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Soil Loss Estimation Within the Nun River Basin Using Revised Universal Soil Loss Equation (RUSLE) Integrated in Geographic Information Systems (GIS)

Ehiorobo, J. O.[1(✉)], Ilaboya, I. R.[1] and Onwo, N.[2]

[1] Department of Civil Engineering, Faculty of Engineering, University of Benin, P.M.B 1154, Benin City, Edo State, Nigeria
[2] Niger Delta Development commision, Portharcourt

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ABSTRACT

River bank erosion can cause undesired river bank expansion, distortion of the river course thereby slowing the river velocity and hindering the water carrying capacity of the river. Slow velocity of the river course can result in fast sediment accretion and accumulation at the bottom of the river. If these trends are not checked, the river may wind down and at best begin to become a delta at its middle course. The focus of this study is to apply GIS and analytical RUSLE equation to estimate soil loss within the Nun Basin.

Core sediment samples were collected from relatively undisturbed areas (nine different stations) using Uwitec Triple sediment cutter. The sediment samples were processed in the lab for sediment particle size analysis (PSA) and Pb-210 atmospheric deposition with age using alpha spectrophotometer. Spatial rainfall data of the study location were employed to generate the rainfall erosivity map in order to determine the erosivity factor (R). Particle size distribution analysis was validated using Scanning Electron Micrograph (SEM) and integrated with Geographic Information Systems (GIS) was employed to create the soil erodibility map which was subsequently used to determine the erodibility factor (K). The cover management factor (P) was determined using the land use land cover map and the resulting data were then employed to model the river bank erosion around the study area.

Result of the study revealed that the maximum annual average soil loss rate was estimated to be 0.66 tons/ha. /year around the Nun River based on GIS application using the Revised Universal Soil Loss Equation (RUSLE).

1. Introduction

River bank erosion is only one process in the total channel system in which erosion is closely linked to other processes such as sediment transport and deposition. River bank erosion occurs when the top soil enclosing a river washes into the river (Walling, 1995). Currently,

*Corresponding author E-mail address: jacehio@uniben.edu

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two main sets of bank erosion processes and mechanisms exist in the literature. They are; fluvial erosion and mass failure. Fluvial erosion is defined as the removal of bank material by the action of hydraulic forces. It generally occurs in combination with weathering processes that prepare bank sediments for erosion by enhancing their erodibility (Thorne, 1982; Lawler, 2005). In general, fluvial-erosion rates depend on the near-bank flow intensity and physical characteristics (i.e., the erodibility) of the bank material. However, the end result of fluvial erosion is that the river gets deeper at the end of the process. Mass failure on the other hand is the collapse and movement of bank material under gravity. Relative to fluvial erosion, mass failure is discontinuous and large-scale movement of bank materials which eventually makes the river longer or wider. Some of the drivers of mass failure include; flooding, land use, uncontrolled clearing of catchment and bank vegetation including excessive dredging (Basher et al., 2018).

River bank erosion is important geomorphologically in effecting changes in the river channel course and also in development of the flood plain. These are amongst the most dynamic elements of the landscape. Therefore, an understanding of the processes of river bank erosion is fundamental to our explanation of the development of fluvial features. River bank erosion is a critical issue from economic perspective due to the loss of farm land and the undermining of structures adjacent to the river channel. Interestingly, this problem is often underestimated in most developed and developing countries of the World. Naturally, river bank erosion results in the formation of productive alluvial terraces and floodplains while unnatural causes may result in sediment loading, channel instability, habitat loss, and eutrophication (EPA, 2012, 2014).

Countries are affected by riverbank erosion to different extents, leading to varying degrees of landscape degradation, environmental and socioeconomic impacts. In Nigeria for example, the release of water from the Lake Chad basin has rendered a lot of havoc on communities that are situated along the river bank. The worst-case scenario was the experience of 2012 occasioned by massive flooding that rendered havoc on states and communities that are situated along the coastal region such as; Bayelsa, Kogi, Edo, Benue and Rivers. The flooding brought along with-it invasive species, contaminants, sediment, etc. River bank erosion is a critical issue from economic perspective due to the loss of farm land and the undermining of structures adjacent to the river channel. Interestingly, this problem is often underestimated in most developed and developing countries of the World.

2. Research Methodology

2.1. Description of study area

The Study area is River Nun in Bayelsa State. River Nun is a bifurcation of the River Niger down stream of the Niger Delta Basin. It has a total length of 195km and an average width of 370m, the Nun River is considered the largest river in Bayelsa State (Seiyahboh et al., 2013). It flows through several communities in Bayelsa State, through sparsely settled zones of freshwater and mangrove swamps and coastal sand ridges before completing its 160km course to the Gulf of Guinea (inlet of the Atlantic Ocean) (Uche et al., 2015). The river is used for domestic purposes, recreational, fishing and ecological assets. Owing to the rapidly expanding developmental activities within its channels, it is subject to the effects and influences of human activities and other interference. It is also prone to flooding especially when the dams up the Niger River are opened. Dredging both at local and industrial scales are common activities in this river. Figure shows the Landsat imagery of the Nun River.

