Modeling and Estimation of Average Annual Soil Loss in Ika South Local Government Area of Delta State, Nigeria.

ABSTRACT

Soil-related phenomenon and the Sustainable Development Goals (SDGs) particularly SDG-15 are strictly tied. A healthy soil ecosystem encourages the existence of life on Earth and for agricultural purposes. One of the key factors that is contributing to unhealthy soil ecosystems is soil erosion.

The research involves the assessment and modelling of soil erosion using the Revised Universal Soil Loss Equation (RUSLE II) with the sole aim of ascertaining the annual Soil loss within the study area, this will be a veritable tool in estimating soil loss in farming systems and in supporting the achievement of the SDGs. It provides a concrete estimation of the distribution of soil erosion at Ika South LGA, through the combination of the influencing factors such as rainfall aggressivity, soil erodibility, topography, vegetation cover, and soil conservation practices.

The soil loss estimated at Ika South ranges from 0 to 49119.93 t/ha/year. Results have shown that 5% of the surface area displays a high rate of soil loss, and it represents zones with moderate to severe soil erosion. These areas are mainly situated in moderate to very high slope where the runoff is high. This loss is favoured by the other factors of erosion, which are also combined to accelerate erosion losses significantly (58% of the total area has a very high rainfall erosivity), moderately erodible soils (49% of the soils show a K factor between 0.128 and 0.27t ha H/ha MJ mm), 78% of the soil have nearly level to gently undulating plains, and 14% of the areas representing steep slopes. The results revealed that, there is a probability that the rate of erosion will increase in the future in this area which pose a great threat to the achievement of the SDG-15. Therefore, proper land-use planning should be adopted such as cropping pattern for agricultural land in local area. Accurate planning should be done as a means for restoring degraded vegetation.

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KEYWORDS: Erosion, Topography, Rainfall, Vegetation, Revised Universal Soil Loss Equation

1. INTRODUCTION

Nigeria has had numerous natural catastrophes throughout the years, including flooding, oil spills, bushfires, drought, and erosion [1]. All of these disasters have had an adverse effect on the environment in one way or another. According to reports from the United Nations, soil erosion is one of the primary landscape catastrophes that annually cost millions to billions of dollars to resuscitate damaged buildings and other physical properties as remarked by [1]. [2] identified the main causes of soil erosion worldwide as steep slopes, discontinuities, weathering, and flooding. These factors all contribute to rainfall-induced erosion.

Rainfall is the main source of soil erosion in West African nations [1]. Nigeria has recently experienced landslides and erosional activities produced by geological settings with a high frequency and variety. In order to ascertain the geotechnical characteristics of the soils, [3] conducted geological assessments of soil erosion occurrences in the Okemesi area of South-Western Nigeria. They concluded that Okemesi's rocks were severely broken, which led to the occurrence of soil erosion there. More over [1], reported that the heavy rains of October, 2013 resulted in new cases of erosion in the Cross River State communities of Enugu and Obudu, causing numerous fatalities and significant financial loss.

In recent years, several cities and communities in South Eastern Nigeria have had to deal with one of the worst environmental catastrophes: soil erosion. As a result, living in this area is now quite dangerous. Every year, hundreds of individuals have direct, detrimental effects and occasionally need to be relocated to higher land. There are several areas within the study area facing the problems of soil erosion as a result of flash floods. During the wet season around April to September, most areas become inundated with floods, thereby becoming uninhabitable for inhabitants and destroying driving routes. Figure 1. shows most part of the region that has been inundated and impacted by erosion.

Figure 1.: Field Observation Showing Soil Loss impacted site in Study Area
Source: Authors Field Work (2022)

Therefore, this study is necessitated on the need to provide a geospatial and accurate data on the extent of soil erosion and degradation in impacted sites of the study area employing the Revised Universal Soil Loss Equation Model (RUSLEII), to evaluate the impact of soil erosion within the study area and provide the necessary data needed for decision makers so as to plan and mitigate the further spread of soil Erosion in Ika South Local Government Area, Delta State, Nigeria. This supports SDG-15 which provides for the protection and restoration of the Earth's land ecosystems. The objectives of this research are as follows:

i. Generate the required data for the determination and computation of RUSLE II model parameters,
ii. Generate the RUSLE II model thematic layers and factors such as the rainfall erosivity factor, soil erodibility factor, topographic factor, conservation practice factor and crop management factor,
iii. Integrate all the RUSLE II model thematic layers for the generation and classification of the soil erosion map within the study area.

