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Case Study **Open Access**

Coupling Universal Soil Loss Equation and GIS Techniques for Estimation of Soil Loss and Sediment Yield in Algash Basin

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Abstract Soil erosion is a global problem which has social, environmental and economical adverse effects. Soil erosion reduces soil productivity and water quality, therefore this study was conducted as an effort to estimate the average and total soil loss and moreover the total sediment yield in Algash water basin which extends from Eritrea to the downstream in east of Sudan. The study utilized from GIS and remote sensing to analyze the soil loss, based on Universal Soil Loss Equation (USLE), this model is one of the most widespread models are used for soil loss estimation. Soil erosion was determined as function of five parameters using USLE, the rainfall erosivity factor (R) was estimated from annual mean rainfall for last 8 years, the soil erodiblity factor (K) was determined based on soil characteristics, topographic factor (LS) was estimated using SRTM, the forth factor is crop management factor (C) and it was estimated using Normalized Difference Vegetation Index (NDVI) and the support practice factor (P) was estimated using derived slope data and a produced land cover map. Based on the above analysis the annual average soil loss ranged from zero to 118.86 ton/ha.year per pixel and the total soil loss from the whole study area was found to be 32,916,840.87 ton/ha.year.

Keywords *Algash Basin; GIS, Remote Sensing; soil erosion; sedimentation; soil loss; USLE*

1. Introduction

Soil erosion is currently considered as one of the most significant concerns; it has negative impacts in soil, water quality and aquatic life. Accordingly, soil erosion represents a serious threat of food security, environment and life quality due to the soil deterioration (Graaff, 1996; Eswaran et al., 2001). It is one of the slowest and slight detectable processes, it mostly happens due to man-made interventions rather than a product of climatic inputs and natural hazards such as volcanoes, cyclones and natural fires. This regard is due to the sustainable passive human contribution on the Earth's surface which significantly affects the permanent vegetation cover. Furthermore, soil erosion such as coastal inundation which on hand is caused by coastal land floods due to e.g. huge tidal waves and storms, or sand swept away. On the other hand, the global warming also has considerable effects such as the growing melting ice caps based on thermal expansion which leads to sea level rise and setting new elevated costal water and losing sediments from land. Based on aforementioned facts, Favis-Mortlock and Guerra (2000) emphasized that the impact of natural processes is negligible with respect to human activities.

Soil erosion is problematic because it leads to the permanent soil degradation where recovery by natural restoration processes may not achieved over decades. Moreover, other off-site damages arise from eroded chemical-sediments caused by deposited materials in the nearby sites which may also affect surface water system. The difficulties in monitoring the erosion processes are due to the limitation of the direct measurements of soil loss over small areas where hydraulic conditions have to be taken into account. The negative impacts of land cover type in watershed ecosystems have been a common concern worldwide. For example agriculture clearing or any objects can intercept water flow which increases the amount of surface runoff and sediments that carried by it. However, when the natural vegetation is permanently converted to agriculture, the frequency and magnitude of floods will change and the sedimentation will occur (Knox, 1977; Jacobson and Primm, 1997; Boix-Fayos et al., 2008).

The Universal Soil Loss Equation (USLE) is a conservation planning and empirical tool that is used to estimate erosion in different land-use patterns. The estimation of the soil loss is based on physical modeling and information that are jointly combined with further in-situ datasets to assist in effective conservation planning. To successfully preserve water and soil resources, the knowledge of the effective key factors and appropriate methodologies is necessary (see e.g. Wischmeier and Smith, 1965, 1978; Wischmeier et al., 1971; Renard et al., 2011). In other words, USLE is an empirical based model which used to quantify the average annual soil loss at the basin scale and simulation of soil erosion. Since the spatial distribution of soil erosion must be considered, remote sensing and geographical information system (GIS) are heavily used in interaction with USLE model due to the amount of data that are needed and the ability of these techniques to handle these types of data (Bayramin et al., 2003).

The joint combination of USLE and GIS is extensively used in different studies for estimation the soil erosion hazard in the past decades by a large group of scientists who utilized USLE-GIS for understanding and analyzing the impacts of the soil erosion. Mati et al. (2000) used USLE and GIS for assessing the soil erosion risk in Ng'iro North Basin of Kenya, Meusburger et al. (2010) assessed the advantages of the vegetation parameters of QuickBird imagery in soil erosion model by considering a supervised classification, Prasannakumar et al. (2012) used the revised form of USLE beside GIS for a quantitative evaluation of the annual soil loss over the mountainous Pampa sub-watershed in India. Ali and Hagos (2016) compiled thematic layers from different data sources and methodologies in the context of USLE to estimate soil erosion in Awassa catchment in Ethiopian Rift Valley due to the loss of the vegetation cover due to the population increase. In this paper, the USLE coupled with the Geographic Information System (GIS) techniques are utilized to estimate soil erosion hazard in Algash Basin of Sudan using data from erosion plots and reconnaissance surveys (cf. Mohammed, 2016). Through years Al-gash River bed rises up mainly due to sedimentation process. Furthermore, Algash Delta agricultural project irrigation system suffers from the same problem, thus, the current study attempts to investigate the risk of sediments carried by Algash River to Sudan in order to assist the concerned authorities toward better environmental management strategies and land use planning. The primary aim of this study is to estimate the aver-age soil loss for year 2015 using rainfall, digital elevation model (DEM), land cover data and soil data, thus the underlying objectives to achieve that aim are firstly producing a land cover map, secondly identifying potential high risk areas of soil erosion and finally, estimating the total annual loss and calculation of the sediment yield.

The organization of this paper comes as follows, the geographic setting of the study area is presented in Section 2, USLE with its necessary factors and GIS techniques are explained in Section 3, the results and analysis are addressed and analyzed in Section 4 and finally the concluding remarks are drawn in Section 5.

