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Assessing the Influence of Soil Properties On Sediment Yield in River Mu, Benue State, Nigeria

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Abstract: *This study assessed soil properties influencing sediment yield in River Mu, Benue State, Nigeria, to understand erosion, deposition, and channel stability dynamics. A field survey using stratified sampling divided the river into three strata; upper, middle, and lower courses, with 60 soil samples collected from both banks of the river. Soil properties analysed include particle size distribution, texture, bulk and particle density, porosity, moisture content, pH, cation exchange capacity (CEC), organic matter, and hydraulic conductivity. Data were statistically analysed and sediment loss was mapped using the Revised Universal Soil Loss Equation (RUSLE) in ArcGIS. The physical properties of the soil investigated showed sand in all the sample investigated are above 50% and textual class of sandy loam. There is low soil fertility and stability, with CEC ranging from 6 to 9 cmol/kg, indicating poor nutrient retention and weak soil structure. Sandy soils upstream had high erodibility, while downstream clay and silt soils promoted deposition but increased siltation and channel instability risks. Soil properties like porosity, cohesion, organic matter, and conductivity critically influenced erosion vulnerability. Low organic matter and weak aggregation made soils prone to detachment and sediment transport. The study concludes that soils in the River Mu catchment are generally low in fertility and stability, with weak nutrient retention (CEC 6–9 cmol/kg) and poor aggregation. Upstream sandy soils are highly erodible, while downstream clay and silt soils promote deposition but increase risks of siltation and channel instability. Soil porosity, cohesion, organic matter, and conductivity strongly influence erosion vulnerability, with low organic matter and weak structure making soils prone to detachment and transport. The study recommends improving soil fertility and stability through organic amendments (compost, manure), promoting conservation agriculture and agroforestry to strengthen soil structure and vegetation cover.*

Keywords: soil erosion, sediment yield, erodbility, river Mu

INTRODUCTION

Soil erosion and sediment yield are critical environmental processes that significantly impact land degradation, water quality, and watershed stability. Sediments are particles suspended in a body of water that eventually settle out and accumulate on the bottom of a river. These particles originate from the weathering and erosion of rocks and soil can accumulate in rivers, lakes, oceans, and other terrestrial or aquatic environments (Owens & Walling, 2019).The physical and chemical properties of soil, alongside the characteristics of water in a given area, strongly influence the magnitude and dynamics of sediment yield (Mba et al, 2024). Soil texture, organic matter content, pH, and cation exchange capacity (CEC) are among the key soil parameters that control sediment detachment and transport (Blanco-Canqui, 2017; Lipiec, & Usowicz, 2018). Similarly, water properties such as flow velocity, pH, and dissolved ions affect sediment suspension and deposition patterns in catchments. Recent studies have demonstrated that sediment yield is not only driven by hydrological factors like rainfall and runoff but also strongly mediated by soil physical and chemical characteristics in the watershed. Furthermore, land use patterns and slope gradients interact with soil and water properties to influence sediment generation and delivery to water bodies (Abua et al., 2023).

In Nigerian watersheds, sediment yield poses a serious challenge to agricultural productivity and water resource sustainability (Olaniyan, 2023). Studies underscore the importance of detailed assessments of soil and water properties to identify erosion hotspots and inform land management practices (Abua et al., 2023; Mba, 2024).

In Benue State, Nigeria, where River Mu is located, agricultural activities, deforestation, and urban expansion have intensified soil disturbance and runoff generation, thereby exacerbating sediment yield into the river. River Mu, an important tributary within the Benue River Basin, supports agricultural livelihoods, fishing, and domestic water use. However, sedimentation poses a significant threat to its ecological health and resource sustainability. Despite the environmental and socio-economic importance of the river, limited research has been conducted on how soil and properties within the catchment influence sediment yield.

This study, therefore, assesses the physical and chemical properties of soil and how theyinfluences sediment yield in River Mu, Benue State. By examining these interrelated factors, the research provides insights into the drivers of sediment production and transport in the catchment. The findings will contribute to formulating strategies for erosion control, watershed management, and sustainable use of riverine resources in Benue State and similar environments.

MATERIALS AND METHODS

The Study Area

River Mu is a tributary of river Benue. River Mu drainage basin is located between latitude 7^0 45'and 8^0 00'N, and longitude 8^0 28' and 8^0 32'E as shown in figure 1. River Mu takes its source from Gboko highland (Apine Village) in Gboko Local Government Area of Benue State and flow through South Western part of Benue State where it empties its water into River Benue in Makurdi Local Government Area of Benue State. The River basin is estimated to have a total area of 156km^2 (Ministry of water resources Makurdi, 2010) as cited in Ade (2014).