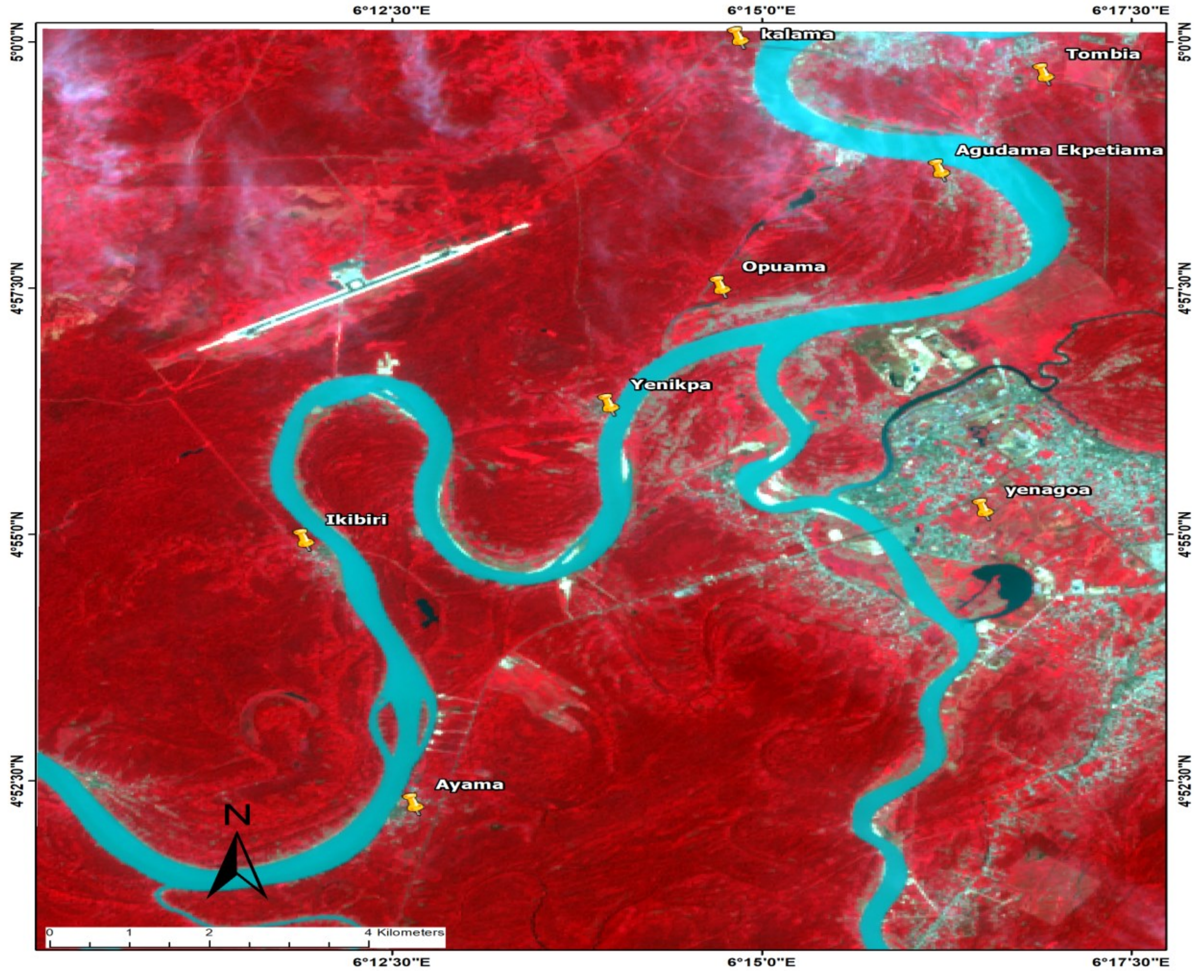

Figure 1. *Landsat Imagery of the Nun River*

2.2. Soil loss estimation

The Revised Universal Soil Loss Equation proposed by Renard, (1997) is an improved form of the Universal Soil Loss Equation (USLE) proposed by Wischmeier and Smith (1978). The equation which was employed in this study to estimate the annual soil loss in the study area is presented as;

$$A = R \times K \times LS \times C \times P \tag{1}$$

Where,

A; is the computed average annual soil loss (tons/ha/year), R is the rainfall-runoff erosivity factor, K; is the soil erodibility factor, LS; is the slope length and slope steepness factor, C; is the cover-management factor and P; is the conservation practice factor.

Digital data such as Landsat imagery, DEM and digital soil data were obtained from the archive of USGS and the Food and Agriculture Organization (FAO) harmonized world soil database (HWSD). GIS software (ArcGIS) was used for processing (pre and post) these digital data in order to extract useful information from them such as LS-factor from the DEM, K factor from the digital soil map, C-factor and P factor from the Landsat imagery and R-factor from the rainfall data. In order to evaluate the soil loss from the study area, these factors were processed in addition to the meteorological data, soil data and remote sensing data by the integration of the RUSLE model with GIS to obtain more spatially accurate results. The schematic diagram of the approach for deriving each parameter is presented in Figure 2.

2.2.1. Estimation of Rusle Parameters

2.2.1.1. Rainfall erosivity factor (R)

The rainfall erosivity factor (R) describes the erosivity of rainfall at a particular location based on the rainfall amount and intensity. It is an important parameter for soil erosion risk assessment under future land use and climate change and is defined according to (Uddin et al, 2010) as;

$$R = 0.5' \ P' \ 1.73 \text{ (in metric unit)} \tag{2}$$

Where; P; is annual precipitation (mm).

In this study, Equation (2) was used for the determination of R-value as it has been found to work well in tropical regions. Therefore, every grid cell of the average yearly rainfall was considered using the equation to get the R-value via ArcGIS. The mean annual precipitation surface was applied to compute the R-factor by the spatial analyst section of the ArcGIS software.

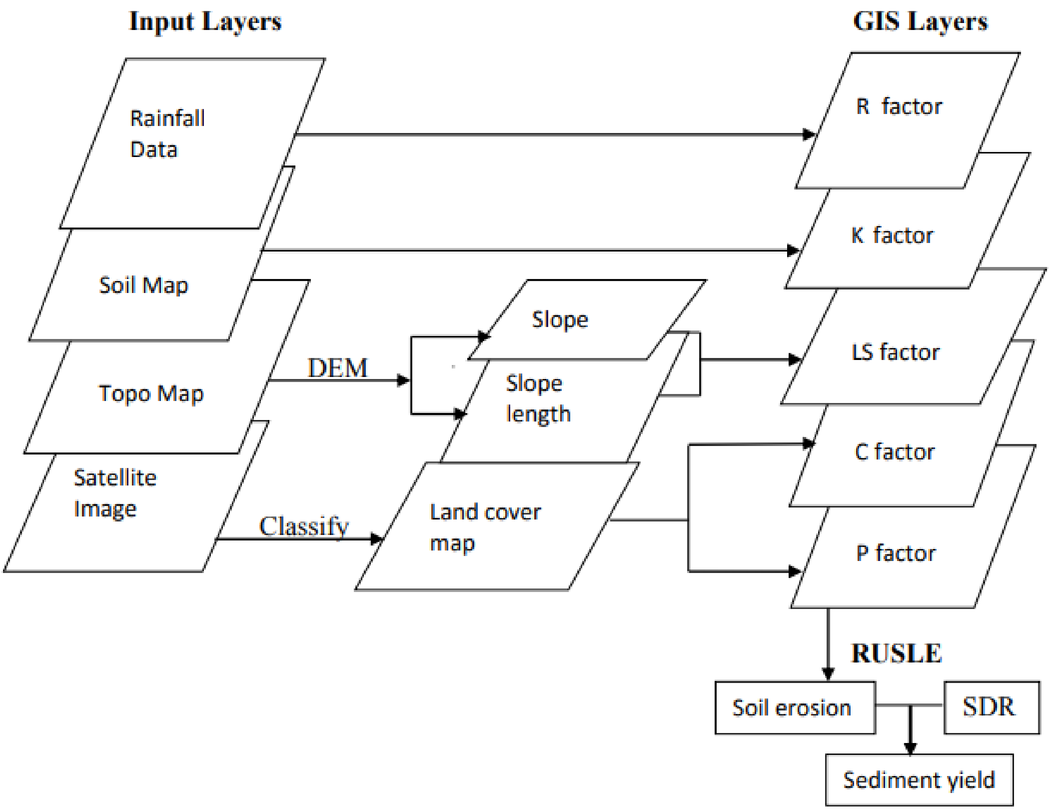

Figure 2. *Schematic chart of GIS applications to soil erosion modelling (Modified from Mongkolsawat et al. 1994)*

2.2.1.2. Soil erodibility factor (k)

The soil erodibility factor (K) is a quantitative description of the inherent erodibility of a particular soil type; it is a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff (Lane et al 1992). The main soil properties influencing the K factor are soil texture, organic matter, soil structure, and permeability of the soil profile. Mathematically, the soil erodibility factor is defined as; (source?)

$$K = \frac{2.1 \times 10^{-4}(12 - OM)M^{1.14} + 3.25(S - 2) + 2.5(P - 3)}{759.4} \tag{3}$$

Where;

K; is the soil erodibility ($tons - yr / MJ - mm$), OM; is the percentage organic matter, P; is the soil permeability code, S; is the soil structure code, M; is a function of the primary particle size fraction given by;

$$M = (\%\,silt + \%\,\text{sand}) \times (100 - \%\,\text{clay}) \tag{4}$$

2.2.1.3. Cover management factor (c)

The cover-management factor is the ratio of soil loss from an area with specified cover and management to that of an identical area in tilled continuous fallow. The cover management factor (C) was generated using the Normalized Difference Vegetation Index (NDVI) calculated from Landsat 8 using the yearly 2018-2019 cloud free images. The regression equation for C factor was developed as follows;

$$C_i = \tag{5}$$

Where

$NDVI_{\max}$ = maximum NDVI value

$$NDVI = \frac{near \text{ infrared (NIR) - red (R)}}{near \text{ inf } rared(NIR) + red(R)}$$

2.2.1.4. Conservation practice factor

The P-factor is the degree of the usefulness of land management customs designed to reduce soil loss in a given area of land. P values range from 0 to 1. On this scale, 0 represents an appropriate man-made erosion-resistant facility while 1 denotes absence of man-made erosion-resistant facility. For this work P for different management practices was extracted from values tabulated in Hann et al. (1994) in this case costal vegetation with a value of 0.8.