2. Study Area

The study area is located between 14°5’9.5” – 15°27’58.5” N and 36°30’7.45” – 39°26’7.5” E in the overlapping area between three East-African neighboring countries which are Eritrea, Ethiopia and Sudan, but the large part of the study area is located in Eritrea (see Figure 1). The drainage area is about 2,203,183.76 ha. The climate is semi-arid over the study area where little rainfalls from June to September due to the Ethiopian summer monsoon. An average of 260 mm of rainfall per year, is concentrating from June to September. Precipitation is lowest in January, with an average of 0 mm. The greatest amount of precipitation occurs in August, with an average of 114 mm at an average temperature of 32.5 (see Merkel, 2009). In Algash Watershed there are six soil types, the classification is according to the existing editions of the FAO World Reference Base for Soil Resources. The most dominant type is Leptosols which is very shallow soils over hard rock or in unconsolidated very gravelly material; it occupies 54.64% of the total study area. The second most dominant type is Cambisols with 21.81% (FAO, 2003).

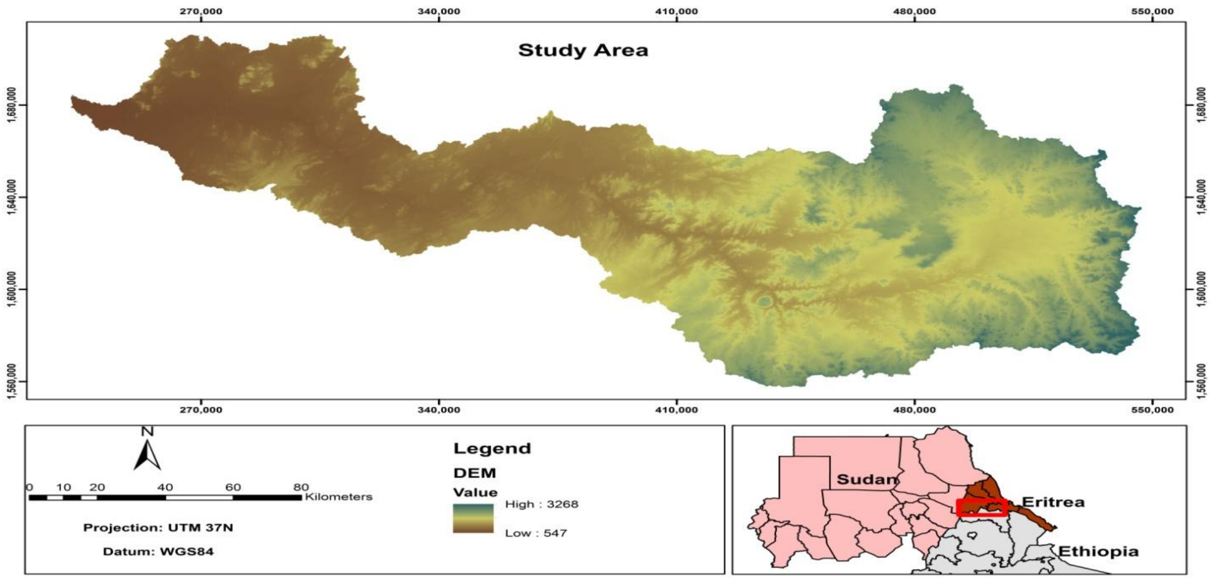

Figure 1: *study area location*

3. Methods and Materials

The USLE and its revised version RUSLE are commonly used to quantify the soil loss in the tropical areas (Khosrowpanah et al., 2001). The USLE model is suitable only for estimating erosion caused by water. It was adopted by the Soil Conservation Service in U.S, the model was developed by (Wischmeier and Smith, 1965) using data for more than 10,000 test plots in U.S. for 20 years (Wischmeier and Smith, 1965). It integrates a number of factors where many methodologies are used to estimate these factors. One of the factors is the rain and runoff-factor (R-factor), also called the soil erosivity factor. This factor determines the erosive effect of precipitation on soil loss. Another factor is the erodibility or K-factor, this determines the influence of soil properties on soil loss during rainfall events (Renard et al., 2011; The, 2011). The USLE soil loss equation is given as follows:

$$A = R \times K \times L \times S \times C \times P \qquad (1)$$

where A is the soil loss in ton/acre or in ton/ha; R, the rainfall and runoff factor, is the number of rainfall erosion index units, plus a factor for runoff from snowmelt or applied water where such runoff is significant, thus the R factor increases with the increase in storm intensity; K, the soil erodibility factor, is the soil loss rate per rainfall erosion index unit for the specified soil under Unit Plot conditions, the K-factor reflects the ability of the soil to be eroded; L and S are the slope length and steepness factors in relation to the conditions on a unit plot; C, the cover and management factor, is the ratio of soil loss from an area with specified cover and management to that from an identical area under the tilled continuous fallow Unit Plot conditions, thus C-factor indicates the crop practices which contribute in soil conservation (C thus ranges from a value of zero for completely non-erodible conditions, to a value of 1.0 for the worst-case Unit Plot conditions); and P, the support practice factor, This factor is similar to the C-factor because it indicates the practices which help in soil conservation but through reducing the runoff amount, P factor is the ratio of soil loss with a support practice such as contouring, strip cropping, or terracing to that with straight-row farming up and down slope (Renard et al., 2011).

Table 1 shows the data used in the current study. Utilizing the GIS techniques, the framework included preprocessing of the DEM which is used to delineate the watershed and generating the slope.

Table 1: *Input datasets*

Dataset	Year	Format	Source
DEM	2015	Digital Raster	USGS
Landsat 8	2015	Digital Raster	USGS
Rainfall	1983-2015	Digital Raster	TAMSAT
Soil	1995	Digital Shapefile	FAO

Furthermore, a landsat 8 image was used to generate the land cover map and cover management factor, raw data of the rainfall are provided by a research group in University of Reading (known as TAMSAT) that cover all Africa by (0.0375 spatial resolution and monthly temporal resolution based on the estimation from the satellite imagery was used in generating the rainfall erosivity factor. Also a soil map of scale (1:5,000,000) was used in this study from world soil map of FAO of the United Nations in order to estimate the soil erodibility K-factor (see Figure 2).

