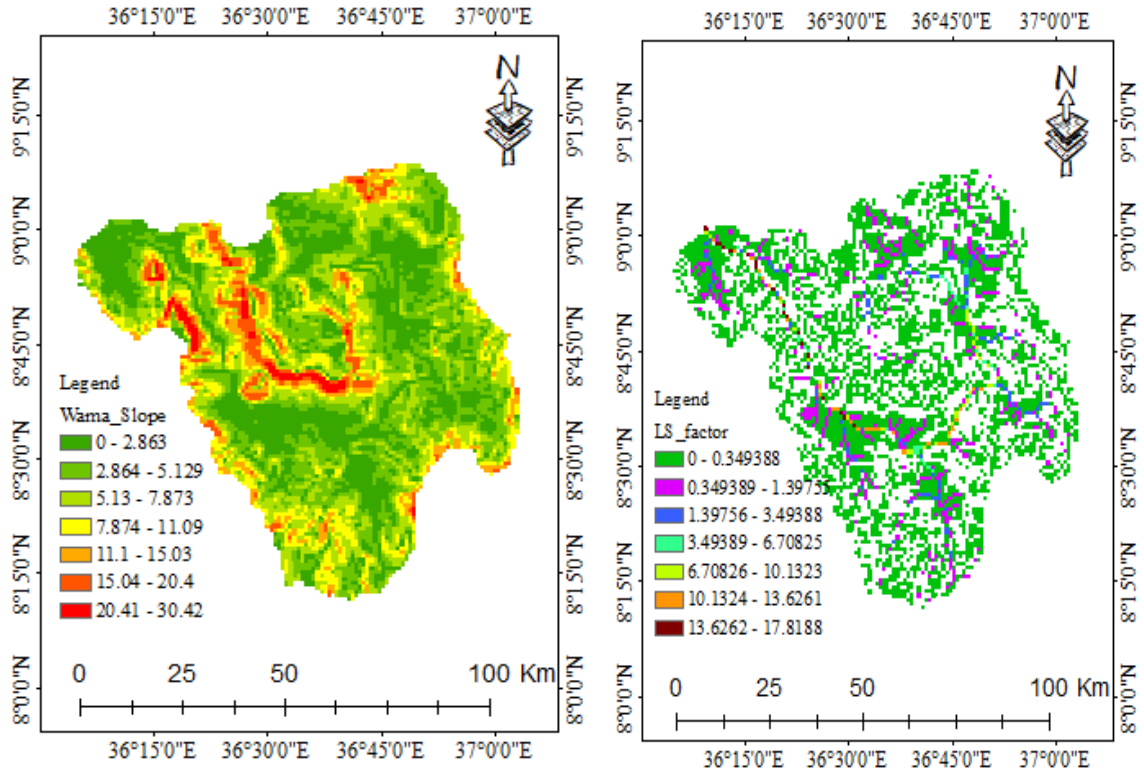
Fig 4. (a) Soil map

(b) Soil erodibility (K factor) map

**Topographic Erosivity (LS Factor)**

The slope steepness map (Figure 4A) was directly generated from the STRM DEM (30-m spatial resolution) map of the watershed. After fixing small flaws and processing flow direction, the flow accumulation map was created from the STRM DEM.

The topographic (slope length and slope steepness) factor was computed based on equation (2) using the Raster Calculator of Spatial Analyst Extension in the ArcGIS environment. The result in Figure 4b indicated that the slope length and slope steepness (LS) factor value of the watershed varies from 0 in flat areas to 17.8 in the stream bank.



**Fig 5. (a) Slope map  
 Crop management (C) factor**

In this study, the land use land cover is the variable to show its potential impact on soil erosion. Land use and land cover of the year 2020, which was prepared from LANDSAT 8 OLI/TIRS through supervised digital image classification technique using EDRLSI was used as an input for generating crop management (C) factor. As shown in (Figure 6) Nine land use land cover classes were recognized currently in the watershed.