[4] examined GIS-based soil erosion susceptibility modelling, adapting bivariate statistical method and AHP approach in Gombe town and its environs in North east Nigeria. The first approach to this study was to generate a reliable soil inventory map and to embark on a detailed field survey. Ten soil erosion predisposing factors were carefully selected considering information obtained from the literature and field survey of the study area. This was followed by the production of thematic maps corresponding with the chosen conditioning factors. ASTER DEM satellite imagery with a resolution of 30 m × 30 m was used to extract topographic related factors such as elevation, slope angle, curvature, aspect, topographic wetness index. The geological map was digitized from a previously existing geological map produced by Nigeria Geological Survey Agency (NGSA), while the soil map obtained from the Institute

for Agricultural Research; Ahmadu Bello University Zaria Nigeria was digitized to produce the soil texture map of the area. Drainage buffer and road buffer were digitized from Google Earth imagery while Landsat 8™ 30 m resolution satellite imagery was employed to produce the land use map in ArcGIS version 10.4.

The result obtained from Frequency Ratio (FR) shows that drainage, soil texture, and slope have the highest correlation with soil occurrence, while the Analytical Hierarchy Process (AHP) model revealed that drainage buffer, soil texture, geology have a high correlation with the formation of a soil. Gully erosion susceptibility maps (GESM) were produced and reclassified into very high, high, moderate, and low zones. The overall accuracies of both models were tested utilizing area under the curve (AUC) values and soil density distribution. FR and AHP model have AUC values of 0.73 and 0.72 respectively; the outcome indicated that both models have high prediction accuracy. The soil erosion density distribution values revealed that gullies are concentrated in the very high susceptibility class and it decreases towards the low class, therefore the GESM produced using these models in this study area is reliable and can be used for land management and future planning.

2. MATERIAL and METHODS

The research materials used include:

Datasets: The following freely available datasets as shown in table 1 were acquired and used for this study. The ALOS DEM and Sentinel-2B data were chosen owing to the high resolution. The software used include ArcMap version 10.3.

Table 1. Characteristics of the Datasets used for the Study.

S/N	Dataset	Scale/ Resolution	Source	Coordinate System	Acquisition Date
1	Sentinel-2B Imagery	30m x 30m	NASA/USGS https://earthexplorer.usgs.gov/	WGS 84 UTM Zone 32N	2020/12/28
2	Advanced Land Observing Satellite - Phased Array type L-band Synthetic Aperture Radar Digital Elevation Model (ALOS DEM)	30m x 30m	https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm	WGS 84	2020
3	Rainfall data (Monthly)	0.25° x 0.25°	UCI CHRS's Data Portal https://chrsdata.eng.uci.edu/	WGS 84	2000- 2010
4	Soil Map		Food and Agriculture Organization (FAO) https://data.apps.fao.org	WGS 84	2020

This research employed the RUSLE II (Revised Universal Soil Loss Equation) model. Figure 2 shows the flowchart of the methodology used for this research.

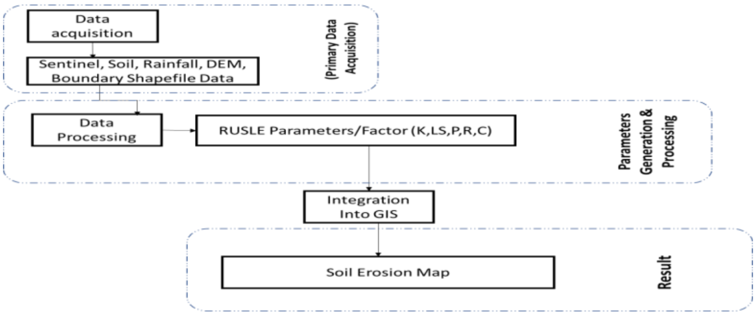

Figure 2: Flowchart Showing Research Methodology
Source: Author (2022)