2.2.1.5. Slope length and slope steepness factors (LS)

The L- and S-factors depicts the topographic erosion vulnerability of a particular location. They were calculated from the DEM. The 30m DEM was downloaded from the USGS repository. The slope length factor (L) was calculated using the following equations:

$$L = \left(\frac{l}{22.13}\right)^m \tag{6}$$

Where;

22.13; is the RUSLE unit plot length (m) and m; is a variable defined as slope-length exponent. The slope-length exponent m is calculated as,

$$m = \frac{b}{(1 + b)} \tag{7}$$

$$b = \left(\sin\theta / 0.0896\right) / [3.0(\sin\theta)^{0.8} + 0.56] \tag{8}$$

Where;

q is the slope angle.

The slope steepness factor (S) is evaluated from McCool et al. (1993) as;

$$S = 10.8 \times \sin q + 0.03 \qquad S > 9\%, S \leq 9\% \tag{9}$$

$$S = \left(\sin q \big/ \sin 5.143 \right)^{0.6} \tag{10}$$

To calculate the slope length and Slope Steepness factor the slope map (degrees) and flow accumulation map were derived from the DEM using Hydrological tools available in Spatial Analyst tool box of ESRI ArcGIS.

3. Results and Discussion

3.1. Result of Rainfall Runoff Erosivity Factor (R)

To determine the rainfall erosivity factor of the study area, the precipitation map was first generated and the erosivity factor map was then created to estimate the average range of R around the Nun River. The Erosivity factor map of the study station is presented in Figure 3.

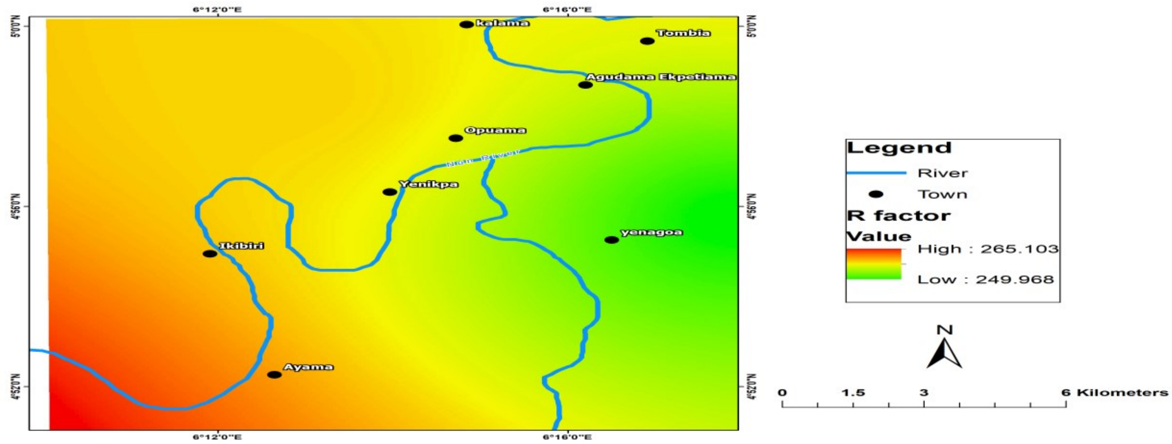

Figure 3. *Rainfall erosivity factor (R) map of the study location along the Nun River*

As observed in Figure 3, the average rainfall-runoff erosivity (R) factors ranges from 249.968 to 265.103 along the Nun River.

3.2. Result of Soil Erodibility Factor (K)

Soil erodibility factor (K) is related to the integrated effect of rainfall, runoff, and infiltration on soil loss. For a particular soil, the soil erodibility factor is the rate of erosion per unit erosion index. To determine the soil class around the Nun River, particle size distribution analysis and microstructural analysis of the soil particles were done. Result of the particle size distribution analysis is presented in Table 1.

Table 1.

Result of sieve analysis of sediment from selected location along the Nun River

Sample No	Dry Sieve Passing %					
	1.18mm	**0.600mm**	**0.300mm**	**0.212mm**	**0.150mm**	**0.075mm**
Stn. 1	98.8	97.4	96.5	95.5		75.6
Stn. 2						50.5
Stn. 3					98.2	41
Stn. 4					99.19	37.64
Stn. 5					97.5	35
Stn. 6					98.7	31.3
Stn. 7	99.1	97.3	96.4	95.4		47.4
Sample No	**Wet Sieve Passing %**					
	1.18mm	**0.600mm**	**0.300mm**	**0.212mm**	**0.150mm**	**0.075mm**
Stn. 1						69
Stn. 2						86.8
Stn. 3						72
Stn. 4						89.8
Stn. 5					97.8	42
Stn. 6					99.3	73.7
Stn. 7	98.8	97.4	96.5	95.5		75.6

Particle size distribution tests carried out on both dry and wet soil samples show distinct similarities in the samples irrespective of sampling location. On the average, the wet soil passing the 0.075 mm sieve ranges from 42 to 89.8%. For the dry sieve, the range is 31.3 to 75.6% which implies that more than 35% passed the 0.075mm sieve. This indicates that the soil is composed of mainly silty clay materials. According to the American Association of State Highway and Transportation Officials (AASHTO), these soils can be classified as A-6. Result of the sieve analysis was checked against the Scanning Electron Micrograph (SEM) and Fourier Transform Infra-red (FT-IR) of the sediment samples presented in Figures 4 and 5 respectively.