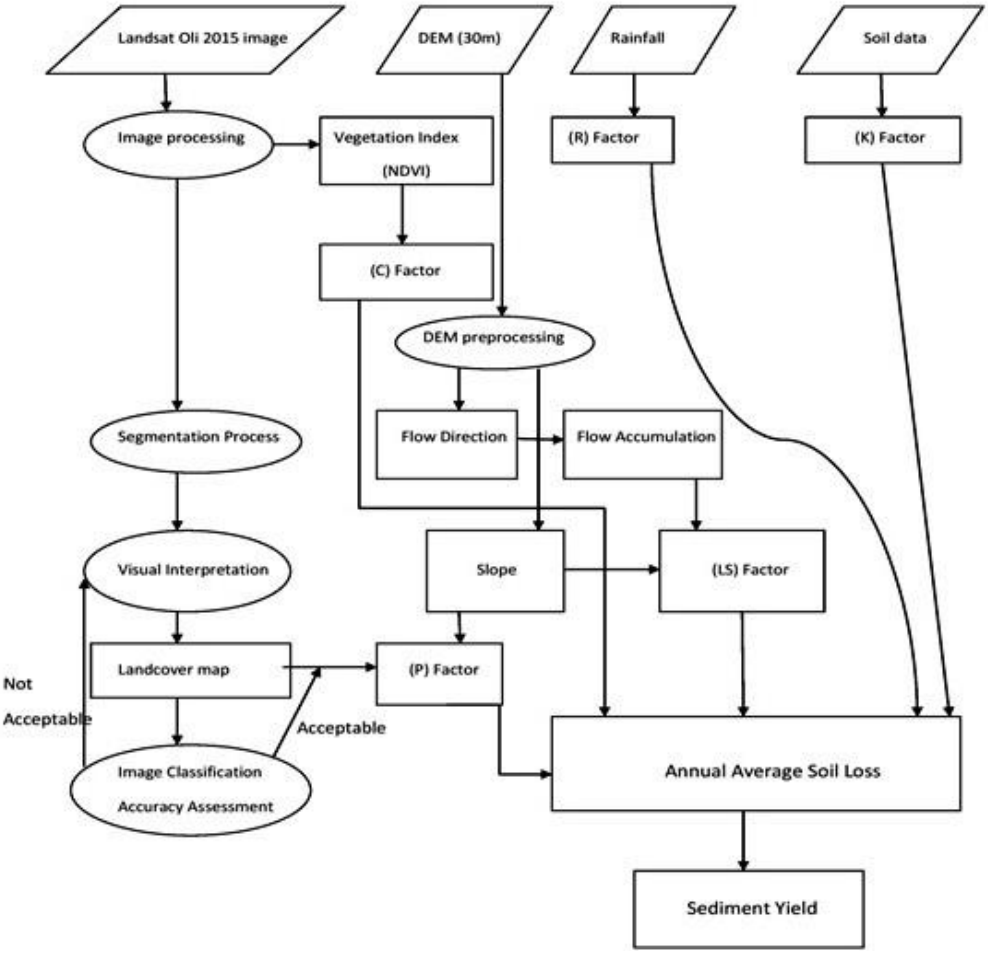

Figure 2: *the frame work*

3.1. Rainfall erosivity factor

Rainfall erosivity factor (R) represents a relation between kinetic energy of the storm and the maximum intensity in thirty minutes, therefore this factor is directly related to the detachment of soil by raindrop. The model that was used to estimate the rainfall erosivity factor is suggested by Eltaif et al. (2010) and it is expressed by formula:

$$R = 23.61 \times e^{0.0048P} \quad (2)$$

where R is the rainfall erosivity factor in MJ.mm/ (ha.hr.year) and P is Annual average rainfall in mm/year.

3.2. Soil erodibility factor

Erodibility of soil refers to how easy that soil could be eroded. Soil erodibility factor depends on the properties (texture, organic content, gravel content and permeability) and the profile of the soil, thus it reflect the effect of the soil type (Renard et al., 1997). The K-factor indicates the ability of soil to be eroded. The K-factor in this study was calculated using the Kuery tool (Borselli et al., 2012), the Kuery tool is available and free over the internet, the tool requires to calculate the climate and gravel content, if the gravel content is more than 10% then the percentage of gravel must be input to the tool in addition to the both sand and clay content, otherwise the organic matter should be input into the tool; therefore a relation between organic matter and organic carbon content was used (see Pribyl, 2010):

$$SOM = 2 \times SOC \qquad (3)$$

where SOM is the soil organic matter (%) and SOC is the soil organic carbon (%).

3.3. Topographic factor

Topographic factor (LS) reflects the topography effect on sheet and rill erosion in respect to USLE model (Wischmeier and Smith, 1965). It consists of two factors: slope length (L) and slope gradient (S). These two factors are usually considered together to make the calculation easy. Slope length increasing causes a rise in runoff amount due to the accumulation of the runoff from unit area to another in downslope direction and the velocity of runoff rises when the slope steepness increases, these two factors contribute together in increasing the soil erosion when their values are high (Kim, 2006). The (LS) factor is calculated based on the DEM and the relevant estimated accuracy depends on the resolution of the DEM. In this study SRTM (30m) was used to calculate the (LS) factor. The raster calculator in ArcMap was used to do this task using the following expression (Mitas and Mitasova, 1999):

LS = Power((“Flow Accumulation” * Cell Size/22.13),0.6) * Power(Sin(“Slope” * 0.01745)/0.0896,1.3)

where the slope is in degrees.

Since USLE model is only suitable for sheet and rill erosion, an upper boundary should be set for the boundary length, this will maximize the flow accumulation to the upper value. In other words, the 6 value in flow accumulation means that the maximum flow length is 180 m results from the flow accumulation cannot exceed 6 pixels multiply by the cell size which is 30 m as shown in Jabbar (2003); Parveen and Kumar (2012).

