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GEOSPATIAL MODELLING OF SOIL EROSION IN ZARIA LOCAL GOVERNMENT AREA, KADUNA STATE - NIGERIA

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ABSTRACT

The devastating effects of soil erosion on man, food and the environment in different parts of the world cannot be quantified. This study thus, modelled soil erosion using Revised Universal Soil Loss Equation (RUSLE) and Geospatial Information System (GIS) in Zaria Local Government Area (LGA). Rainfall data, soil, digital elevation model (DEM) and Land Use Land Cover (LULC) map of the area were used to determine rainfall erosivity (R-factor), soil erodibility (K-factor), slope factor (LS-factor) and cover management (C-factor), respectively in a GIS environment. The result was integrated based on the RUSLE to estimate the rate of soil erosion. The sediment yield of the study was estimated to be between 0 and 1445.22 t ha^{-1} year^{-1}. The study indicated that about 78.259 km^2 (19.88%) of the study area have erosion rate of 0 - 606.42 t ha^{-1} year^{-1} while the rates of erosion in 59.113 km^2 (15.018%), 74.462 km^2 (18.917%), 148.09 km^2 (37.623%) and 33.693 km^2 (8.56 %) of the study area were 606.42 - 770.78, 770.78 - 861.46, 861.46 - 918.14 and 918.14 - 1445.22 t ha^{-1} year^{-1}, respectively. It was also revealed that high rainfall erosivity, moderate to high slope factor and decreasing vegetal cover are the major driving factors of soil erosion in the area. It was, therefore, recommended that deforestation should be discouraged and agricultural practices such as terracing and cover cropping should be encouraged to reduce soil loss in the area.

Keywords: *Geospatial Modelling, RUSLE, Soil Erosion, Soil Erosion Factors and Vegetation*

1.0 INTRODUCTION

Soil erosion is a global environmental problem affecting the quality of soil and the environmental condition of an area (Babatunde *et al.*, 2016; Nwakwasi, 2018). This is often caused by anthropogenic activities such as farming, settlements and deforestation amongst others (Emeribeole and lheaturu, 2015; Ochoa *et al.*, 2016; Abdulkadir *et al.*, 2019). It is also caused by natural forces such as water, wind and gravity (Hacısalihoglu *et al.*, 2010; Thlakma *et al.*, 2018). The occurrence of erosion in an area affects food production, degrades the quality of the environment and creates an atmosphere that is unfavourable to man, plants and animals (Nwakwasi, 2018). This is a typical situation in Nigeria and Zaria in particular where lands meant for agriculture and other developmental activities are degraded by soil erosion. This has led to the destruction of settlements, infrastructure as well as farmlands (Thlakma *et al.*, 2018).

Given this situation, many studies have been carried out in Nigeria (see Anejionu *et al.*, 2013; Mallam *et al.*, 2016; Thlakma *et al.*, 2018) and Zaria in particular (see Odunze, 2002; Obeta and Adewumi, 2013) to address the menace of soil erosion. For instance, the study by Odunze (2002) assessed the level of soil loss from mulching farmlands in Zaria. The result revealed that soil erosion was highly pronounced in cultivated farmlands particularly at the beginning of the rainy season when most parts of the soil are bare due to low crop cover. Obeta and Adewumi (2013) on the other hand compared the soil loss in Samaru, Zaria using EUROSEM and the WEPP erosion model. Both studies focused on a small part of Zaria to address the erosion in the area. However, the study areas used were not sufficient to represent Zaria. There is also the need for an up-to-date dataset of soil erosion in the area.

Meanwhile, erosion is still on the increase in Zaria which suggests that more research effort is needed to attenuate the problem. The aim of this study, therefore, is to model soil erosion using the Revised Universal Soil Loss Equation (RUSLE) and Geospatial Information System (GIS) (Gaubi *et al*., 2017; Das *et al*., 2018) with the view to generate vital spatial datasets on the spatial distribution, development and impact of land degradation in the area under study. This was achieved by identifying and mapping the existing erosion sites within the study area; determining the factors causing erosion in the study area, and estimating the annual soil loss and creating a soil erosion potential map of the area under study.

2.0 STUDY AREA

Zaria LGA is one of the LGAs in Kaduna State located between latitude 10°57′30″ and 11°07′30″N of the equator and longitude 7°37′30″ and 7°47′30″E of the Greenwich meridian with an elevation of about 644 metres above mean sea level (MSL). Zaria LGA shares boundaries with Sabon Gari L.G.A, Soba L.G.A, Igabi, L.G.A and Giwa L.G.A all in Kaduna State (see Figure 1). The native population of the Zaria LGA is predominantly Hausas. However, many other tribes such as Yoruba, Ibo, Tiv, Jabba, Igala and Idoma amongst others.

The climate of the study area is divided into two parts; the dry and wet season. The wet season spans from May to October characterized by rainfall. The dry season spans from November to April characterized by dry wind (harmattan) that blows southwards from the north-east starting from November to March, during which visibility becomes difficult due to the presence of dust (Azua *et al.*, 2020).