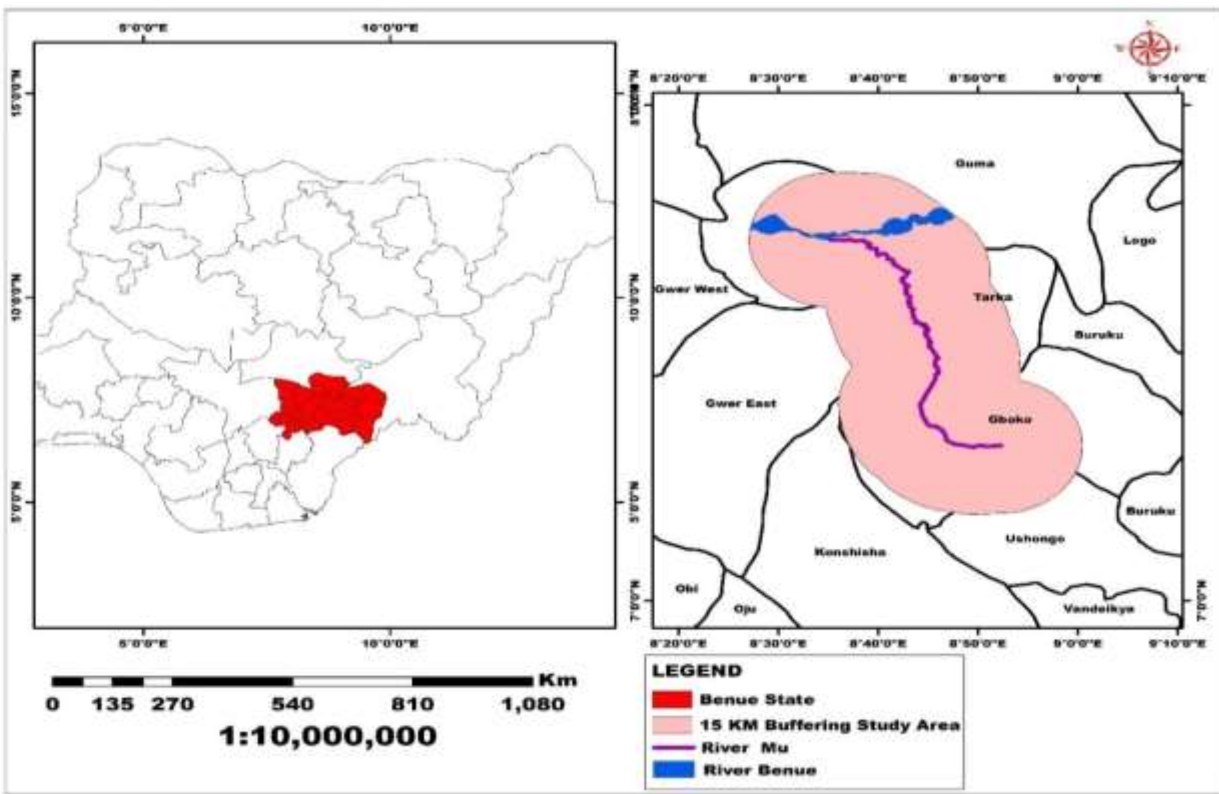

Figure 1.Location of River Mu
Source: Source: Author's GIS Analysis, 2024.

The geology of the study area is made up of rocks of Precambrian period originated from early cretaceous rifting of the central West African basement complex. The rocks form a regional structure exposed from Northern frame of the Niger Delta and runs north east for about 1000km up to Lake Chad, where it terminated. It has a width of about 150km between Jos Plateaux and Cameron mountain ranges or eastern highland. Mu drainage basin falls within the Benue trough and is characterised by similar rock. The banks and plains of River Mu also contain layers of alluvium deposit in some places many meters thick (Iorchir, 2018).

The soils of the area are typical entisols. The soils are loamy, slightly acidic in reaction, less leached with very high base saturation derived from basement complex rocks. The uniform forms of soils are either sandy or clayed; the gradation forms are usually a gradual shift from sandy surface soil to more clayed sub-soil, while the duplex display an abrupt transition from sandy or loamy surface soil to compact sub soil kaolinite clay. A most common feature of this soil is the movement of clay within the profile, a process which tends to produce a sandy surface soil rather low in organic matter, cation exchange capacity and is unconsolidated, a compact sub soil where they have illuviated (Ade, 2014; Iorchir, 2018; and Vambe, 2021).