2.1 RUSLE II Parameter Estimation

The main factors affecting soil erosion are topography, climate, soil, vegetation, land use, and man-made developments as reported by [5]. Amongst all, climate is assumed to be beyond human control, and vegetation and to a lesser extent soil and topography may be controlled through management [6]. Predictions of soil erosion and sediment yield are necessary for guiding the making of rational decisions in conservation planning. Therefore, soil erosion prediction equations are developed to enable planners to predict the average rate of soil erosion for alternative combinations of cropping systems, management techniques, and erosion-control practices on any site [6]. These equations combine the factors representing these erosion-influencing characteristics. One of these equations is the Universal Soil Loss Equation (USLE) developed originally by Wischmeier and Smith [7,8]. The relationships in the USLE are based on thousands of plot-years of data from runoff plots and small watersheds.

The USLE predicts soil loss from sheet or inter rill erosion and rill erosion from roughly planar hillslope areas [6]. Using this equation, land management planners can estimate average annual soil erosion rates from upland slopes for a wide range of rainfall, slope, soil, cover, and management conditions. This equation is a good asset for land management planners to select alternative cover and management combinations that would limit erosion rates to acceptable levels. In the RUSLE model, it is assumed that soil detachment and deposition are controlled by the sediment load in the flow. Also, it assumed that the erosion, which is not source limited, is only limited by the flow capacity. Under this condition, soil detachment can no longer occur once the sediment load exceeds the sediment flow capacity. The following equation is used to compute average annual soil erosion expected on upland (field) slopes:

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

Where:

A is the Average Annual Soil Erosion,
R is the Rainfall Erosivity Factor,
K is the Soil Erodibility Factor,
L is Slope Length Factor,
S is the Slope Steepness Factor,

C is the Cover Management Factor,
P is the

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2.1.1 Rainfall-Runoff Erosivity Factor (R)

[9] avers that the numerical value used for R in RUSLE must quantify the effect of raindrop impact and must also reflect the amount and rate of runoff likely to be associated with the rain. The rainfall runoff erosivity factor (R) derived by Wischmeier appears to meet these requirements better than any of the many other rainfall parameters and groups of parameters tested against the plot data.

[7] proposed a predictor of rainfall erosivity factor (R):

$$R = \frac{1}{n}\sum_{j=I}^{n} \quad \left[\sum_{k=I}^{m} \quad (E)(I_{30})_k)\right] \tag{2}$$

where E is the total storm kinetic energy (MJ ha^{-1}), I_{30} is the maximum 30 min rainfall intensity (mm h^{-1}), j is an index of the number of years used to produce the average, k is an index of the number of storms in each year, n is the number of years used to obtain the average R, and m is the number of storms in each year.

However, the formula~~e~~ proposed by [10] was adopted in this research.

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$$R = -8.12 + (0.562 * P) \tag{3}$$

where P is the mean annual rainfall.

In this study, we calculated the annual rainfall erosivity using the empirical equation proposed by [10], because the R factor of RUSLE requires long-term rainfall intensity data (I_{30}) which are not available for the study area.

2.1.2 Soil Erodibility Factor (K)

The estimation of the soil erodibility factor K was based on the soil textures. K values show the rate of soil loss per rainfall-runoff erosivity (R) index. Soil erodibility factors (K) computed from using equation (4) are best obtained from direct measurements on natural runoff plots.