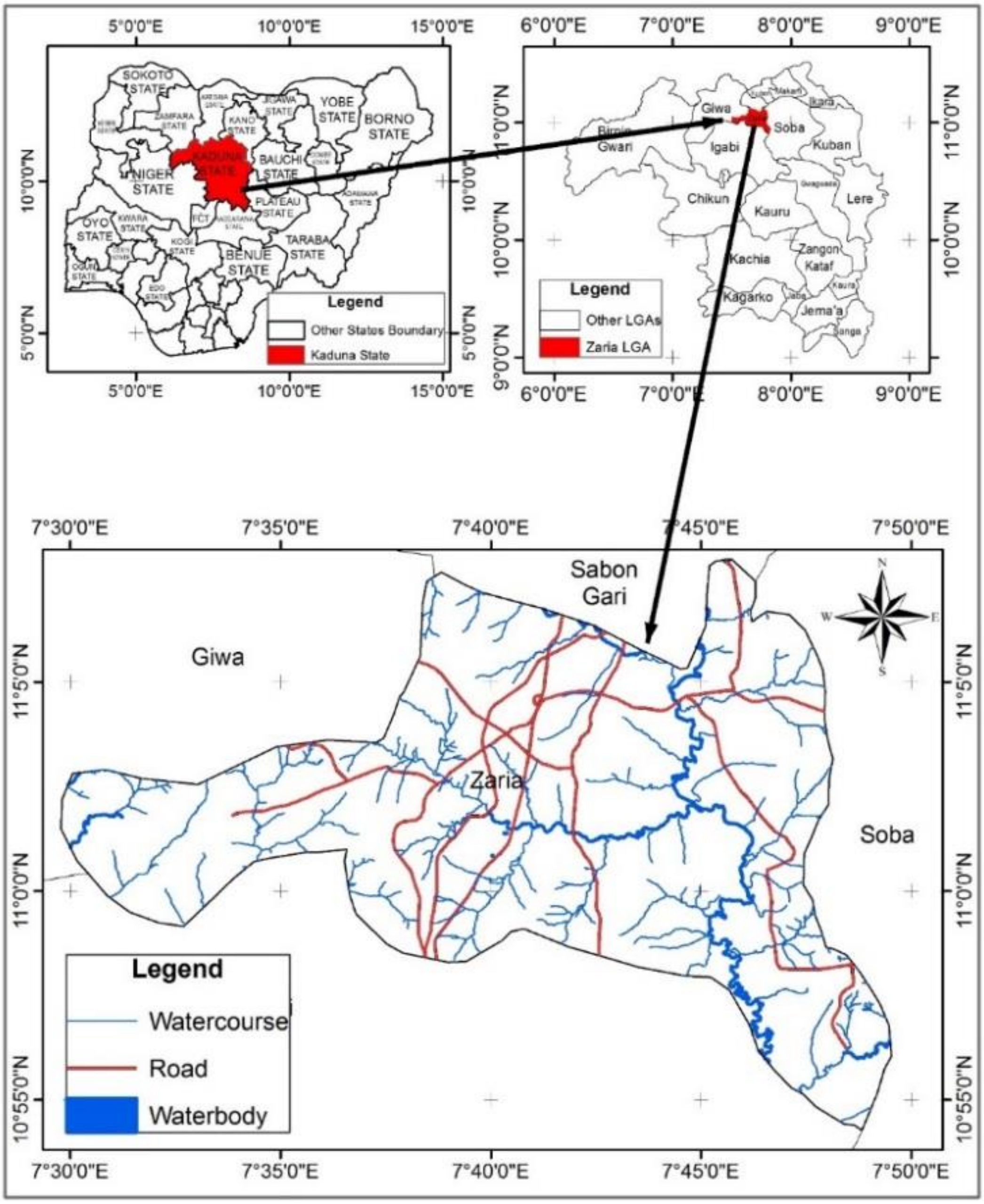


Figure 1: The Study Area: *Top left; map of Nigeria; Top right; map of Kaduna State; and bottom; Zaria LGA.*

3.0 MATERIALS AND METHOD

Software and Equipment (Hardware) used

For this study, different types of software and equipment were used as shown in Table 1.

Table 1: Software and Equipment used

S/N	Software/Equipment	Purpose
1	Arc GIS 10.5	Clipping, Data integration, visualization and data presentation
2	IDRISI Selva	Composite band and Classification (supervised)
3	Quantum GIS 10.	Gap Filling
4	Erdas Imagine 9.2	Accuracy Assessment
5	Google Earth pro	Imagery Downloads
6	Mobile Topographer	Locating existing erosion sites
7	Hand-held GPS Receiver (Garmin GPS Map 765CSX)	Identifying existing erosion points.

Datasets and Sources

This study made use of both primary and secondary data sets as presented in Table 2.