Research Methods

Field survey design was adopted. Stratified sampling method was adapted where the River was divided into three strata, upper, middle and lower course. At each River course 20 soil samples were taken, 10 soil samples on Bank A and 10 at bank B cumulating into 60 samples i.e 30 soil samples on bank A and 30 samples on bank B. Soil samples were collected in the field and tested in the soil science laboratory toachieve the set objective. Soil characteristics analysed such as particle size distribution (sand, silt and clay), textural class, bulk density, particle density, porosity, moisture content, PH, cation exchange capacity, organic matter and hydraulic conductivity was determined. Data were presented in tables and graphs and analysed using descriptive statistics such as percentages and means, Revised Soil Loss Equation (RUSLE) was used in GIS and soil loss in the area was determined and mapped.

RESULTS AND DISCUSSION

Soil properties influencing sediment yield in River Mu

Table 1: Soil physical properties along River Mu

River course	Sample points	BANK A Sand %	Silt %	Clay %	TC (USDA)	BANK B Sand %	Silt %	Clay %	TC (USDA)
Upper	Apine 1	77.52	13.28	9.2	SL	73.52	17.28	9.2	SL
	Apine 2	81.52	9.28	9.2	SL	75.52	15.28	9.2	SL
	Apine 3	85.52	7.28	7.2	SL	69.52	19.28	11.2	SL
	Luuper	77.52	13.28	9.2	SL	77.52	13.28	9.2	SL
	Namkwagh	85.52	7.28	7.2	SL	81.52	9.28	9.2	SL
	Ugo	79.31	12.22	8.47	SL	75.52	17.36	7.12	SL
	Gbor mu 1	83.12	8.68	8.2	SL	72.50	18.30	9.2	SL
	Gbor mu 2	75.63	15.07	9.3	SL	69.48	18.40	12.12	SL
	Tyopev	76.52	15.28	8.2	SL	77.52	15.38	7.1	SL
	Akpaer	84.52	6.28	9.2	SL	78.52	14.81	6.67	SL
	Total	**806.7**	**107.93**	**85.37**	**SL**	**751.14**	**158.65**	**90.21**	
	Mean	**80.67**	**10.77**	**8.54**		**75.11**	**15.87**	**9.02**	

Middle	Gungun	27.52	29.76	42.72	Clay	61.52	19.28	19.2	SL
	Orkula	77.52	13.28	9.2	SL	57.52	23.28	19.2	SL
	Aperepe	81.52	9.28	9.2	SL	73.52	17.28	9.2	SL
	Agba1	75.52	15.28	9.2	SL	81.52	9.28	9.2	SL
	Agba 2	85.52	7.28	7.2	SL	81.52	9.28	9.2	SL
	Mbabaagu	78.22	15.58	6.2	SL	82.14	9.46	8.4	SL
	Mbakwadan 1	80.12	12.76	7.12	SL	80.22	10.58	9.2	SL
	Mbakwadan 2	74.38	16.62	9.0	SL	79.24	11.76	9.0	SL
	Asebe	82.12	10.48	7.4	SL	84.00	6.6	9.4	SL
	Kuji	86.24	7.08	6.68	SL	86.22	6.58	7.2	SL
	Total	**746.68**	**140.42**	**112.9**		**767.42**	**123.38**	**109.2**	
	Mean	**74.67**	**14.04**	**11.29**		**76.74**	**12.34**	**10.92**	
Lower	Agena	39.52	31.28	29.2	CL	77.52	13.28	9.2	SL
	Ikyume	69.52	19.28	11.2	SL	37.52	33.28	29.2	CL
	Ikyaa	43.52	27.28	29.2	CL	77.52	13.28	9.2	SL
	Buur	85.52	7.28	7.2	SL	73.52	17.28	9.2	SL
	Tyo mu1	69.52	19.28	11.2	SL	49.52	19.28	31.2	CL
	Tyo mu 2	78.26	15.62	6.12	SL	62.12	27.76	10.12	SL
	Fiidi	62.52	25.28	12.2	SL	58.24	22.46	19.3	SL
	Airforce	64.22	27.38	8.4	SL	56.18	25.70	18.12	SL
	Air water intake	68.24	21.96	9.8	SL	72.12	15.48	12.4	SL
	Mu mouth	74.22	15.58	10.2	SL	58.32	27.48	14.2	SL
	Total	**655.06**	**210.22**	**134.72**		**622.58**	**215.28**	**162.14**	
	Mean	**65.51**	**21.02**	**13.47**		**62.26**	**21.53**	**16.21**	

Source: Author's laboratory analysis, 2024.