The soil textures present in this study area includes clay loam, sandy clay and sandy loam.

$$k\ Factor = F_{sand} * F_{Clay} * F_{Orgc} * F_{silt} \tag{5}$$

$$f_{sand} = \left\{0.2 + 0.3exp\left[-0.0256m_{sand}\left(1 - \frac{m_{silt}}{100}\right)\right]\right\} \tag{6}$$

$$f_{clay} = \left[\frac{m_{silt}}{m_{clay}+m_{silt}}\right]^{0.3} \tag{7}$$

$$f_{OrgC} = \left\{1 - \frac{0.25\ org\ C}{[org\ C+exp(3.72-2.95org\ C)]}\right\} \tag{8}$$

$$f_{silt} = \left\{1 - \frac{0.7\left(1-\frac{m_{sand}}{100}\right)}{\left\{\left(1-\frac{m_{sand}}{100}\right)+exp\left[-5.51+22.9\left(1-\frac{m_{sand}}{100}\right)\right]\right\}}\right\} \tag{9}$$

where: m_{sand} = proportion (%) of sand content (0.05*2.0 mm diameter particles), m_{silt} = proportion (%) of silt content (0.002-0.05 mm diameter particles), m_{Clay} = proportion (%), of clay content (<0.002mm diameter particles), and Orgc = amount (%) of the organic carbon content of the layer (%).

2.1.3 Topographic Factor (LS)

The topographic factor represents a ratio of soil loss under a given condition to that at a site with the standard slope steepness of 9% and slope length of 22.6m. Topographical factor constitutes two factors which are slope length (L) and slope steepness (S). The effects of slope steepness have a greater impact on soil loss than slope length. The Steeper the slope, the greater the erosion. The worst erosion occurring between 10 and 25% slope.

$$L = (m+1)\left(\frac{\lambda_A}{22.1}\right)^m \quad (10)$$

L is the slope length factor, λ_A is the area of upland flow, m is an adjustable value depending on the soil's susceptibility to erosion, 22.1 is the unit plot length.

$$S = \left(\frac{sinsin(0.01745\times\theta_{deg})}{0.09}\right)^n \quad (11)$$

Where θ is the slope in degrees, 0.09 is the slope gradient constant, and n is an adjustable value depending on the soil's susceptibility to erosion.

2.2 Creating a Depression less DEM

A digital elevation model (DEM) free of sinks—a depression less DEM—is the desired input to the flow direction process. The presence of sinks may result in an erroneous flow-direction raster. A sink is a pit or depression in a DEM that will obstruct the natural drainage of water downstream. Sinks are present in the data due to errors, or presence of natural depressions, ponds, or lakes.

Since the maximum value after carrying out the sink operation was displayed as No Data or 0, thus the depression less DEM has been created, and the DEM was used in estimating the LS factor.

2.2.1 Crop Management Factor (C)

The cover management factor (C) is a crucial factor to the erosion because it is a readily managed condition to reduce erosion as reported by [11]. Soil erosion decreases exponentially with increase in vegetation cover as opined by [12].

[13] method was adopted to estimate the C-factor, which is suitable in areas with tropical climate conditions, and more intense rainfall.

$$C = exp\ exp\left(-\propto\cdot\frac{NDVI}{\beta-NDVI}\right) \quad (12$$

2.2.2 Conservation Support Practice Factor (P)

The conservation practice factor (P) represents the ratio of soil loss by a support practice to that of straight- row farming up and down the slope, and it is used to account for the positive impacts of those of support practices. The P factor accounts for control practices that reduce the erosion potential of the runoff by their influence on drainage patterns, runoff concentration, runoff velocity, and hydraulic forces exerted by runoff on soil opined by [14].

3. RESULTS AND DISCUSSION

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In line with the first Objective of the research work which was the generation of the required data that would be used in determining the parameters that would be used in the RUSLE II model that would be in turn used for the estimation of the annual Soil loss within the study area. In line with the second objective which is the generation of the thematic layers for the different factors incorporated in the RUSLE II model are shown in Figure 3.

3.1 Rainfall Erosivity Factor (R)

The rainfall data was obtained in raster format from UCI CHRS's Data Portal, and the Map Algebra tool: Raster Calculator, from the Spatial Analyst processing tool box in ArcGIS Pro software, was used for determining the mean annual rainfall raster dataset (see Figure 3) and rainfall erosivity factor (see

Figure 4). It is observed that the highest rainfall occurred in the south-eastern part of the study area and the lowest rainfall occurred in north-western region of the area.