Table 2: Data sets used

S/n	Name	Date/Source	Scale/Resolution	Purpose
1	GPS Coordinates	Fieldwork		Mapping existing erosion sites
2	Soil map	1997	1:250,000/nil	For soil erodibility
3	Landsat 8 OLI	19/01/2019/ Glovis	30m	For land use classification
4	SRTM	2019/USGS	30m	For elevation Model
5	SRTM	2010/F. K Salako		For rainfall erodibility
6	Topo map	1976/	1;50000	Base map

GPS: Global Positioning System; OLI: Operational Land Imager; SRTM: Shuttle Radar Topographic Mission; Sec: Secondary.

4.0 METHODS

Data processing and analysis

The following are the data processing and analysis steps adopted in this study:

i. The SRTM was used to generate a digital elevation model (DEM), where the slope and the slope length (LS) were obtained. These were the parameters used in estimating the average amount of soil loss in the study area.
ii. The rainfall erosivity data used in this study is derived from rainfall erosivity map developed by Salako (2010). This map was developed using daily rainfall data collected from 17 meteorological stations located at the various ecological zones in Nigeria covering a span of 10–33 years.
iii. The soil data were processed using the spatial analyst tool in the ArcGIS 10.5 environment to produce a soil map from which the soil factor (K) (soil erodibility factor) used in RULSE was extracted.

iv. Landsat 8 OLI of 2019 was sub-set to the study area using the administrative map of Zaria LGA. A supervised classification (for six classes namely bareland, built-up area, cultivated land, forest, grassland and waterbody) was carried out to produce the land use land cover management and support practice maps from which the cover management factor (C) and support practice factor (P) were estimated.

Mapping of Existing Erosion Sites

During the reconnaissance survey, erosion sites were identified and mapped using a handheld GPS receiver (Garmin GPS Map 765CSX). The coordinates of erosion sites and other places of interest such as markets, worship places, schools, etc. were acquired. Further, the topographic map was scanned and digitized using the on-screen digitization in the ArcMap environment. Features such as water body, roads, erosion sites and some selected junctions were extracted and merged with the ground control points of the erosion site to produce a soil erosion map of the study area.

Factors of Erosion in the Study Area

The factors of erosion were determined by calculating the erosion of potential areas using RUSLE as outlined in the following procedures.

i. Slope Length and Steepness Factor (LS) Derivation

An increase in slope steepness (S) increases the velocity and erosivity of runoff. Slope length (L) is defined as the ratio of soil loss from the field slope length to that from a 22.1 m length under otherwise identical conditions. The slope length and steepness (LS) were generated using the DEM of the study area. The L and S factors are usually considered as a single topographical factor and can be estimated using equation 1 (Liu *et al.*, 2000)..

$$LS = \left(\frac{FA \times Cell\ size}{22.13}\right)^m \times \left(\frac{Sin(slope\,angle)/0.01745}{0.09}\right)^n \qquad 1$$

Where FA is flow accumulation, cell size is the size of the DEM data (30 by 30m). Slope angle is in degrees (°), and 0.01745 is the parameter to convert degrees to radians.

Therefore, m and n were assigned 0.5 and 1.3, respectively as recommended by Mitasova and Mitas (1999) and Liu *et al.*, (2000). The Slope map was also generated in ArcGIS 10.5 environment using DEM.

ii. Cover Management Factor (C)

The cover management factor (C) represents the effects of vegetation, management and erosion control practices on soil loss. As with other RUSLE factors, the C value is a ratio comparing the existing surface conditions at a site to the standard conditions of the unit plot. In the RUSLE model, the C value is equal to 1 when the land has continuous bare fallow and has no coverage. This value is, however, lower when there is more coverage of a crop for the soil surface resulting in less soil erosion (Soo, 2011). To generate the scenario of LULC, Landsat 8 OLI imagery of Zaria LGA was classified using maximum likelihood supervised classification in the ERDAS IMAGINE 9.2 environment. Six classes; built-up, cultivated land, bare land, forest, grassland, and water body were obtained. Based on the LULC map derived, the C factor values were assigned for the various classes as in Kouli *et al.* (2009) (see Table 3).

Table 3: C factor for different land use within the study area

S/N	**Land Use**	**C Factor**
1	Built-up	0.00
2	Cultivated land	0.63
3	Grassland	0.01
4	Bare land	0.45
5	Forest	0.003
6	Waterbody	0.00

iii. Practice Factor (P)

The support practice factor (P) is used to show the effect of LULC on the amount and rate of surface run off which determines the amount of soil erosion. This factor was estimated based on Troeh, *et al*. (1999). For this study, the P values were chosen based on land use instead of the slope and cultivation method. This was done using Landsat 8 OLI satellite imagery. The theme was converted from vector to grid form with the cell size of 30m. Table 4 shows the P factor adopted from the Troeh *et al*. (1999) factor list.