**(b) LS\_factor map**

The raster land use/land cover map was converted to vector format, and each land-use class was assigned a C-value based on cover values proposed by the author (14) (Table 3). Finally, the land use/land cover map was converted to a C factor map via reclassification and vector to raster conversion (Figure 6 (b)). The C-factor ranged from 0.05 to 0.75.

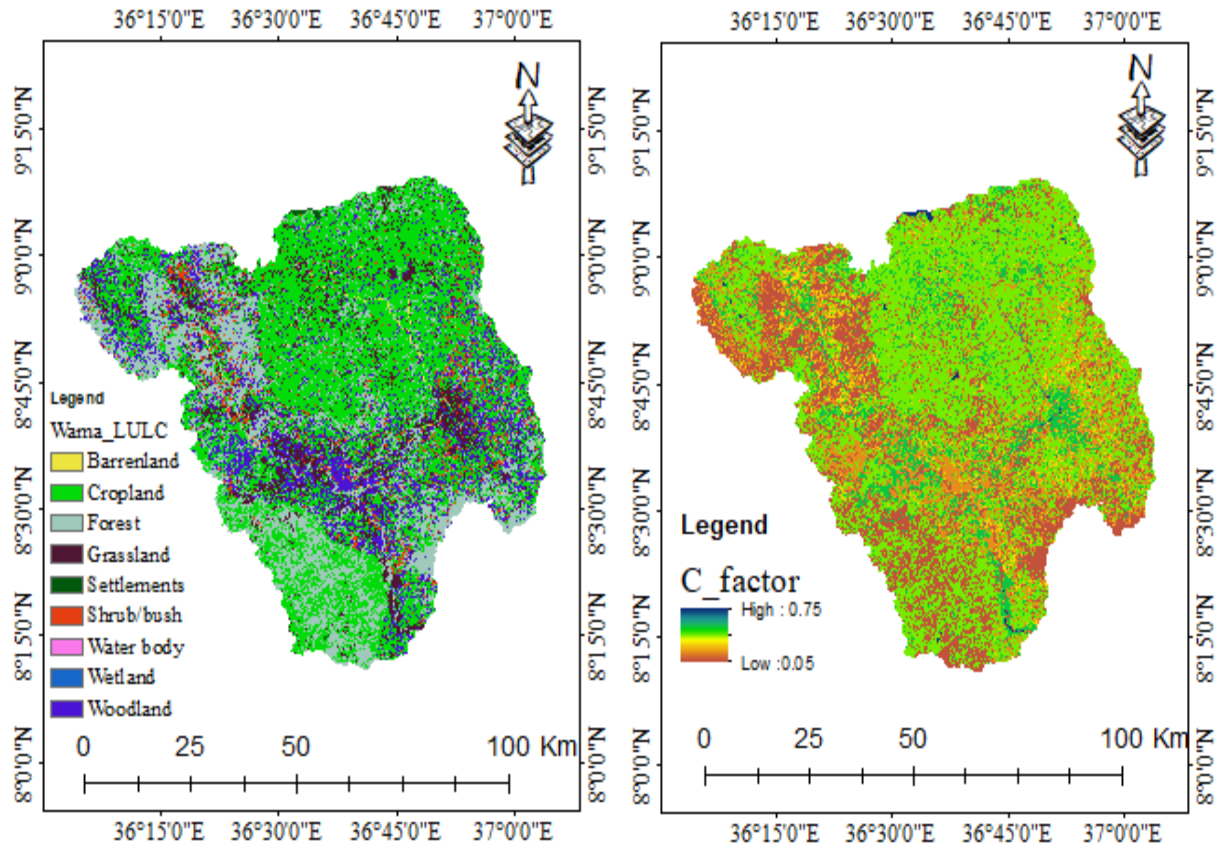


Fig 6 (a) LULC map

(b) C- factor map

**Conservation Practice factor (P factor)**

The P values vary from 0 to 1, where the value 0 represents a very good erosion resistance practice and the value 1 represents no resistance practice. In the present study, P factor value of 1 was adopted for

Contour farming is used as support practice in the upper non-agricultural areas, where there are no support practices, and it depends on the slope and type the crop for agricultural land.