3.4. Cover management factor

The cover management or C-factor is related to land cover type, it represents a management to reduce the soil erosion amount. Basically this factor represents the relation between erosion in bare lands and erosion under a cropping system. The C-Factor depends on the vegetation type, stage of growth and cover percentage (Parveen and Kumar, 2012). One of remotely sensed based methods to calculate the C-Factor depends on normalized difference vegetation index (NDVI) which indicates the existence of vegetation cover (Van Leeuwen and Sammons, 2004). The C-Factor basically is the percentage of vegetation (Parveen and Kumar, 2012). Since the study area is located in a tropical climate, the following formula is used to determine the dimensionless C-factor (Durigon et al., 2014):

$$C = \frac{1 - NDVI}{2} \qquad (4)$$

3.5. Support practice factor

The support practice factor or P-factor reflects the effect of practices which reduce the water runoff and then reduce the soil erosion. Kim (2006) defined the P-factor as the ratio of the soil loss with a specific support practice to the corresponding soil loss with straight row upslope and downslope tillage and it depends on the slope. It varies from zero to one, where zero represents very good practices that reduce soil erosion and one represents no practices, thus any land cover except the agricultural land has one value unless there are some management practices such as terracing. The land cover map of the study area was produced using the eCognition software and visual interpretation of the Landsat scene where P-factor values were assigned. The collection of the ground truth points for the accuracy assessment of the image classification is not always achievable, instead, higher resolution images could be used to extract test points (Mather, 2005). In this study 140 reference points based on Google Earth images were used and randomly distributed. Then kappa coefficient method was applied to assess the accuracy in addition to the overall accuracy. Kappa coefficient was calculated using an extension script imported to ArcGIS software environment. The support practice factor was determined according to the criteria of the developers of USLE model (Wischmeier and Smith, 1965) as shown in Table 2.

Table 2: *P-factor values*

Land use type	Slope (%)	P-factor
Agricultural land	0 - 5	0.1
	5 - 10	0.12
	10 - 20	0.14
	20 - 30	0.19
	30 - 50	0.25
	50 - 100	0.33
Other land	All	1

3.6. Sediment yield and sediment delivery ratio

Sediment yield is defined as the sediment amount which actually discharged from the catchment area (Vanoni, 1975). Erosion process consists of three processes: detachment, transport and sedimentation. The runoff takes the eroded soil particles in downslope direction and some of these particles are considered as suspended sediments during the transportation process until the runoff reaches the outlet of the basin. In the outlet point (the lowest point within the catchment area) the sediment is measured and it is called the sediment yield. The sediment yield has an inverse relationship with the drainage area (Walling, 1983) and many factors are controlling sediment yield (such as the soil erosion rate, stream capacity and annual precipitation), thus there are many formulas that link up the sediment yield to the soil erosion. The most common formula that defines the sediment delivery ratio as a ratio of sediment yield to total annual soil loss of the basin is found in (Brune, 1953; Williams, 1977):

$$\text{SDR}= \frac{SY}{SL} \tag{5}$$

where SDR defines sediment delivery ratio which is varying from 0 to 1, SY is the sediment yield and SL is the soil loss per unit area above the measuring point.

The above equation is reasonable to model the relationship between sediment yield and soil loss since the amount of sediment as a function of land cover, soil type and conservation practice which are incorporated factors in USLE model for determine soil loss (Robinson, 1977). Many recent researches have attempts to model this relationship, with different included factors (e.g. sediment yield and drainage density) whereas other studies consider landuse as most influence factor in sediment yield (Syvitski, 2003), or topography, while the climate is considered as a dominant factor (Walling, 1996). Many researchers build a model to determine the sediment delivery ratio (Williams, 1977; Renfro, 1975; Williams and Berndt, 1972). Usually these models are not applicable except where they were developed (Becvar, 2005), the most generalized model is that which was globally tested on a number of 300 watersheds around the world. It inversely relates the sediment delivery ratio to the drainage area using a power function Vanoni (1975) as follows:

$$SDR = 0.42 \times A^{-0.125} \quad (6)$$

where SDR is sediment delivery ratio and A is the basin area (in squared miles).

4. Results and Discussion

4.1. Rainfall erosivity factor

The R-factor is highly affected by the density and duration of the rain storm. It has a great influence on the soil erosion, particularly, at the first two phases of erosion soil process (detachment and transportation), the higher value of rainfall erosivity factor, the higher risk of soil erosion (Kefi et al., 2009).

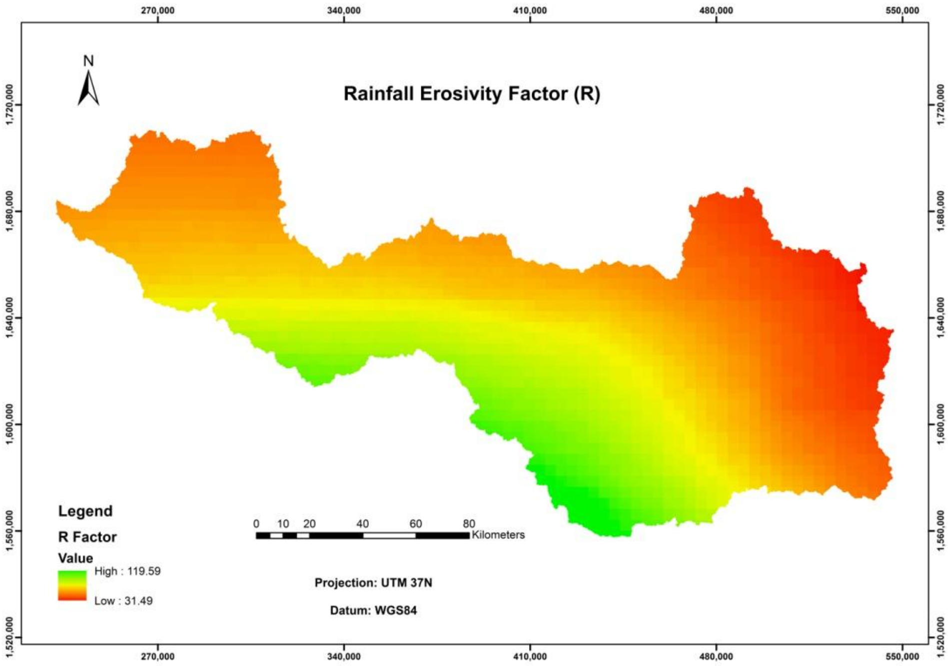

Figure 3: *Rainfall erosivity factor*

The result of erosivity calculation showed that the rainfall erosivity is bounded by 31.9 and 119.59 MJ mm/ha year with a mean value of 61.95 MJ mm/ha year. Figure 3 shows that the high values of erosivity were concentrated in the southern part of the study area (green). Whereas the low values were concentrated in north-east part (red). This pattern is following the natural distribution of the rainfall over the area.