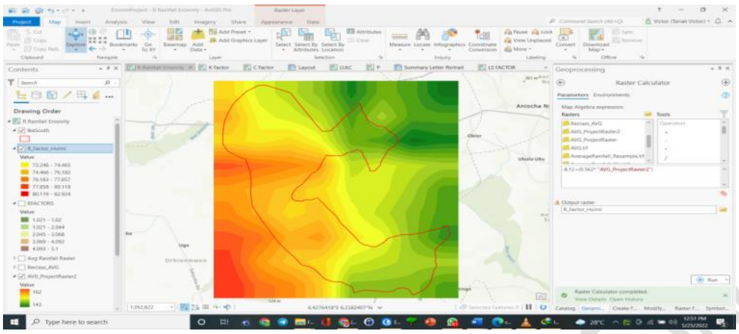

Figure 3: Figure Showing Annual Rainfall Raster. ***Source: Author's field work, 2022.***

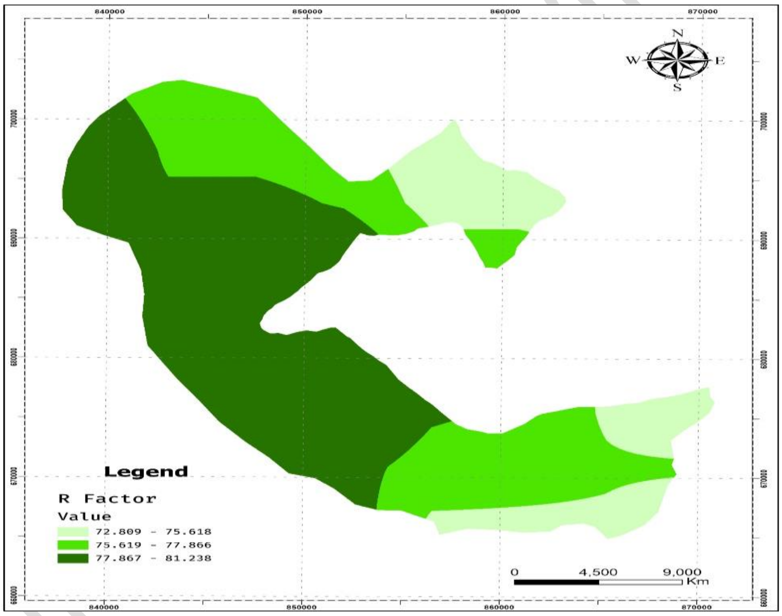

Figure 4: Rainfall Erosivity of Ika South Local Government Area, Delta State.
Source: Author's field work, 2022

3.2 Soil Erodibility Factor (K)

Soil classification of the Ika South was done using the Soil map of Nigeria (1990). Two major Soil types; Rainforest soils and wetland soils were found within the study area. In this study, Soil erodibility (K) was estimated using the relationship between soil texture class, and organic matter content proposed by [15]. The organic matter content is assumed to be 0.5% because there is no organic matter content survey data for Ika South. Table 2 presents the soil erodibility factor (K) based on the soil texture class [16].

Table 2: Soil Erodibility Factor(K)

	Organic Matter Content (%)	
Textural Class	0.5	2
Fine Sand	0.16	0.14
Very Fine Sand	0.42	0.36
Loamy sand	0.12	0.10
Loamy very fine sand	0.44	0.38
Sandy loamy	0.27	0.24
Very fine sandy loam	0.47	0.41
Silt loam	0.48	0.42
Clay loam	0.28	0.25
Silty clay loam	0.37	0.32
Silty Clay	0.25	0.23

Source: [16]