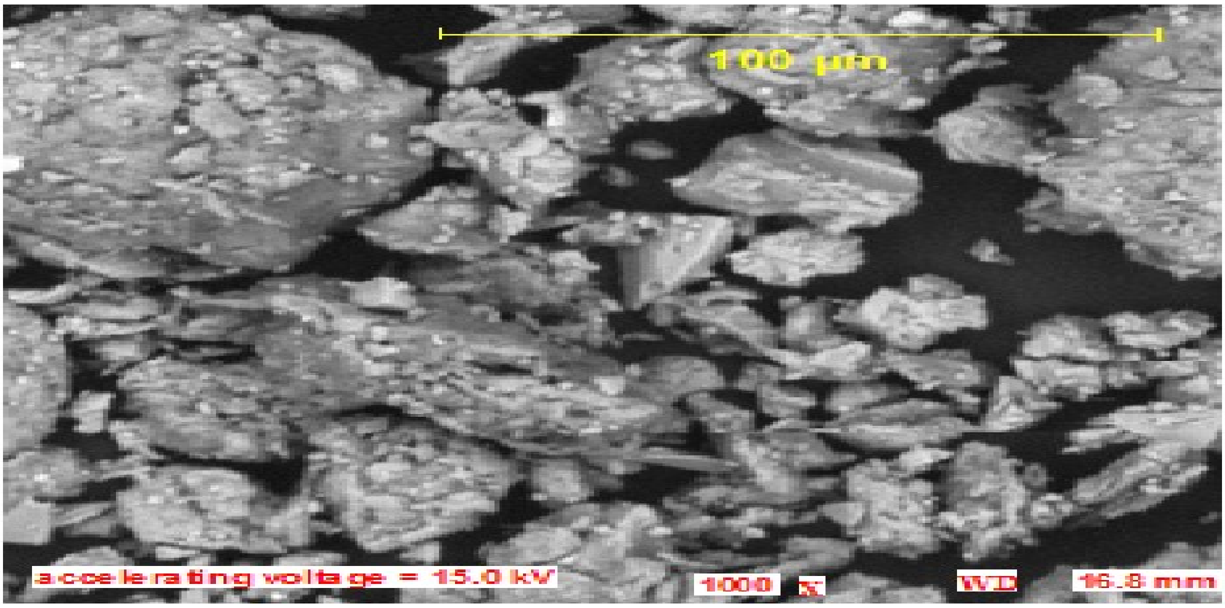

Figure 4. *SEM result of sediment from the study location along the Nun River*

The irregular nature of the SEM result presented in Figure 4 is an indication that the soil is amorphous in nature (loosely packed) which is reminiscence of a silty soil.

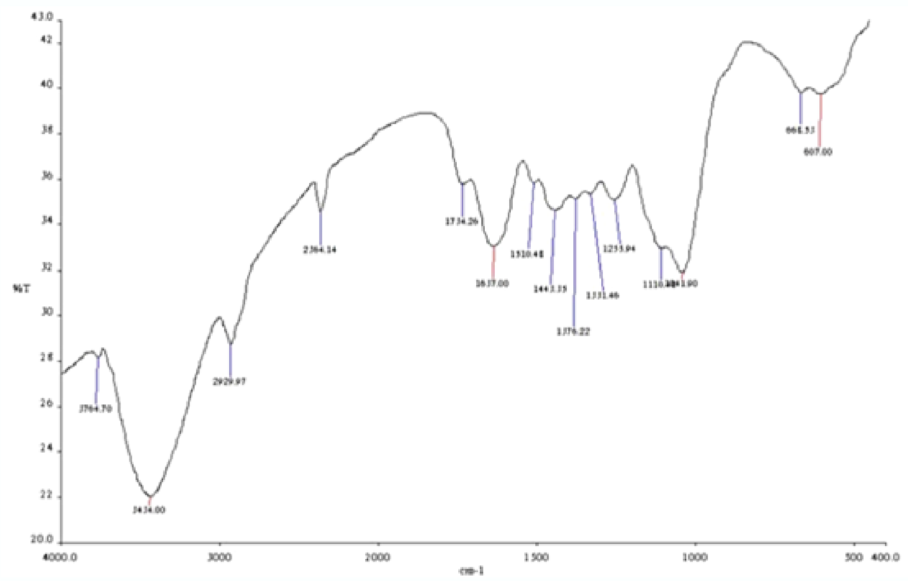

Figure 5. *FT-IR result of sediment from the study location along the Nun River*

To identify the functional group based on the FTIR spectra presented in Figure 5, absorption assigned bands from the works of previous researchers were adopted and employed to analyze and evaluate the spectrum of the sediment and result is presented in Table 2.

Table 2.
Fourier Transform Infrared Spectrum of sediment sample

S/No	Wave Number (cm^{-1})	Bond Source
1	3434.00	O-H stretching mode of hydroxyl groups N-H stretch
2	1637.00	N-H bending of amides,
3	1510.42	Quinonic and carboxylate groups, N-H bending,
4	1445.55	CH_2 and CH_2 bend, pyrones and aromatic group
5	1376.22	Organic phosphate, (P-O stretch)
6	1110.24	Organic siloxane or silicone, Si-O-C stretch
7	661.58	Disulphides (C - S stretch)

Since the dominant function group is O-H stretching mode of hydroxyl groups which is a weak bond, it was further confirmed that the soil type is not crystalline but amorphous in nature. The soil erodibility factor ranges in value from 0.02 to 0.69. Soils with high clay content have low K values, about 0.05 to 0.15, which is mainly due to their resistance to detachment. Texture is the principal factor affecting the K values. Coarser texture soils, such as sandy soils, have low K values that range from 0.05 to 0.2. It is due to low surface runoff caused by excessive infiltration even though these soils are easily detached. Medium texture soils, such as the silt loam soils, have moderate K values which typically range from 0.25 to 0.4. It is due to their moderate susceptibility to detachment and moderate runoff.

To determine the erodibility factor of the study location, the soil shape file of the study location was added as layer into ArcGIS. Soil map attribute table was edited based on the results of Table 2 and K factors were assigned to generate the K value map. Figure 6 presents the soil erodibility (K) map of the study location along the Nun River.

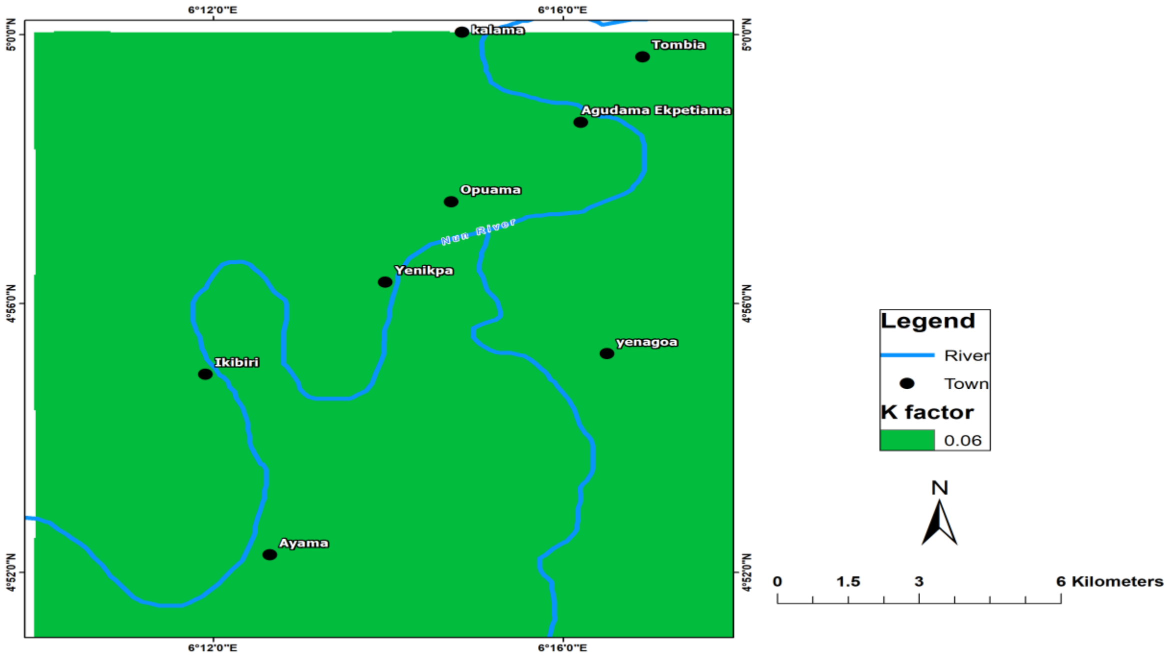

Figure 6. *Soil erodibility factor (K) map of the study location along the Nun River*

Based on the result of Figure 6, the soil erodibility factor was estimated as 0.06 which further validate the result of the sieve analysis in which the sediments were classified as silty clay.