Table 4: P factor for different land use within the study area

S/N	Land use	P Factor
1	Bare land	1.00
2	Built up	0.00
3	Cultivated land	0.50
4	Grassland	1.00
5	Forest	1.00
6	Waterbody	0.00

iv. K-Factor Map

The K-factor map was produced from the soil map of the study area in the ArcGIS 10.5 environment. The soil map attribute table was edited by adding a new field of K values under the edit menu in the attribute view before the K factors were produced. The following steps outlined the procedure employed to determine soil parameters.

a. Soil Classification Map

The soil classification of the study area was carried out with the aid of GIS during which the soil was classified into 3 soil types; sandy loam, sandy clay and clay loam.

b. Soil Erodibility Factor (K)

The soil erodibility factor (K) represents the susceptibility of soil or surface material to erosion, transportability of the sediment and the amount and rate of runoff given a particular rainfall input as measured under a standard condition. Erodibility varies with soil texture, aggregate stability, infiltration capacity and organic and chemical contents (Chmelova and Sarapatka, 2002). In this study, a polygon vector file of the soil map was digitized. This was then rasterized and converted into a K value map by reclassing each soil polygon into its corresponding K value as shown in Table 5 (Ezeabasili *et al.*, 2014).

Table 5: Soil type and K factor

S/N	Soil type	K factor
1	Sandy loam	0.09
2	Sandy clay	0.10
3	Clay loam	0.19

v. Rainfall-runoff Erosivity Factor (R)

The rainfall erosivity data used in this study is derived from the annual EI30 Isoerodent map of Nigeria developed by Salako (2010) (see Figure 2). The rainfall erosivity maps were developed from daily rainfall amount collected from 17 meteorological stations covering all the ecological zones in Nigeria within a period of 10–33 years. The daily rainfall was used to calculate rainfall erosivity using the power-law relationships developed by Salako (2008) expressed as:

$$Erosivity\,\mathrm{Index} = \mathrm{a}\mathrm{A}^{\mathrm{b}} \tag{2}$$

Where A is daily rainfall amount (mm), a and b are parameters with different values for the sub-humid and humid regions (Salako, 2010).

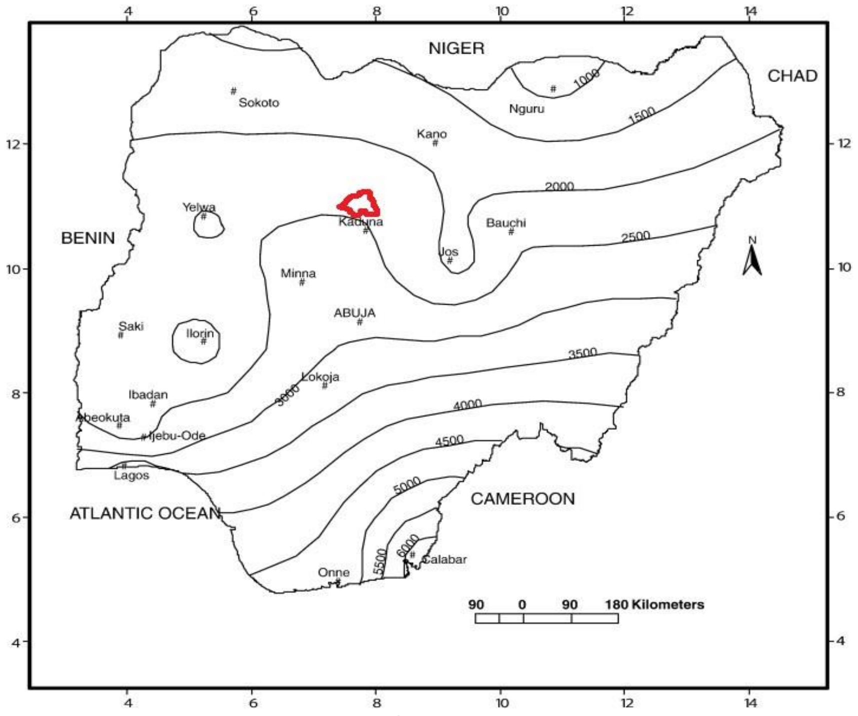


Figure 2: Isoerodent data of Nigeria (*Source*: Salako, 2010).

Estimation of the Annual Soil Loss

Once the raster layers for R, K, C, P and LS were created, the last step was to combine these parameters to produce an erosion raster map. This was done using the Raster Calculator under the Spatial Analyst tool. The RUSLE equation was used to calculate the annual soil loss in ton/ha/yr. The images produced were used as inputs in the RUSLE equation as follows:

$$A((tons/ha)/yr) = R \times K \times LS \times C \times P \qquad 3$$

Where A is the annual soil loss, R is the rainfall erosivity factor, K is the soil erodibility factor, L is the slope length factor, S is the slope steepness factor, C is the crop management factor, P is the support practice factor.

The result of the equation was an image showing the qualitative and quantitative volumes of soil loss of the area. It is worth noting that the RUSLE model is widely applicable for its simplicity and data availability, however due to its calibration on the basis of observations it cannot evaluate the real picture of soil erosion based on limitation resulting from non-standardized factors and weights (Biswas and Pani, 2015).