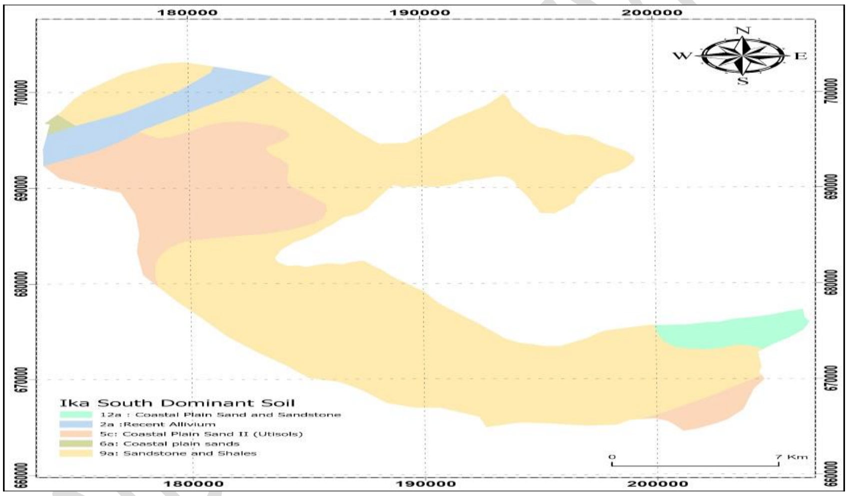

Figure 5: Dominant Soil Within the study area. ***Source: Author's field work, 2022***

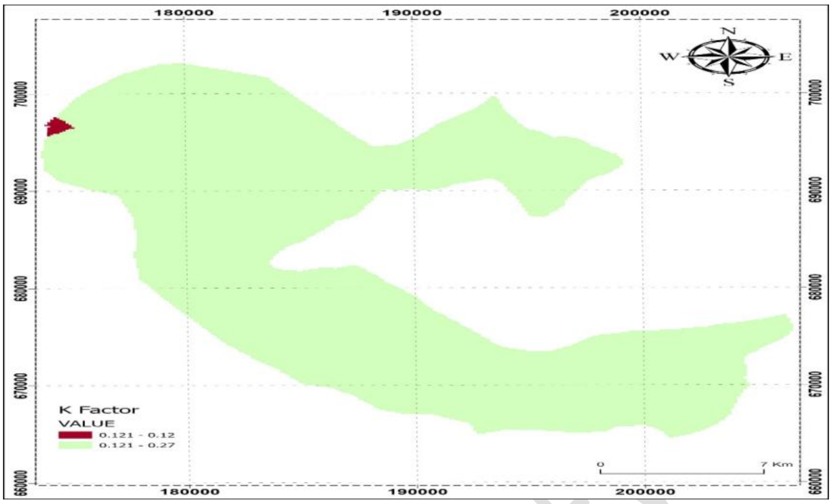

Figure 6: Soil erodibility (K) Map of Ika South. ***Source: Author's field work, 2022***

3.3 Topographic Factor (LS)

The tools in the Hydrology toolset of the ArcGIS Pro Spatial Analyst extension, were used in preparing a depression less elevation surface. Since the maximum value after carrying out the ***sink*** operation was displayed as No Data or 0, thus the depression less DEM was created, and further used in estimating the Topographic **(**LS) map (see Figure 7)

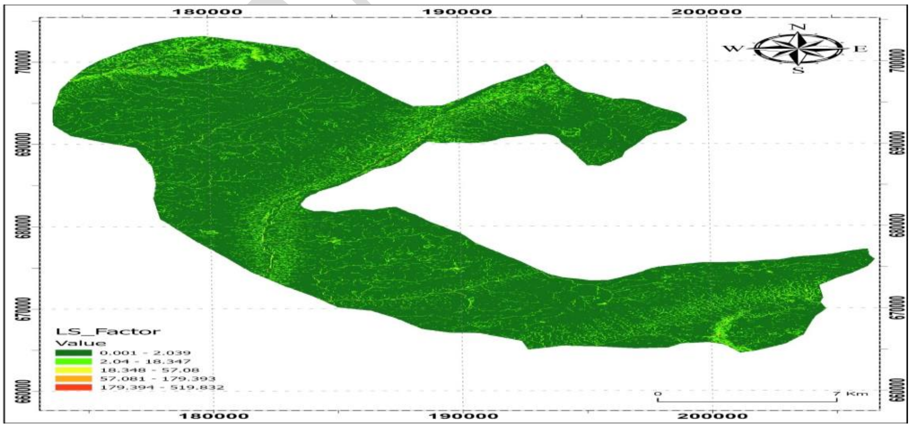

Figure 7: Topographic (LS) Map of Ika South. ***Source: Author's field work, 2022***

3.4 Crop Management Factor (C)

In relation to the C-factor as in equation (12), it was concluded that tropical climate conditions use values 2 and 1 as the best representatives of equation parameters α and β, respectively. The NDVI was generated using the raster calculator tool function in the map algebra toolbox in the ArcGIS Pro software. The C-factor formula was also used in determining the Cover management map using the raster calculator tool as shown in Figure 8.