3.3. Result of Slope Length and Slope Steepness Factor (LS)

It is known that an increase in the slope length (L) will results in increase in soil erosion per unit area due to the progressive accumulation of surface runoff on downslope direction. As the slope steepness (S) increases, the velocity and soil erosion of surface runoff also increases. The value of the slope length and slope steepness factor (LS) for the study location along the Nun River was estimated from the topographic LS factor map presented in Figure 7.

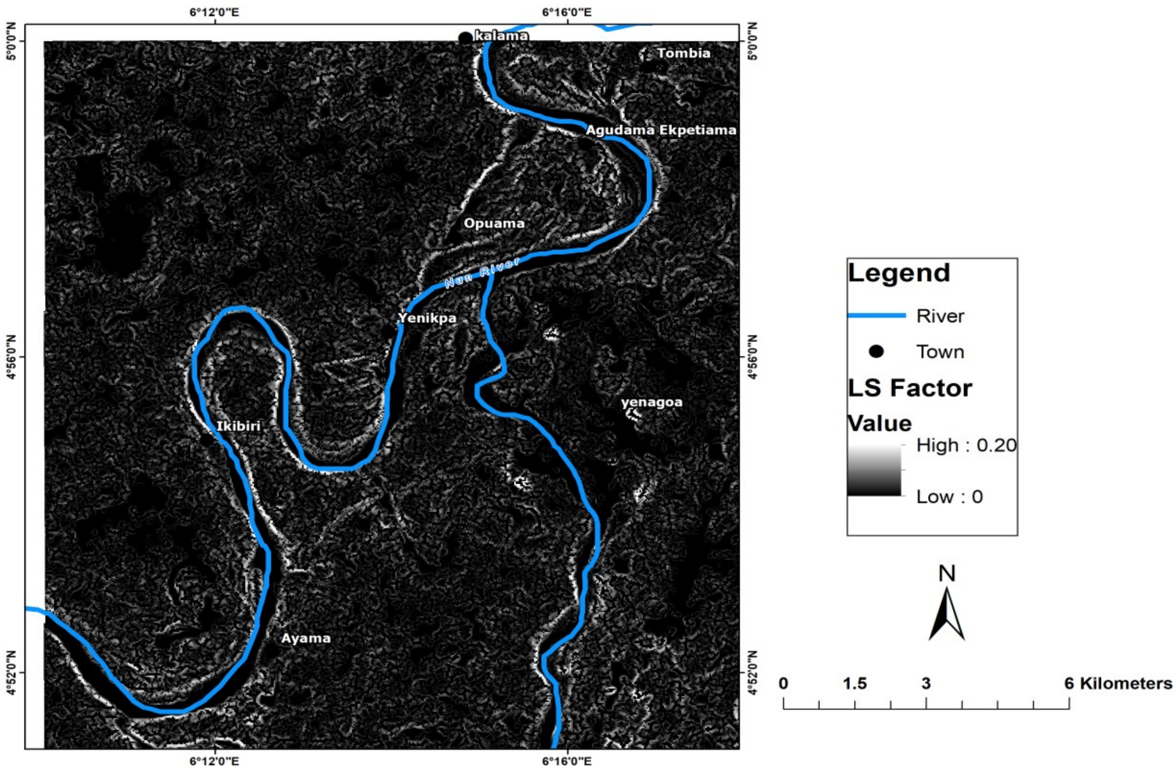

Figure 7. *Slope length and slope steepness factor (LS) map of the study location along the Nun River*

As shown in Figure 7, the average slope length and slope steepness (LS) factors ranges from 0 to 0.20 along the Nun River.

3.4. Result of Cover Management (C) Factor

The Cover Management (C) Factor shows the effect of vegetation cover, cropping and management practices on soil erosion rates. The C factor is the ratio of soil loss from a particular site with a specified cover and management. The C factor of the study location was generated from the land use land cover map. Result of the land development changes within the Nun River from the period 1990 to 2019 generated using Environment for Visualizing Images based on supervised image classification is presented in Figures 8a, 8b and 8c respectively.