5.0 RESULTS AND DISCUSSION

Spatial Distribution of Erosion Sites within the Study Area

Figure 3 shows the spatial distribution of existing erosion sites mapped in the study area. A total of eighteen (18) erosion sites were identified and mapped in the area under study. The result showed that 12 out of the 18 which represent 66.67% of the total erosion sites mapped in the area were located along the roads while the remaining 6 which represent 33.33% were located along the river beds. Most of these erosion sites are situated within the municipal region of the study area (see Figure 3).

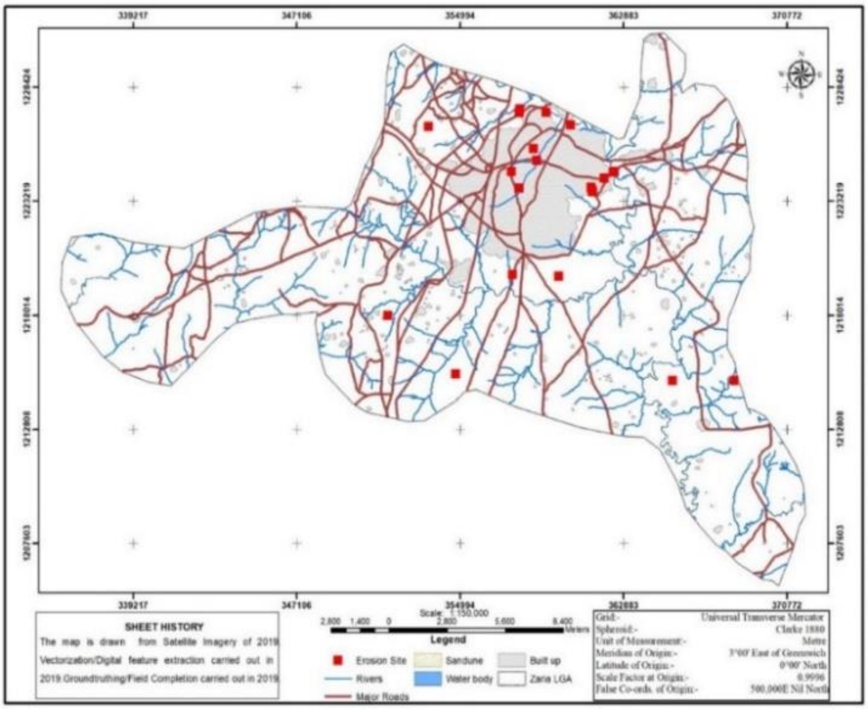


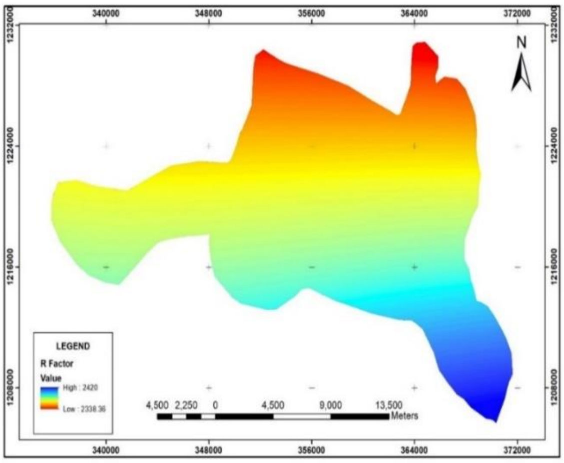
Figure 3: Spatial Distribution of Erosion Sites in Zaria LGA

Factors of Erosion

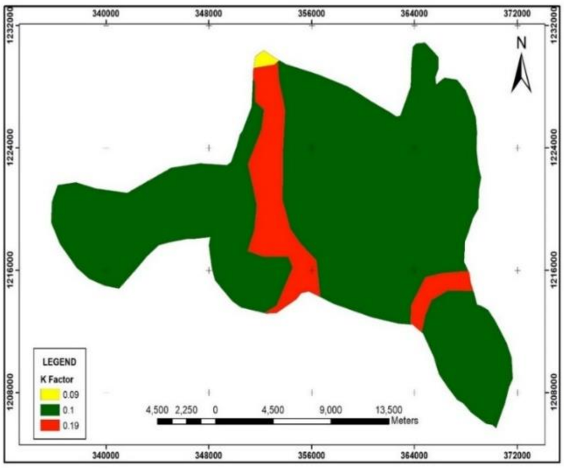
Several maps were produced based on the factors of erosion considered for this study as shown in Figure 4. Details of the results for each factor is discussed below.