Note; SL = sandy loam, CL= clay loam.

Based on information presented in Table 1, the soil particle size distribution for 30 samples along River Mu shows sandy loam texture dominated by sand particles above 60% except at Agena (39.52%) and Ikyaa (43.52%) in the lower course. Sand content tends to decrease from the upper to lower river courses, with mean sand percentages on bank A ranging from 80.67% (upper) to 65.51% (lower) and on bank B from 75.11% to 62.26%. High sand content indicates loose soil with moderate to high infiltration rates, promoting erosion through easy detachment by raindrop impact and contributing to sediment yield, especially on slopes with moderate rainfall..The finding aligns with Abua,et al (2023) who investigated sediment yield across different land-use surfaces in the Calabar River Catchment, Nigeria. Their findings indicated that areas with higher sand content exhibited increased sediment yield, emphasizing the role of soil composition in sediment dynamics.

Silt content shows a downstream increase, from about 8.68-15.87% in the upper course to over 21% in the lower course on both banks, reflecting finer particles that remain suspended longer and accumulate in lower-energy zones, thus adding to suspended sediment load. Clay content also increases slightly downstream, from around 7-9% upstream to over 13-16% downstream, with bank B showing a higher increase. Clay particles, being fine and cohesive, reduce soil erodibility and stabilize channels but contribute to fine sediment retention rather than mobility. Findings agrees with Budi, et al, (2024) studied the Effect of hydrological variability on suspended sediment load at River junction. The study highlighted that suspended sediment concentration typically rises downstream due to the inclusion of finer materials like silt from tributaries and non-point sources. This accumulation is more pronounced during periods of reduced flow velocity, leading to increased sediment deposition in the middle and lower courses.

Overall, the dominance of sandy soils leads to higher erosion and sediment yield, while increasing silt and clay contents downstream reflect sediment deposition and channel stability. These findings align with other studies in Nigeria and Ethiopia, confirming that soil texture, particularly sand content, significantly influences erosion and sediment dynamics in river basins.

Other soil properties investigated include from figure 2 -11.

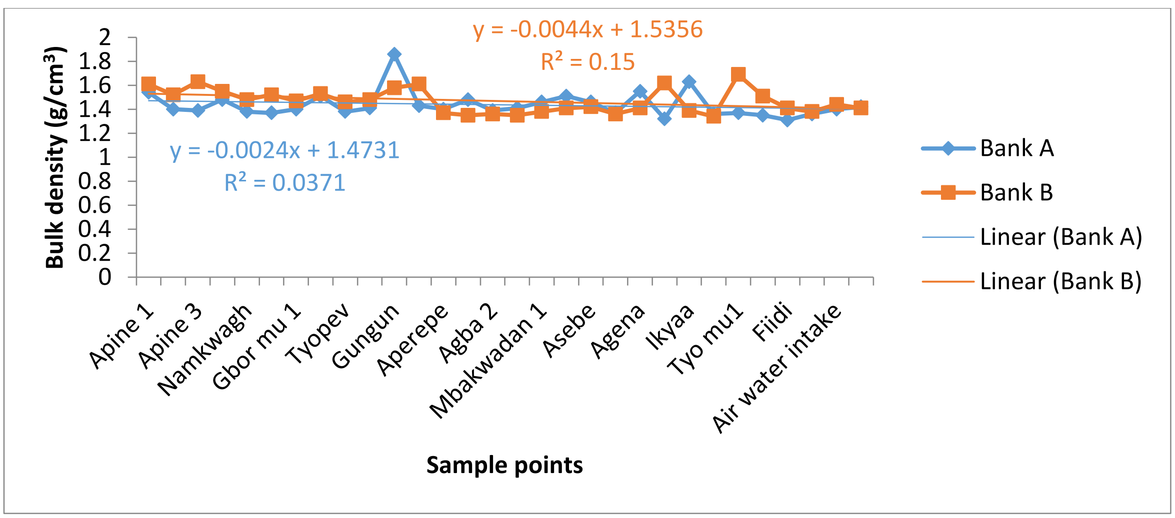

Figure 2: Variation in bulk density in River Mu
Source: Author's field Analysis, 2024.