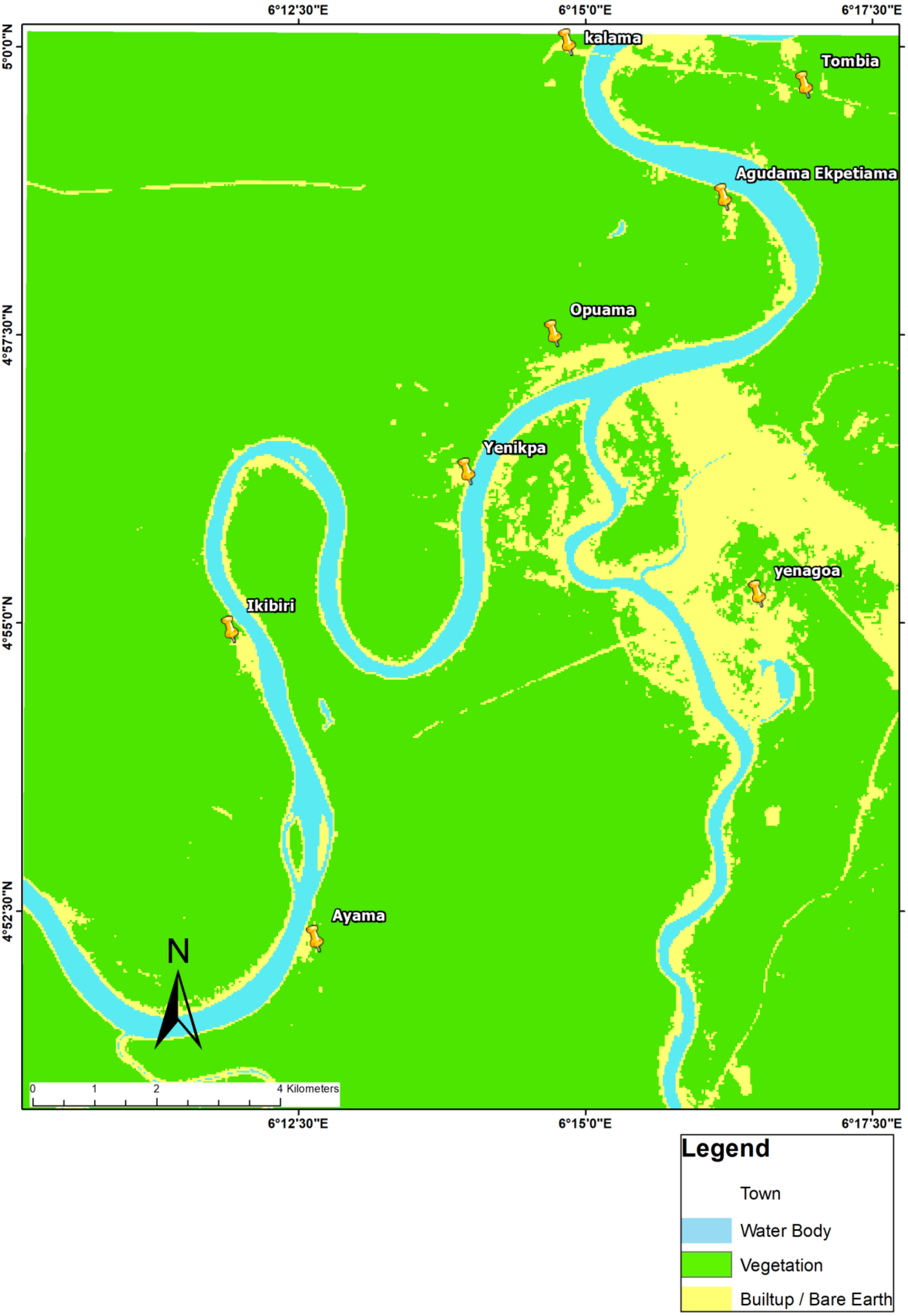

Figure 8a. *Land use land cover map of the Nun River (2000)*

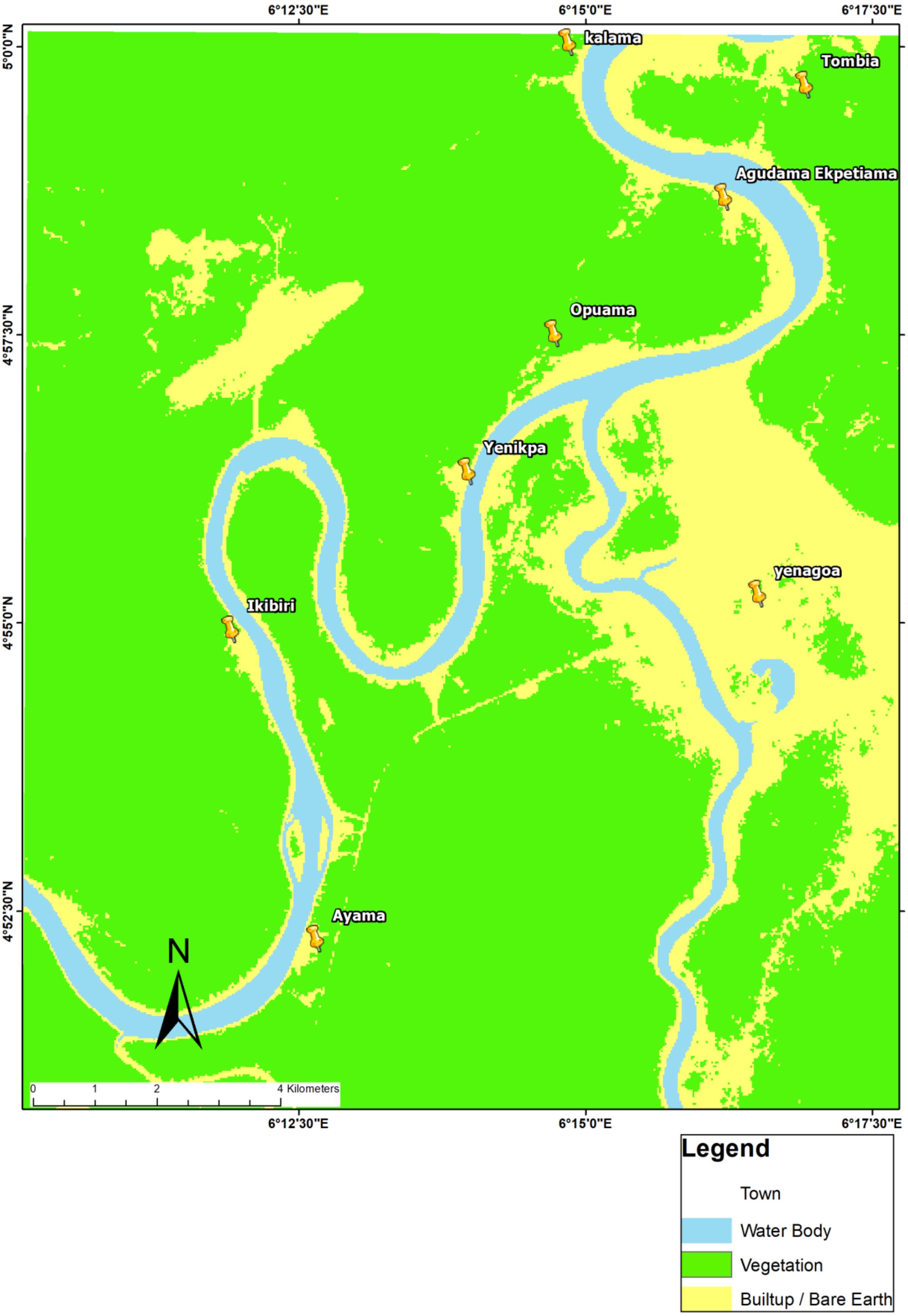

Figure 8b. *Land use land cover map of the Nun River (2010)*

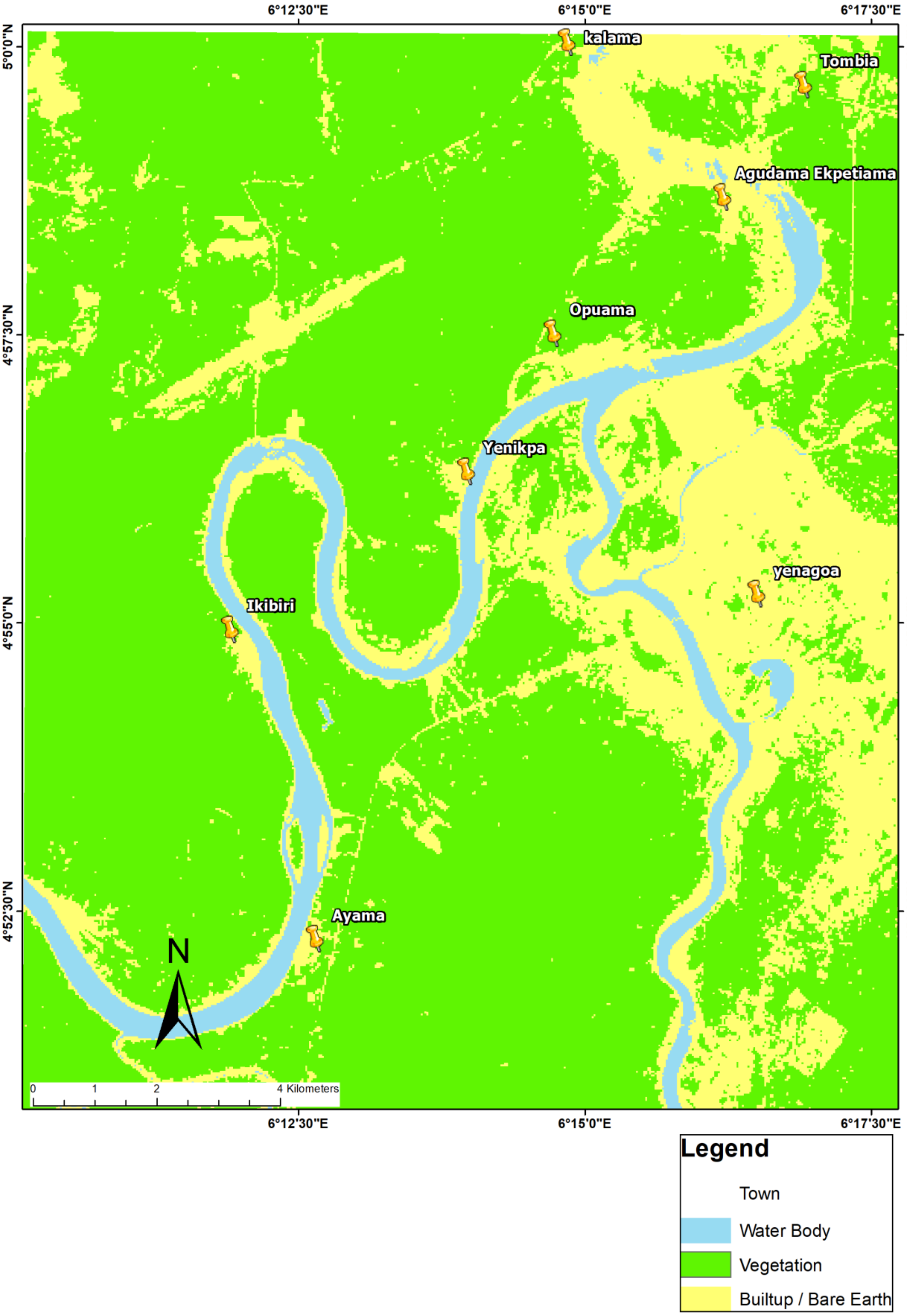

Figure 8c. *Land use land cover map of the Nun River (2019)*

Result of Figures 8a, 8b and 8c show a progressive increase in the built-up areas / bare earth. A breakdown of the percentage of land areas occupied by water, vegetation and built-up areas is presented in Table 3.

Table 3.
Land use land cover statistics around the study area

Year	Class	Land Cover Area (sq.m)	Percentage Cover (%)
	Water Body	14,927,400	5.829795012
2000	Vegetation	214,693,200	83.84697579
	Bare Earth/Built-up Area	26,433,000	10.3232292
	Water Body	16,200,900	6.327151815
2010	Vegetation	191,166,300	74.65870427
	Bare Earth/Built-up Area	48,686,400	19.01414391
	Water Body	13,275,000	5.184461378
2019	Vegetation	181,070,100	70.71570171
	Bare Earth/Built-up Area	61,708,500	24.09983691

Result of Table 3 shows that the percentage land covered by vegetation decreases from 83.8470% in the year 2000 to 70.0998% in the year 2019 resulting to an increase in percentage built-up area from10.3232% in the year 2000 to 24.0998% in the year 2019.
Vegetative cover protects the soil from the erosive power of the torrential tropical rains which is capable of dislodging particles into concentrated channels. It is normal that regions which have suitable forest and pasture vegetation are less prone to degradation and soil erosion. A decreasing land cover percentage as observed in Table 3 suggest the occurrence of sediment transport across the Nun River occasioned by the erosive power of the rain which subsequently dislodge the soil particles thereby resulting to high volume of soil loss.