4.2. Soil erodibility factor

This factor indicates the ability of soil to be eroded; the soil erodibility factor depends on the soil structure, permeability, organic matter content and particle size, as well as on chemical and physical properties of the soil. The Leptosols type was the dominant type with 54.64% of the study area, followed by Cambisols with 21.81%. Leptosols is the only type which contains more than 10% gravel contents, generally, the sandy soils has low K values because of low runoff and due to the high infiltration rate, The Leptosols case in Table 3 shows that the soil types are easily detached. The Vertisols have lower value than Nitisols due to higher clay content.

Table 3: *Percentages of soil texture (sand, silt and clay), organic content (SOC and SOM)*

Soil type	Sand	Silt	Clay	SOC	SOM	Gravel	K
Leptosols	50	30	20	0.72	1.44	31	0.00898
Fluvisols	44	33	23	0.73	1.46	1	0.02254
Cambisols	45	31	24	0.87	1.74	1	0.02249
Lixisols	63	15	22	0.6	1.2	1	0.0244
Vertisols	21	25	54	1.07	2.14	1	0.01587
Nitisols	24	27	49	2.45	4.9	1	0.0189

As seen in Figure 4 below, the dominant erodibility factor was 0.00898 which associated with Leptosols soil type (green color) and followed by (K factor) value 0.02249 which associated with Cambisols soil type (orange color).

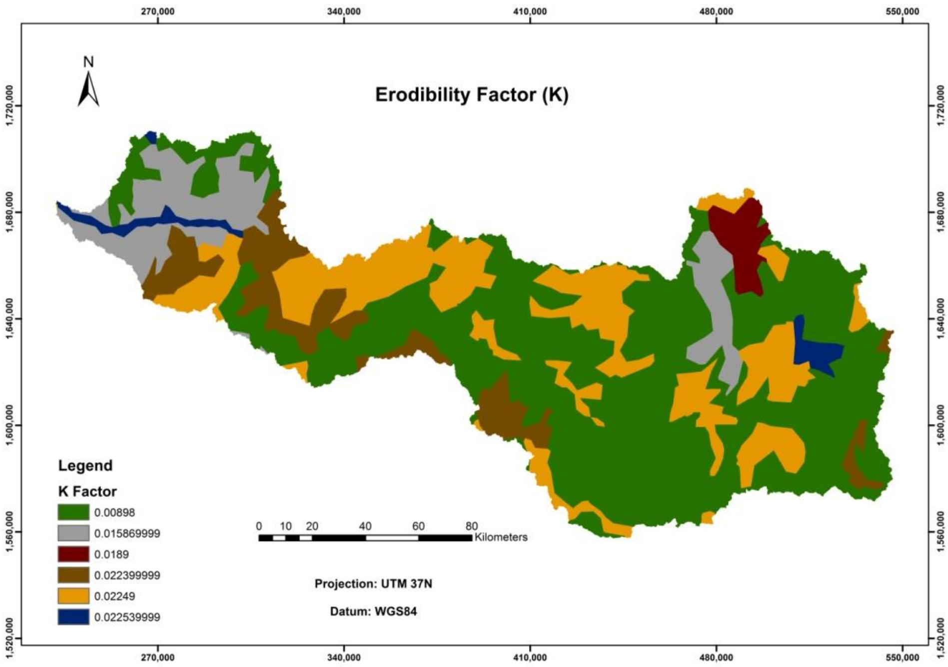

Figure 4: *Soil erodibility factor*

4.3. Topographic factor

The topographic factor (LS) reflects the effect of the slope length and slope gradient in the soil erosion. The higher the slope length and slope gradient, the greater erosion will occur. Topographic factor along with rainfall erosivity are the key factors in USLE that means if these two factors are high, the sediment generation will also be high as mentioned before (Kefi et al., 2009). The LS-factor varies from 0 to 77.08 with a mean value of 4.21, the increase in LS-factor increases the erosion because the runoff will be faster and then its energy will increase. From Figure 5 vast areas have high LS values between 40 and 77.

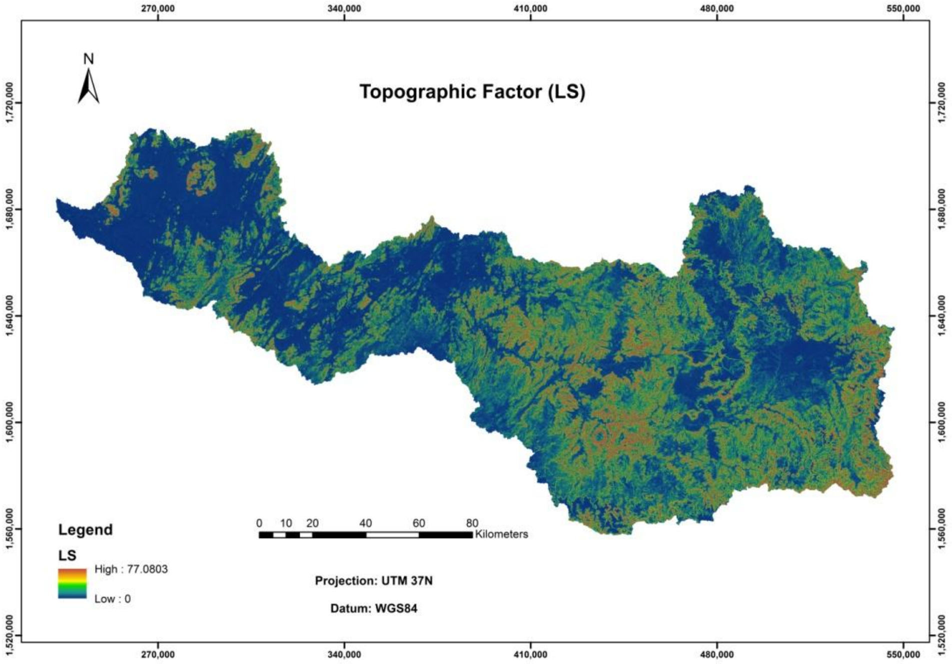

Figure 5: *Topographic factor*

4.4. Cover management factor

The crop management factor basically related to the vegetation percentage. The soil erosion is sensitive to vegetation cover (Renard and Ferreira, 1993; Benkobi et al., 1994; Biesemans et al., 2000), thus the NDVI can be calculated and then the C-factor will be determined, C and NDVI are inversely proportional. C-factor varies from 0.181641 to 1 as shown in Figure 6. When the C-factor is lower, this means that the ability of the area to be eroded is less. The highest values were found in urban and bare areas due to lack of vegetation (dark green), while the lowest values were found in the sides of the main channel (bright green), also in south area there is some vegetation which results in brighter area.