(i) Rainfall erosivity map

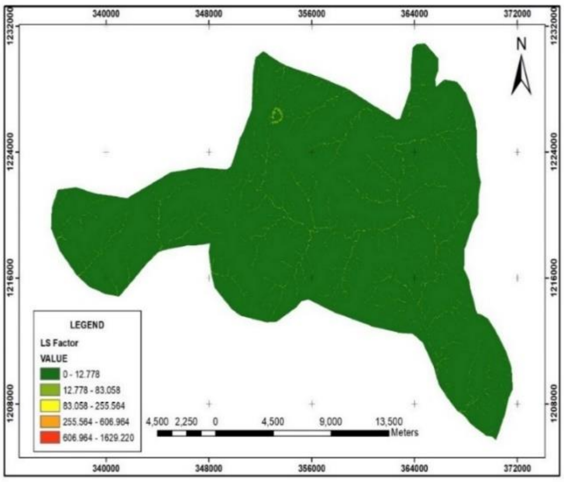
The rainfall erosivity of the study area shows the maximum and minimum values of 2420 and 2338.36 MJ mm ha^{-1} h^{-1}, respectively while the mean and standard deviation are 2373.81 and 15.487 MJ mm ha^{-1} h^{-1}, respectively. The highest values occur in the southern part of the study area and decrease gradually toward the northern part. The rainfall erosivity map (see Figure 4a) shows that rainfall distribution varies within the study area and the use of a single R-value cannot sufficiently capture the rainfall variability in the area.



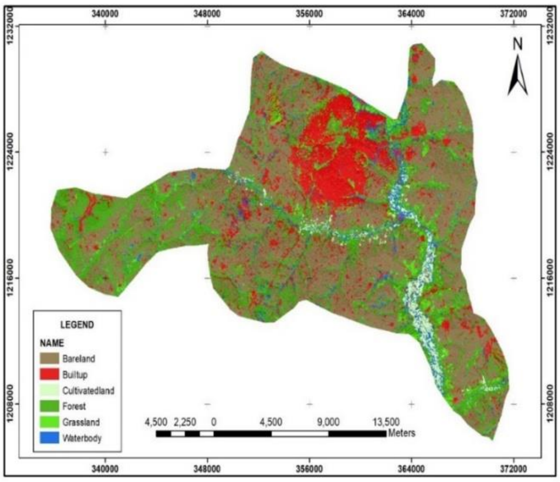
(a) Rainfall Erosivity (R Factor Map).



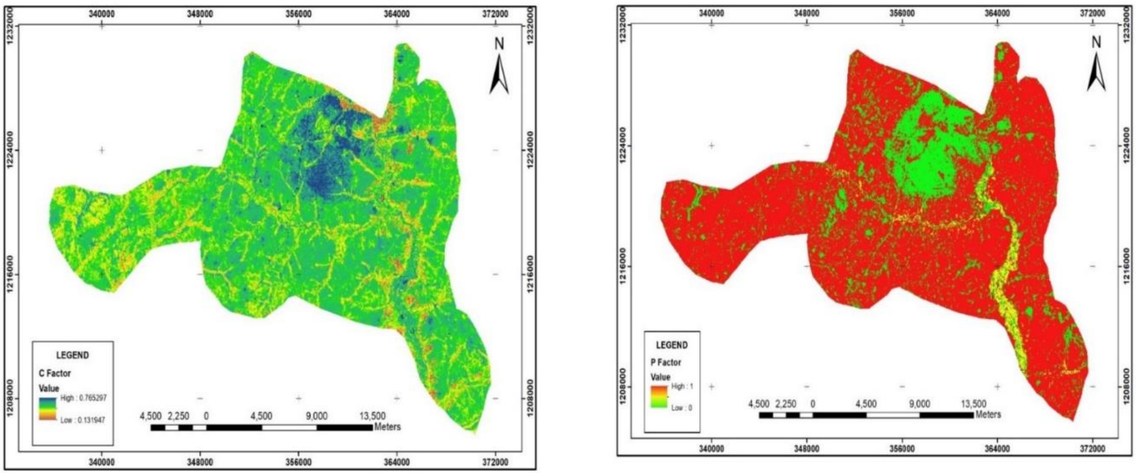
(b) Soil Erodibility (K Factor Map).



(c) Slope Length and Slope Steepness (LS) Map



(d) Land Use Classification Map.



(e) C Factor Map. (f) P Factor Map.

Figure 4: Results of Factors Used in RUSLE

(ii) **Soil erodibility map (K factor)**

Figure 4(b) shows the spatial distribution of soil erodibility in the study area. The erodibility values were assigned to each soil type based on the soil description and information available in Ezeabasili *et al*. (2014). The soil type with the highest K value is clay loam soil (0.19) which has been described as having the highest clay ratio (Ezeabasili *et al*., 2014) and covers an area of about 44.501 km^2 (11.30%) of the study area. This is followed by sandy clay soil having K-value of 0.1 covering an area of about 347.924 km^2 (88.36%), thus, representing the soil with the highest area. The soil with the lowest K-value is sandy loam (0.09) with an area coverage of about 1.35 km^2 (0.34%) thus, having the least area as shown in Table 6.

Table 6: K value

Soil type	K-value	Area (km^2)	Percentage (%)
Sandy loam	0.09	1.35	0.343
Sandy clay	0.1	347.924	88.356
Clay loam	0.19	44.501	11.301

(iii) Slope length and steepness factor (LS)

Figure 4(c) shows the slope length and steepness of the area under study. The LS values ranged from 0 to 42 while the computed slope length and steepness factor ranged from 0 to 1629.22 having a mean and standard deviation of 0.7751m and 10.5478, respectively.