The high soil erosion risk around the Nun River is due to the poorly protected landscape by vegetative cover and high gradient of the topography. Zones susceptible to moderate to high erosion risks are very few and these occur in built-up and exposed landscapes. The highest soil loss occurs in river valleys and the erosion tends to increase downstream as a result of increase in flow accumulation down slope from the source towards catchment outlet. High run-offs generated during rainfalls cause serious urban erosion, creating rills/gullies and entraining sediments into gutters/gullies which are channeled into nearby streams and rivers.
To produce C factor map, the land-use shape file was added in ArcGIS. C factors were assigned to each land-use type with its valid field ID in excel sheet and inserted to the ArcGIS for join and related process. After joining the assigned C factors with land-use shape file, the land use shape file was converted from shape file to raster with 85m cell size. Figure 9 shows the land cover management factor (C) map of the study location along the Nun River.

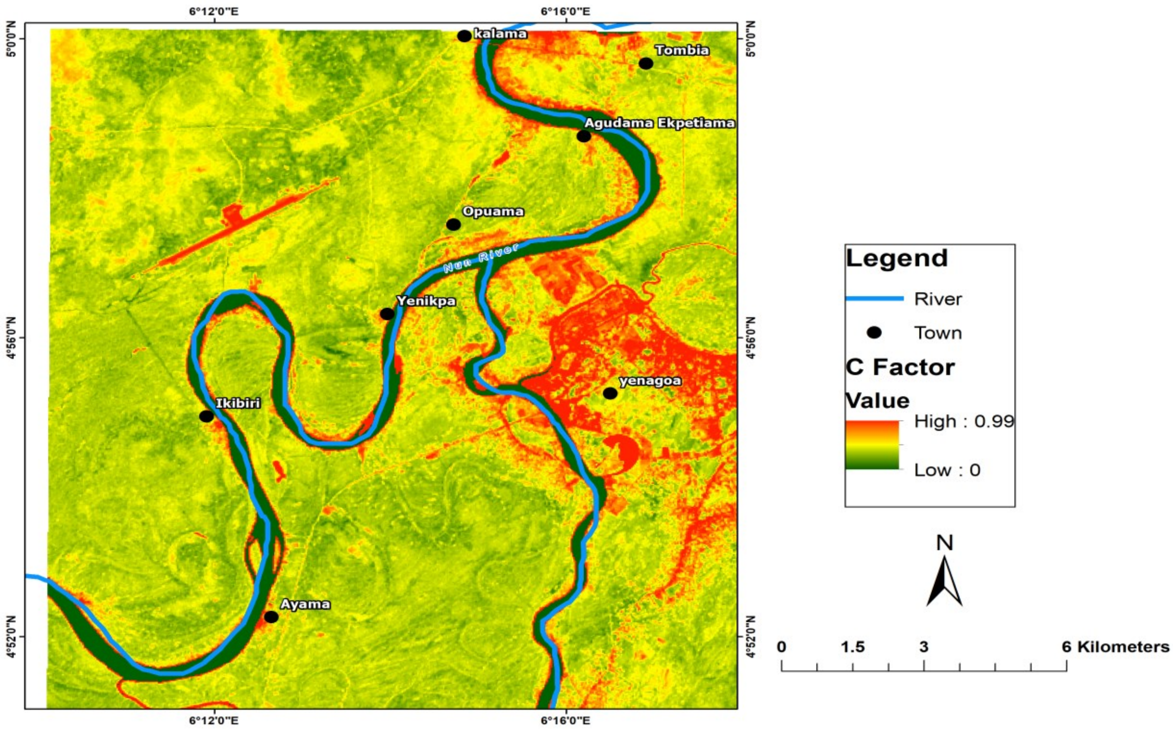

Figure 9. *Cover management factor (C) map of the study location along the Nun River*

As observed in Figure 9, the cover management (C) factors ranges from 0 to 0.99 along the Nun River.

3.5. Result of conservation practice factor (P)

Conservation or support practice factor (P) ranged from 0 to 1. It is equal to 1 when the land is directly plowed on the slope and less than 1 when the adopted conservation practice reduces soil erosion. Terracing and contouring are common and effective support practices on the field level. The effects of terracing are reflected in the hill slope length and gradient because it reduces the length of the hill slope, the flow direction and consequently causes runoff to flow around the hill slope rather than directly downslope. Conservation practice factor map of the study location along the Nun River is presented in Figure 10.