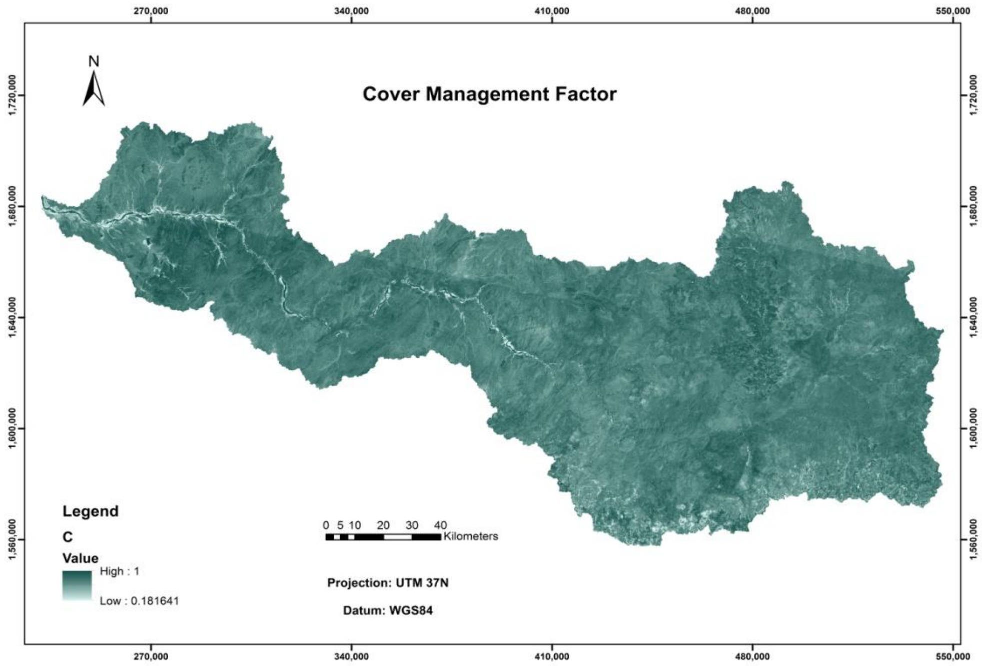

Figure 6: *Cover management factor*

4.5. Support practice factor

In order to obtain the P-factor, the land cover map was produced. It consists of five classes (water, bare land, natural vegetation, urban area and agriculture) and no more detailed classes due to spatial resolution (15m) of Landsat images (more detailed classes require higher resolution images). The most important advantage of using satellite images in land-cover mapping is their large coverage. There was no need to apply the geometrical correction since the images were geometrically corrected. With an overall accuracy of 80% and Kappa coefficient 71.41%, the land cover classes in the study area are produced as shown in Figure 7. It can be clearly seen that the urban areas are isolated among the study area and the water bodies represent small portions of the area. The agricultural areas are found on the valley strip due to abundance of water in rainy seasons, except a few discrete farms in the north of the study area and several ones in south west area.

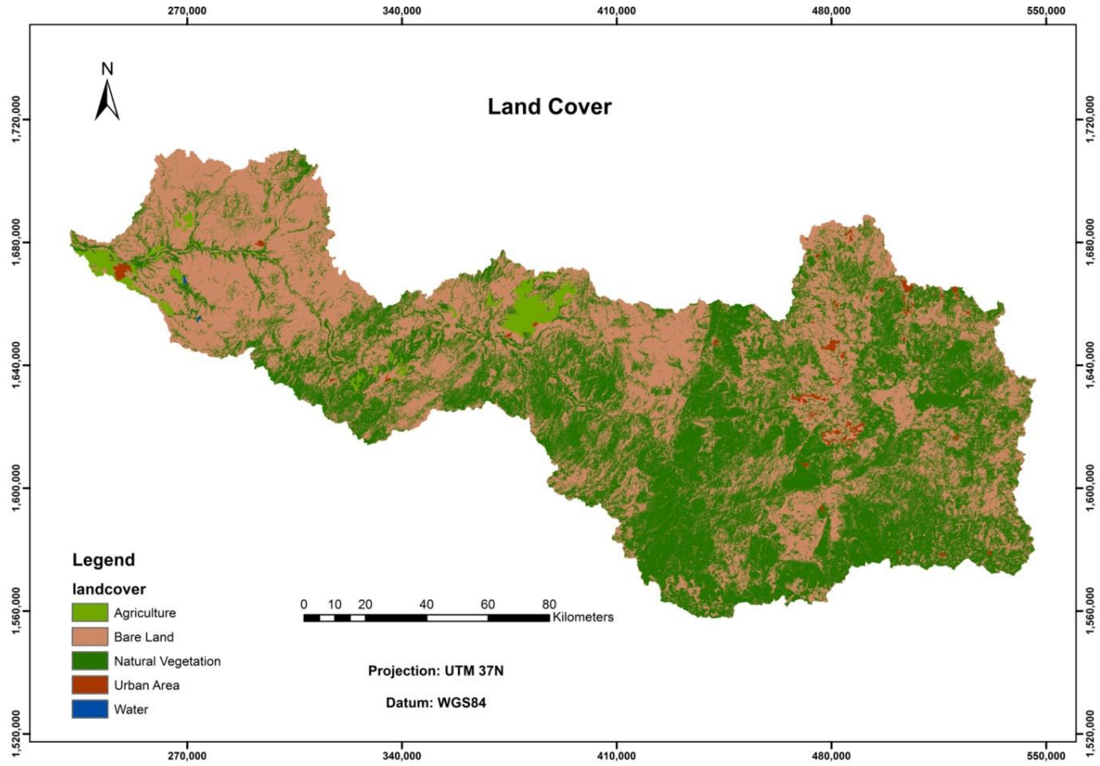

Figure 7: *Land cover map*

Since there is no support practice in the study area, each land cover type has a value of one except the agricultural areas (see Figure 8) as the support factor depends on the slope Wischmeier and Smith (1965).