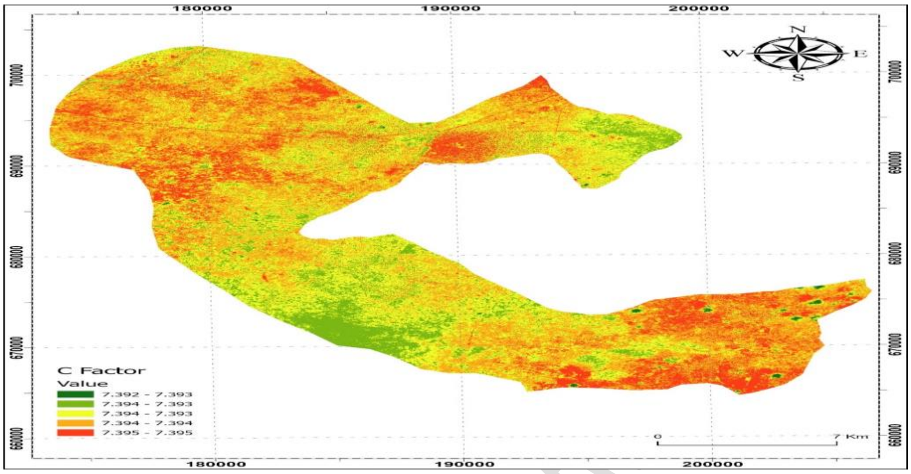

Figure 8: Crop management (C) map of Ika South. ***Source: Author's Field Work, 2022***

3.5 Conservation Support Practice Factor (P)

The Slope Map from which the P-factor map was generated is shown in Figure 9. The region with good conservation support practice is depicted in steel blue colour with the value of 0.5, while areas with poor conservation support practice is depicted with light Apple green colour respectively. Areas with 1, has high susceptibility to soil erosion and this amounts to about 91% of the study area. The value of *P* factor ranges from 0 to 1, the value approaching to 0 indicates good conservation practice and the value approaching 1 indicates poor conservation practice.