(iv) Crop management (C factor)

Vegetation and LULC are important factors in the erosion process. The cover management factor describes the effect of LULC on erosion. The amount of vegetation cover has a significant influence on the rate of erosion. Figure 7 and Table 7 show the LULC of the study area. This result was used to estimate the cover management and support practice factors as shown in Figure 4(d). The overall accuracy and kappa coefficient of this classification are 84% and 78%, respectively indicating a good classification result.

Table 7: Land Use Land Cover Classes and Area covered for Zaria LGA.

Land Cover Types	**Area (square km)**	**Area (hectares)**
Bare land	17.604	1760
Built-up	60.683	6068
Cultivated land	97.1541	9715
Forest	189.562	18956
Grassland	16.063	1606
Waterbody	3.623	362
Total	**390.139**	**39012**

(v) Support practice factor (P)

Figure 4(e) shows the P factor map generated based on the land use classes (built-up, cultivated land, forest, grassland, bare land and water body) in the area. The results show P factor values ranging from 0.00 to 1.00. High values of P factor are observed in most of the study area except in the north-central where low values were depicted.

The Rate of Annual Soil loss

All the computed factors were substituted in equation 3 to produce the soil erosion map of Zaria LGA. as shown in Figure 5.

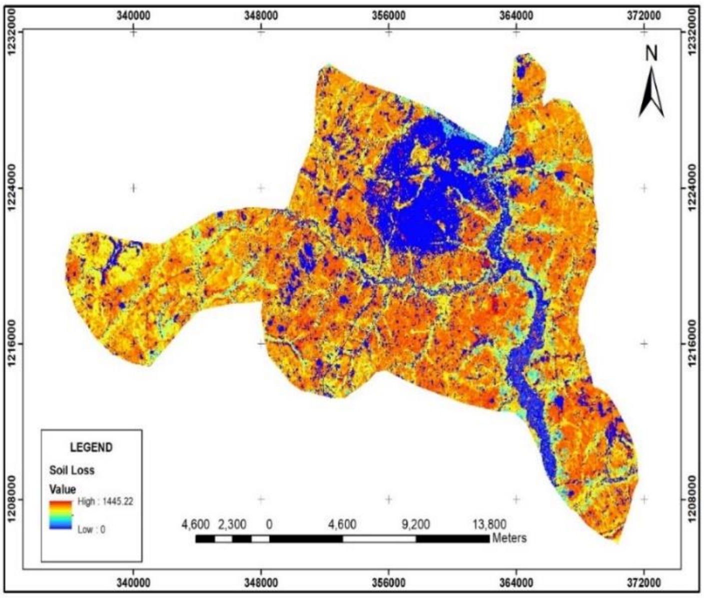


Figure 5: Soil loss Map.

The average annual soil loss rate of Zaria LGA is estimated by implementing equation 3 which involves multiplying the factors developed as raster data. The annual soil loss is depicted in Figures 6 and 7, respectively. Five classes of soil vulnerability (low, moderate, high, very high and severe) were mapped in the area. The mean value of the estimated soil loss is 78.724 t ha^{-1} year^{-1}.

The estimated soil erosion is further categorized into five classes (see Table 8) to reveal the severity of soil loss. The classification shows that about 78.259 km^2 (19.88%) have erosion rate of 0 - 606.420 t ha^{-1} year^{-1} which can be considered as the low rate of erosion, while about 59.113 km^2 (15.02%) experienced moderate soil loss between 606.420 - 770.780 t ha^{-1} year^{-1}. The areas under high, very high and severe classes of erosion are 74.462, 148.09, and 33.693 km^2, respectively which correspond to 18.917, 37.623 and 8.56 %, respectively.

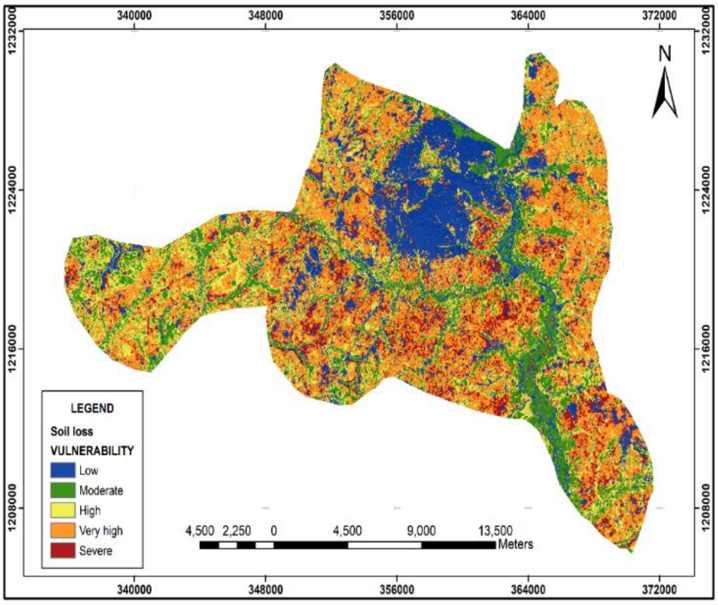


Figure 6: Soil Erosion Vulnerability Map.