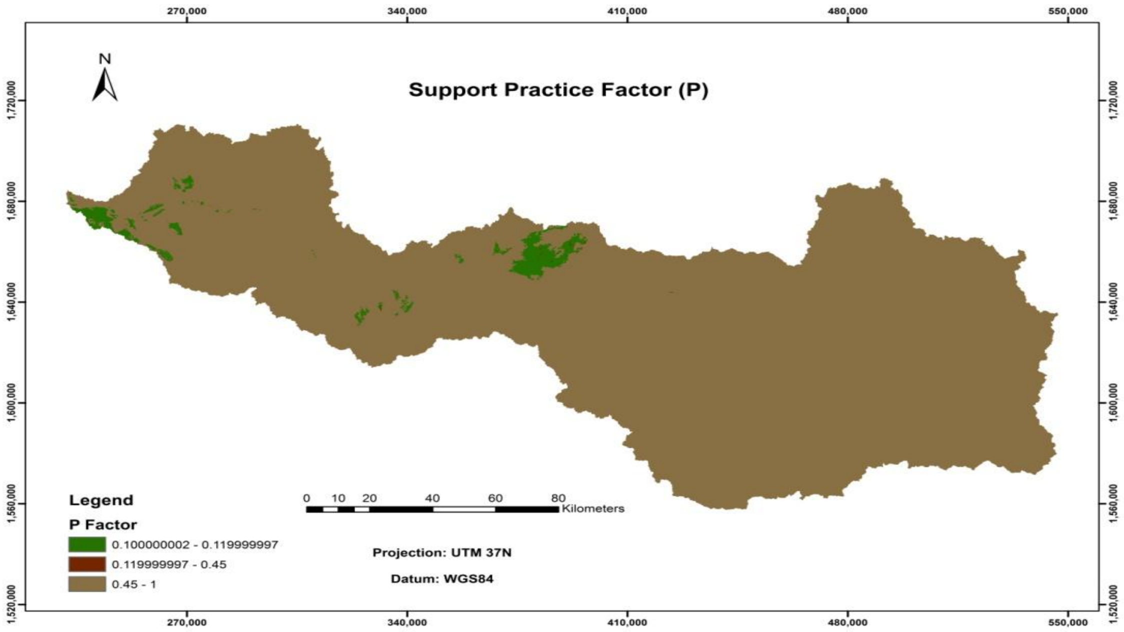

Figure 8: *P-value map*

4.6. Soil loss

The USLE parameters were calculated as shown above to quantify the soil loss amount by applying equation 1. The average annual soil loss on pixel scale varies from zero to 118.86 (ton/ha/year). The average soil loss for the whole study area was estimated as 1.4 ton/ha/year. These amounts are considered as on-site effect which reduce the soil productivity in the study area. Figure 9 shows the spatial distribution of soil erosion amounts.

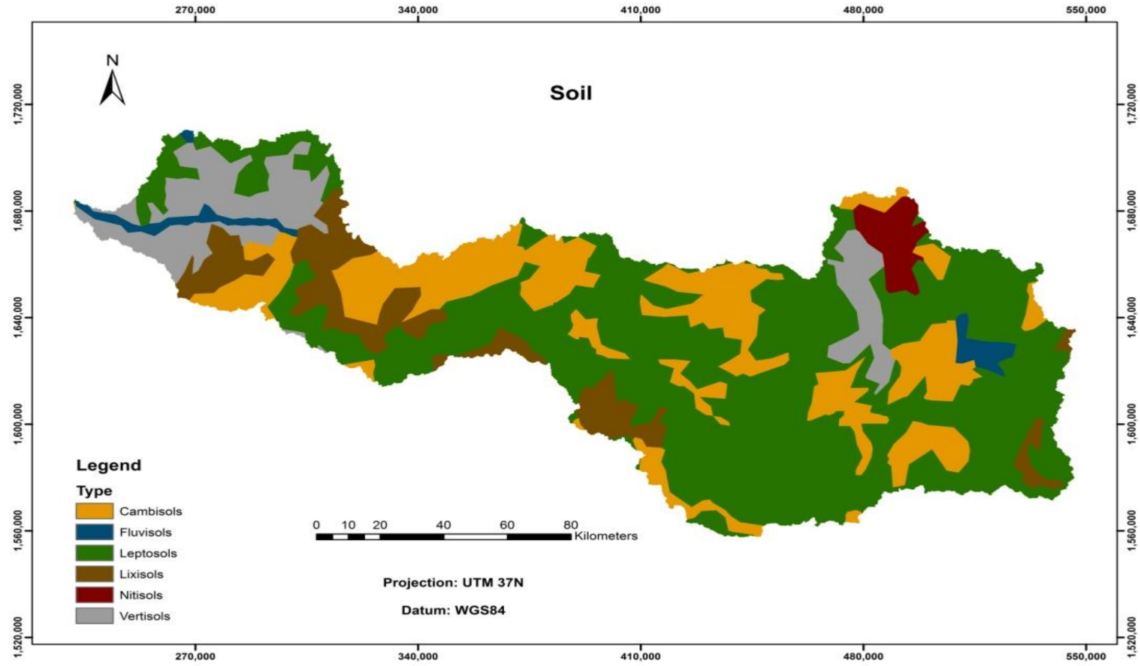

Figure 9: *Soil loss amount*

It can be seen from Figure 9 that there is a spatial variation in average soil loss amount. That is due to the variability in the factors (rainfall, topography, vegetation, soil types and their characteristics, and the human practices effect in agricultural and urban areas) which influence the soil erosion rates. Based on Morgan (2005), the soil erosion results were classified into seven zones as illustrated in Figure 10.