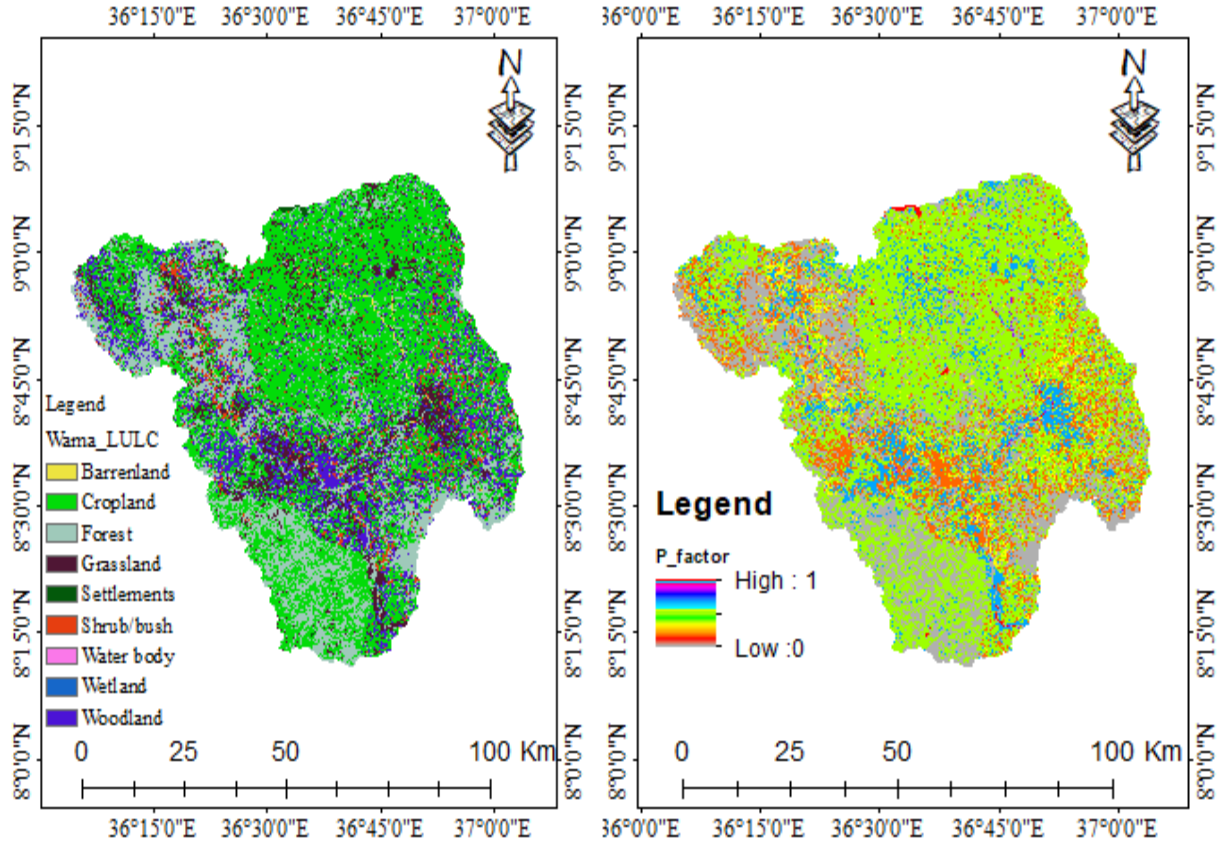


Fig 7 (a) LULC map (b) P-Factor map

**Estimation of annual gross soil loss rate**

In this study, the rate of annual soil loss ranging from 0 to 53200.7t ha<sup>-1</sup> yr<sup>-1</sup> with an average value of 357t ha<sup>-1</sup> yr<sup>-1</sup> was estimated with the RUSLE model, Remote sensing, and GIS tools. The map of composite factors represents the soil erosion potential of different grid cells. High values of this term indicate a higher potential of soil erosion in the cell and vice-versa. Soil erosion risk differs spatially in the study area because of its rugged topography, geomorphology, landform, soil types, land cover, and land use. Based on the analysis in Wama watershed there is a high rate of soil erosion which was categorized into five classes. This class was recognized because of the presence of intensity differences in soil erosion factors. The study area was classified into five severity classes as, Low (0 – 15 t h<sup>-1</sup> yr<sup>-1</sup>), Moderate (15.1 – 35 t h<sup>-1</sup> yr<sup>-1</sup>), High ((35.1 – 50 t h<sup>-1</sup> yr<sup>-1</sup>), Very High (50.1 – 75 t h<sup>-1</sup> yr<sup>-1</sup>) and Severe (>75 t h<sup>-1</sup> yr<sup>-1</sup>). An area that covers 62% (2074.82 sqr. km) of the watershed has low soil loss which indicated more than half of the area has low soil

loss while 38% (1269.58 sqr. km) of the watershed has severe to moderate soil loss. The study found that potential soil loss is often greater along the steeper slope banks of streams. Other low soil erosion areas are distributed throughout the watershed. Moderate to severe soil erosion areas are also concentrated in the cultivated hilly area of the watershed as shown in (figure 12), 38 % (226958 ha) of land was under moderate to the severe class which is greater than the maximum tolerable soil loss (15 tons ha<sup>-1</sup> yr<sup>-1</sup>). The result of this study was revealed with the finding of who (20) reported that there is a high soil loss rate at the steep slope of the Hanger watershed near the study area. (2) quantify the soil loss of Fincha’a watershed and assess the spatial distribution of soil loss was consistent with our result. The findings of many studies including (6) (16) (3) (17) (5) (5) (4) (7) (24) (25) (26), agreed with our result. Thus, the estimated soil loss rate was generally realistic as compared to results from previous studies in other areas.