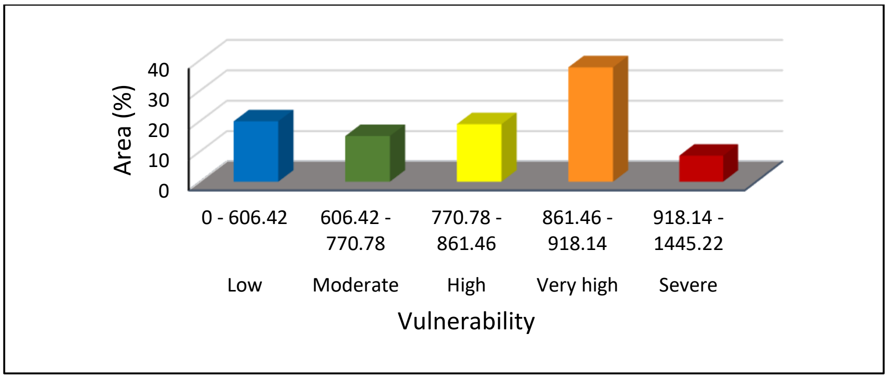


Figure 7: A Chart of the Soil Loss.

Table 8: Annual Soil Loss

Vulnerability level	Soil erosion rate (t ha^{-1} year^{-1})	Area (Km^2)	Area (%)
Low	0 - 606.42	78.259	19.88
Moderate	606.42 - 770.78	59.113	15.02
High	770.78 - 861.46	74.462	18.92
Very high	861.46 - 918.14	148.09	37.62
Severe	918.14 - 1445.22	33.693	8.56
	Total	**393.617**	**100.00**

DISCUSSION

Figure 6 showed flashes of yellow, orange and red, which indicate high, very high and severe erosion sites, respectively. The rate of annual soil loss determined using the RUSLE model ranged between 0 and 1445.22 t ha^{-1} year^{-1} as generated by the multiplication of the input factors shown in Table 8 above. Based on this result, very high eroded sites cover over 37% of the entire area. These areas were mostly seen along roads and croplands where high rainfall and lack of vegetation cover exposed the soil to erosion. This result corroborates the findings of Adewuyi *et al.* (2019) who reported that the presence of roads and lack of vegetation contributed to high erosion sites in Chikun LGA of Kaduna State. This is because, when an area is deforested, the land is exposed to direct rainfall and other factors, posing huge erosion risks. Besides, the low, high and moderate eroded sites occupy 19.88, 18.92 and 15.02%, respectively. This implies that the factors of erosion had already existed in the study area which contributed to the presence of low, high and moderate eroded sites. This calls for measures to control the effects of these factors to reduce the expansion of erosion sites. Failure to do so might lead to the high cost of recovering the land for any meaningful purpose (Wang *et al.*, 2015).

Implication and Remedy

This study has shown that a large portion of the study area is affected by erosion at various levels. This has many implications. First and foremost, it affects the agricultural activities which serve as a major source of food and income to the host community. The effects of soil erosion reduce the fertility of the soil which could cause food insecurity in the area. Besides, most of the people depend on subsistence agriculture for livelihood. Increased erosion may take away their source of food and livelihood. Secondly, erosion can also lead to an increase in sedimentation in streams and rivers thereby clogging the waterways and reducing water quality. This may affect not only man but also aquatic organisms living in the area. Further, degraded lands are also often less able to hold on to water, which can worsen the effects of flooding.

However, a considerable portion shows severe soil loss which requires conservation measures. Sustainable land-use practices can help to prevent soil loss and the loss of valuable land to erosion. Similarly, the improvement of drainages can help to prevent soil loss, where all buildings and roads should have gutters or pipes that can drain water effectively out of any affected area. Planting of trees can go a long way in reducing erosion. Tree roots have the potential to hold the soil together thereby preventing it from being eroded, while their leaves block raindrops and prevent it from breaking the soil into smaller particles to avoid soil loss.

6.0 CONCLUSIONS

This study has successfully modelled soil erosion in Zaria LGA of Kaduna State. The result has shown that rainfall and lack of vegetation are the most contributing factors in the area. The study further showed that a larger part of the study area has experienced very high soil loss; however, a considerable portion shows severe soil loss which requires conservation measures. Large quantities of soil get eroded from the study area annually. The high rainfall erosivity associated with the frequent short-interval intensity rainfall in the region plays a significant role in the amount of soil erosion. Based on this result, it is suggested that agricultural practices like strip cropping and cover cropping should be employed while deforestation, bush burning and clearing of land for developmental activities should be discouraged. Future studies could evaluate soil erodibility by adopting a modified RUSLE model with selected standardized factors and weights.

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