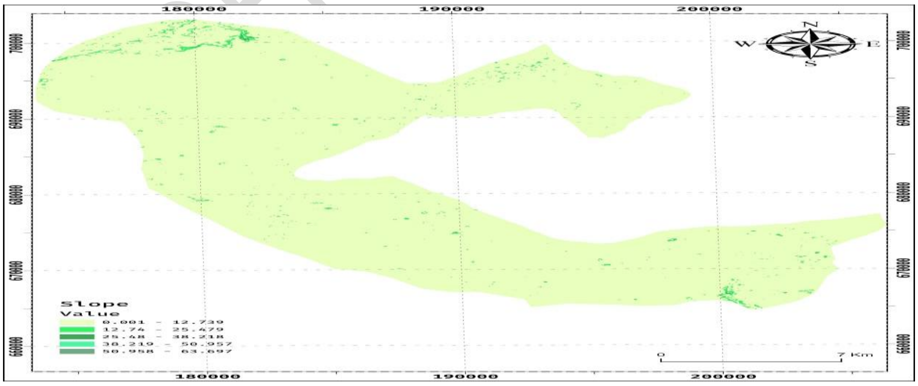

Figure 9: Slope Map for Ika-South. ***Source: Author's Field Work, 2022***

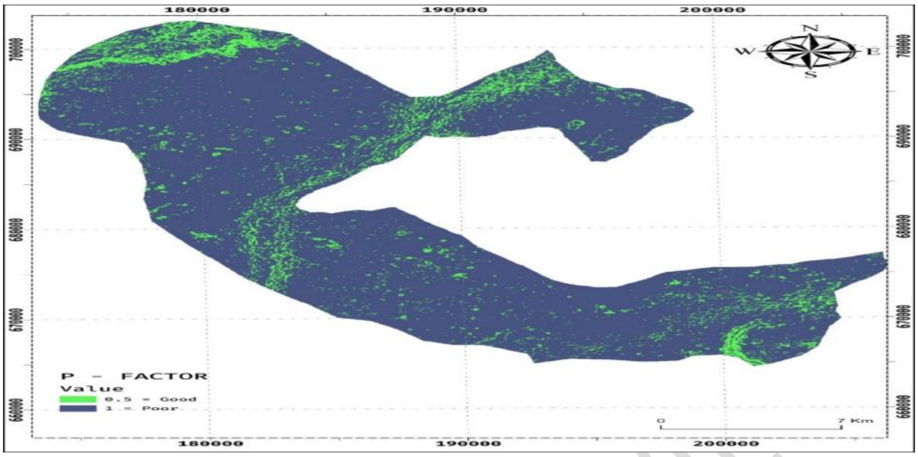

Figure 10: Support Practice (P) Map of Ika South. ***Source: Author's Field Work, 2022***

3.6 Integration of RUSLE II Parameter into GIS

In line with Objective three, the different thematic layers generated from the various data sets obtained were integrated into the GIS environment (see Figure 11). Six parameters of the RUSLE II model were multiplied using the raster calculator function tool in the ARCGIS Pro toolbox. Figure 11, represent the average annual soil loss rate within Ika South LGA. The total annual average soil loss rate of the Ika South is about 49,000 tons/year.

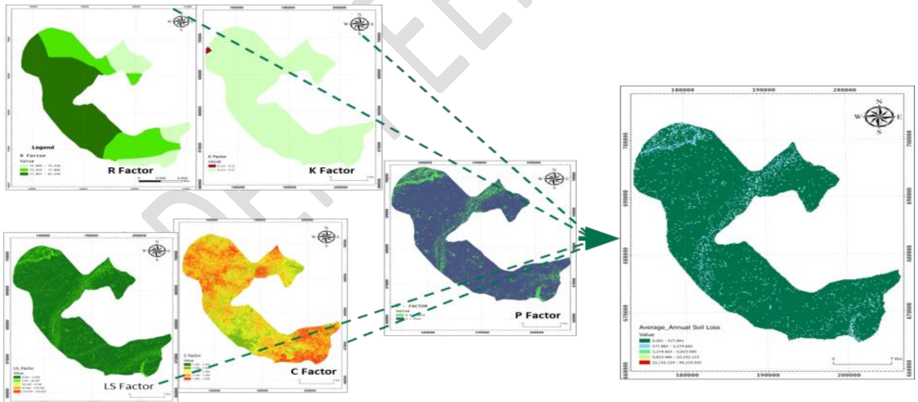

Figure 11: RUSLE II Parameter integration into GIS Environment. Source: Author's Field Work, 2022

4. CONCLUSION

Soil erosion is a common phenomenon that harmfully impacts the ground. This study mainly deals with the estimation of potential soil erosion areas using the RUSLE method and GIS techniques. It provides a concrete estimation of the distribution of soil erosion at Ika South LGA, throughout the combination of the influencing factors such as rainfall aggressivity, soil erodibility, topography, vegetation cover, and soil conservation practices.

The soil loss estimated at Ika South ranges from 0 to 49119.93 t/ha/year. Results have shown that 5% of the surface area displays an important rate of soil loss, and it represents zones with moderate to severe soil erosion. These areas are mainly situated in moderate to very high slope where the runoff is important. This loss is favoured by the other factors of erosion, which are also combined to accelerate erosion, significant losses (58% of the total area has a very important rainfall erosivity), moderately erodible soils (49% of the soils show a K factor between 0.128 and 0.27t ha H/ha MJ mm), 78% of the soil have nearly level to gently Undulating plains, and 14% of the areas representing steep slopes. These statistics show that the Ika South is subject to a medium to high erosion risk and even severe to some specific areas.

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