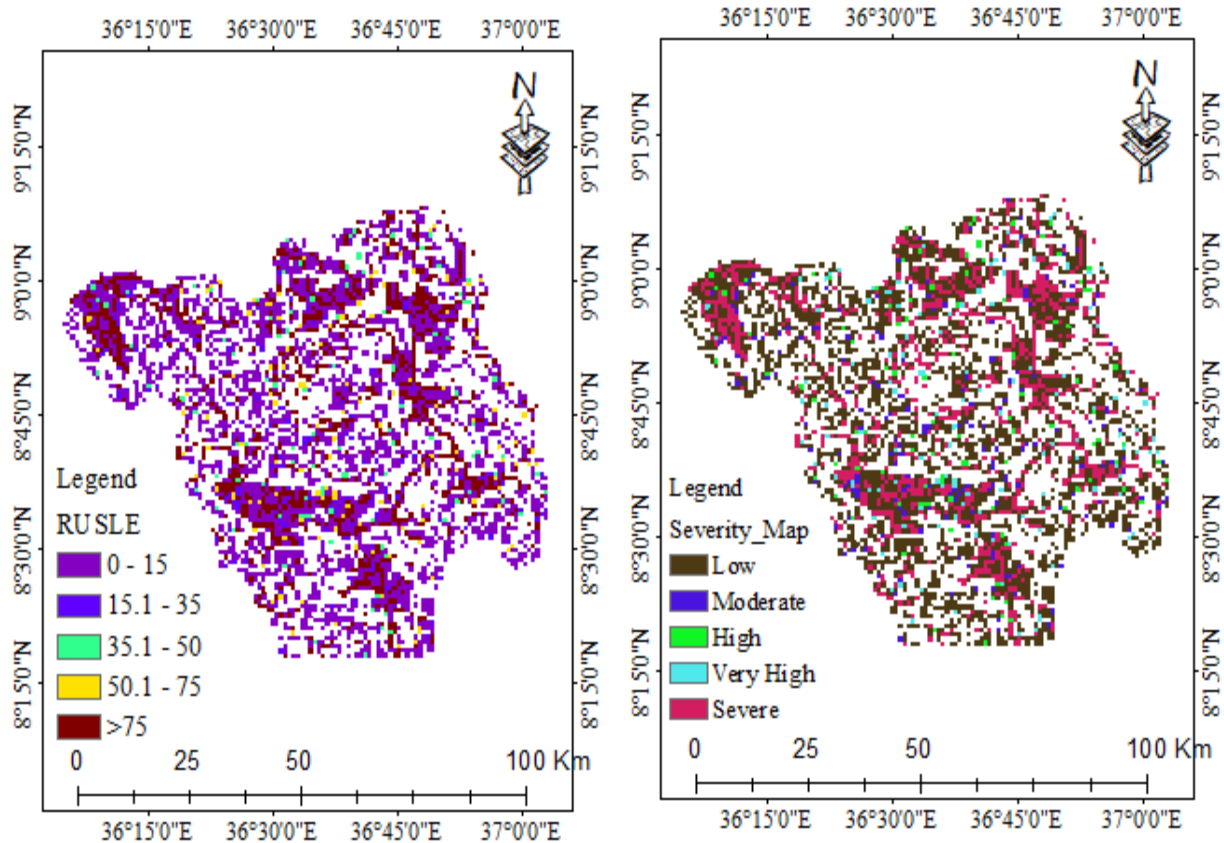


Fig 8. (a) Annual soil loss rate, extent, and distribution map

(b) Soil Loss Severity map

**CONCLUSION**

In an intermediate watershed like Wama, quantitative and spatial soil loss information obtained through simulation of RUSLE parameters using GIS and remote sensing techniques ensures the easy and efficient handling of spatially variable data and inaccessible areas where ground-based observation is difficult. The goal of this study was to provide a comprehensive overview of the state of erosion in the study area and its distribution in the watershed under current watershed conditions and with planned watershed management strategies. The finding of this study reveals that the study area is currently experiencing severe soil erosion by water. The result showed that the annual soil loss rate of the watershed was 1340000ton/ha/yr with an average soil loss of 357 t/ha/yr from the entire watershed. According to the study result, areas that are classified as severe erosion class covers an area of 905.57Km<sup>2</sup> which is about 27% of the total watershed while high and very high soil loss risk class covers an area of 198.87Km<sup>2</sup>(6 %), moderate soil loss risk class covers an area of 165.34Km<sup>2</sup> (4.9%) and low-risk class covers more

than have of the study area which accounts about 2076.82Km<sup>2</sup>(62%).

The study area was classified into five severity classes as, Low (0 – 15 t h<sup>-1</sup> yr<sup>-1</sup>), Moderate (15.1 – 35 t h<sup>-1</sup> yr<sup>-1</sup>), High ((35.1 – 50 t h<sup>-1</sup> yr<sup>-1</sup>), Very High (50.1 – 75 t h<sup>-1</sup> yr<sup>-1</sup>) and Severe (>75 t h<sup>-1</sup> yr<sup>-1</sup>). The watershed's soil loss map also revealed that, for sustainable land use, practically the whole watershed requires the deployment of various types of soil and water conservation measures. For proper soil and water conservation treatment, the sub-watershed was prioritized based on their average annual soil loss.

The integration of the RUSLE model and GIS platforms is also presented in this study as a powerful and relevant strategy for estimating and monitoring the spatial distribution of the rate of soil loss for sustainable soil resource management. This catchment's soil erosion-prone zones will aid in the implementation of soil conservation measures. The upper and lower-lying sections of the catchment are very sensitive to soil erosion, according to this study, and a soil conservation strategy should be established to minimize the loss of top fertile soil in the catchment. To reduce the effects of erosion, farmers and soil

conservation professionals should get capacity-building training.

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