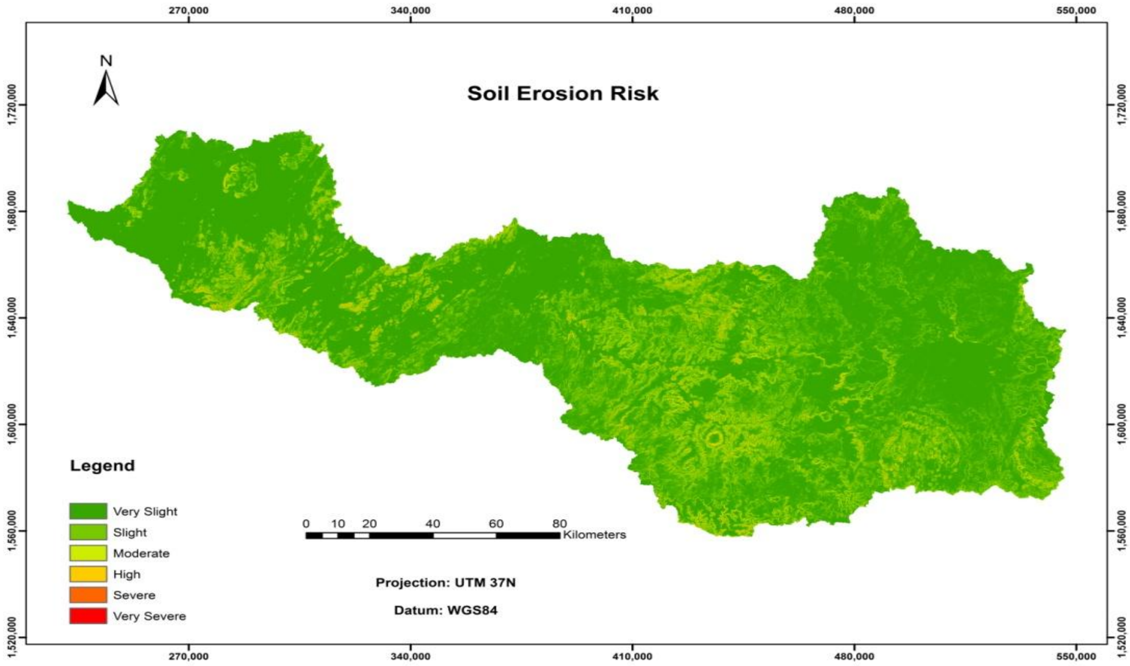

Figure 10: *Soil erosion risk map*

From Table 4, it can be clearly seen that the very slight zone (0 – 2 ton/ha.year) was occupied by the most of the study area (77.27%), followed by slight and moderate zones which are 15.16% and 6.05% respectively. Only 0.0002796% and 0.0000042% were classified as severe and very severe potential risk respectively.

Table 4: *Soil erosion zones*

Soil type	Sand	Silt	Clay	SOC	SOM	Gravel	K
Leptosols	50	30	20	0.72	1.44	31	0.00898
Fluvisols	44	33	23	0.73	1.46	1	0.02254
Cambisols	45	31	24	0.87	1.74	1	0.02249
Lixisols	63	15	22	0.6	1.2	1	0.0244
Vertisols	21	25	54	1.07	2.14	1	0.01587
Nitisols	24	27	49	2.45	4.9	1	0.0189

Figure 11 below proves that the mean annual soil loss is proportional to the slope due to the effect of topographic factor as mentioned by Zhang et al. (2015). When the slope is more than 140% the mean annual soil loss will reach the maximum mean annual soil loss (7.76 ton/ha.year), in contrast when the slope is very low (0-2%), the mean annual soil loss will be very low (0.08 ton/ha.year).

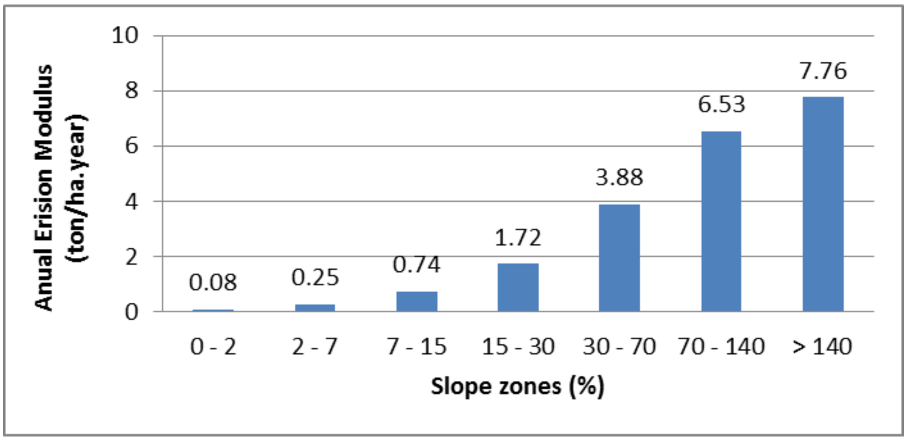

Figure 11: *Slope zone and equivalent average annual erosion*

4.7. Sediment delivery ratio and sediment yield

The total annual soil loss in the study area is estimated to be 32,916,840.87 ton/ha.year which is a significant amount of soil erosion but it is reasonable with respect to some previous studies (Bizuwerk et al., 2003; Ouyang et al., 2005), this amount is directly related to the on-site effect of soil erosion, the off-site effect was on Algash Delta (Sudan). Large amount of eroded soil will be available as suspended matter during the transportation process, therefore the sediment delivery ratio after applying equation 6 was 0.0337836 and the sediment yield normally enters Sudan was 1,112,048.778 ton/ha.year and that result was found using equation 5.

5. Conclusion

The Universal Soil Loss Equation model and GIS techniques were combined to analyze the soil erosion rate and to identify high risk areas in the study area located in the overlapping area between Eritrea, Sudan and Ethiopia. Furthermore, the off-site effect of eroded soil was quantified and the sediment yield was estimated after calculating the sediment delivery ratio. The mean annual soil loss was 1.4 ton/ha.year per pixel and bounded by 0 and 118.86 ton/ha.year. The analysis showed that the slope has a significant effect on soil erosion rate, higher value of slope, higher rate of soil erosion. The maximum value of the soil erosion modulus which was 7.6 ton/ha.year in areas where slope was more than 140% and by 6.53 ton/ha.year for 70 - 140% slope zones as shown in Figure 11. The results showed that 77.27% of study area within the very slight soil loss zone and 15.16% in the slight zone, whereas only 0.000284% of the study area was falls in the severe and very severe zone. The off-site effect was represented by soil yield value and sediment delivery ratio was 0.0337836. Therefore, the sediment yield entered into East of Sudan is estimated as 1,112,048.778 ton/ha.year.

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