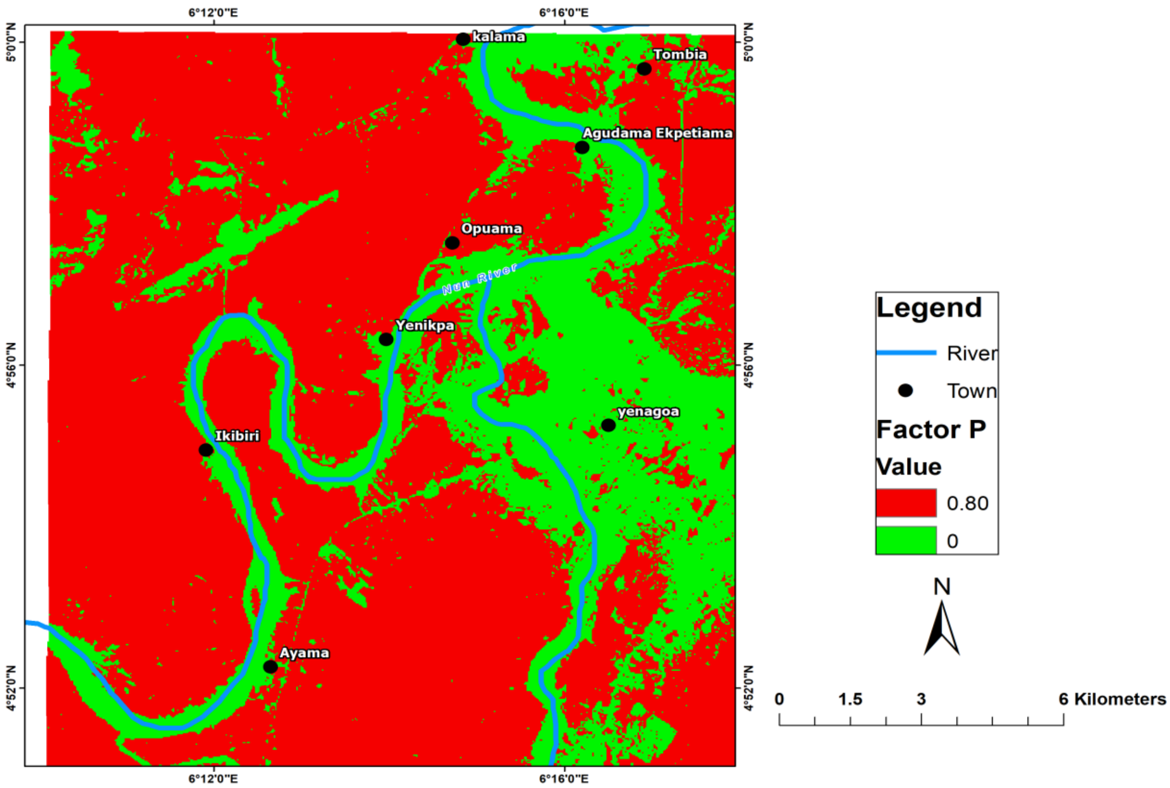

Figure 10. Conservation practice factor map of the study location along the Nun River

As observed in Figure 10, the conservation or support practice (P) factors ranges from 0 to 0.80 along the Nun River.

3.6. Generation of soil loss map in the Nun River using GIS

Around the Nun River; based on the location of rainfall stations, the annual average R value ranges from 249.968 – 265.103. The maximum rainfall-runoff erosivity (R) factor is estimated in the South Eastern region of the Nun River with the value of 265.103. Based on the soil classification of the basin, soil erodibility (K) factor ranges from 0 to 0.06 where the maximum value of 0.06 was assigned to the regions with high silt clay. Slope length and steepness (LS) factor also known as topographic LS factor, estimated using the DEM ranges from 0 to 0.20. The cover management factor (C) range from 0 to 0.99. Based on the C factor map, the barren land with the maximum value of 0.99 is prone to severe erosion. The support practice factor (P) ranges from 0 to 0.80.

In order to estimate the annual average soil loss rate for the study location around the Nun River, the above five parameters were multiplied using the raster calculator tool. Figure 11 present the annual average soil loss rate map for the study location along the Nun River.

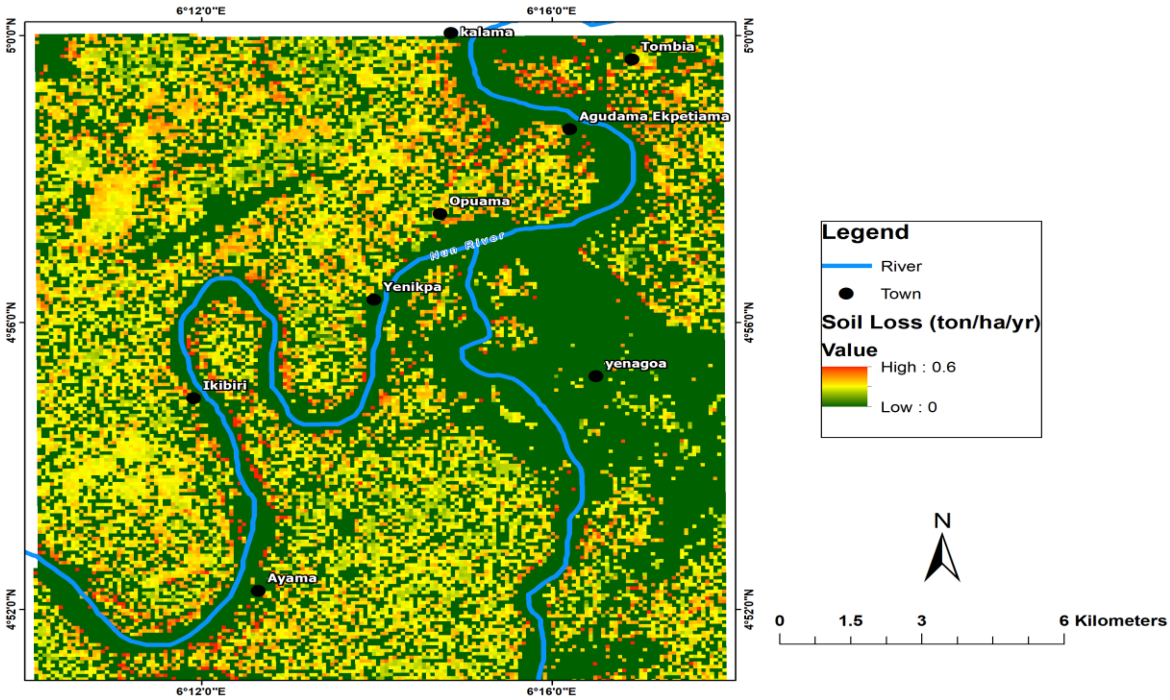

Figure 11. *Annual Average Soil loss rate map of the Nun River*

The maximum annual average soil loss rate was estimated to be 0.66 tons/ha. /year around the Nun River based on GIS application and the Revised Universal Soil Loss Equation (RUSLE).

4. Conclusion

The Nun River is one of the two arms of the River Niger that empties directly into the Gulf of Guinea carrying materials along and discharging directly into the Ocean. Studies on river bank erosion and sediment accretion in the Nun River are scarce. The present study determined river bank erosion using the Reversed Universal Soil Loss Equation (RUSLE). The RUSLE applies GIS to generate layers of satellite imageries over the last 30 years to determine rate of river bank erosion in hectares.

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