Results presented in figure 2 displays the variation in bulk density across 30 soil sample locations for two river banks, Bank A and B along the River Mu. Bulk density (measured in g/cm³) is a key indicator of soil compaction and porosity, and it directly influences the susceptibility of soil to erosion and the rate of sediment yield in river systems. The bulk density fluctuates on Bank A with the mean at the upper course of 1.43g/cm^{3,} middle course with 1.48 g/cm3 and lower course with 1.41 g/cm^3 with a slight decreasing trend (y = -0.0024x + 1.4731) , indicating low/weak bulk density along the channel while bank B values also range within a similar band slightly higher on average than Bank A with mean bulk density at the upper course of 1.53 g/cm3, middle course 1.42 g/cm3 and lower course 1.46 g/cm3 with decreasing trend (y = -0.0044x + 1.5356). Both bank A and B have low bulk density along River Mu. The lower bulk density indicates more porous soil, which can absorb water more easily and is more prone to particle detachment and erosion under high-flow conditions. Bank B has a higher average bulk density than Bank A and exhibits slightly more fluctuation. This suggests that soil in Bank B are more compacted than bank A as a result reduce the rate detachment and entrainment. The weaker compaction on Bank A implies more erodible and contributes more sediment to River Mu during peak discharge events. Soils with lower bulk density are typically more prone to detachment by water action, thus contributing higher amounts of sediment to the river. This aligns with findings by Eze and Abua (2018), who observed that River bank soils with lower bulk density along the Cross River contributed more sediment during the rainy season.

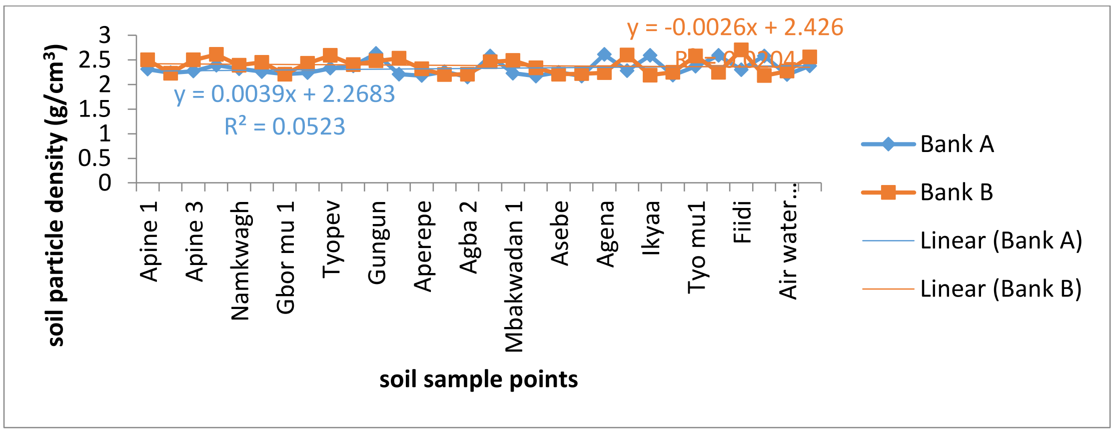

Figure 3: Soil particle density along the River Mu
Source: Author's field Analysis, 2024.

Results presented in figure 3 illustrates the variation in soil particle density across 30 soil sample locations on two river banks, A and B along River Mu. Particle density (expressed in g/cm³) is a measure of the mass of solid soil particles per unit volume, excluding pore spaces. It reflects the mineral composition of the soil and is essential in evaluating soil behaviour, especially in relation to erosion and sediment yield. Bank A has a mean particle density at the upper course of 2.30 g/cm³, middle course 2.28 g/cm³ and lower course 2.40 g/cm³ which shows a slight increase ($y = 0.0039x + 2.2683$), along the River channel while Bank B shows recorded the mean values at the upper course of 2.43 g/cm³, middle course 2.35 g/cm³ and lower course 2.38 g/cm³ with a decreasing trend line ($y = -0.0026x + 2.426$), indicating slight reduction in particle density along the River course. The standard value for mineral soils typically lies around 2.65 g/cm³. The values here suggest the presence of some organic matter or less dense mineral composition in both banks, with Bank A being marginally less dense. Lower particle density, suggests lighter soil materials that are more susceptible to detachment and transport during rainfall or high river discharge events. Soils with higher particle density tend to consist of heavier minerals like quartz, which resist erosion and thus reduce sediment yield. The lighter soil composition in River Mu means it may contribute more fine sediments to River Mu, especially during peak runoff or flash floods. The particle density map is shown in figure 4.

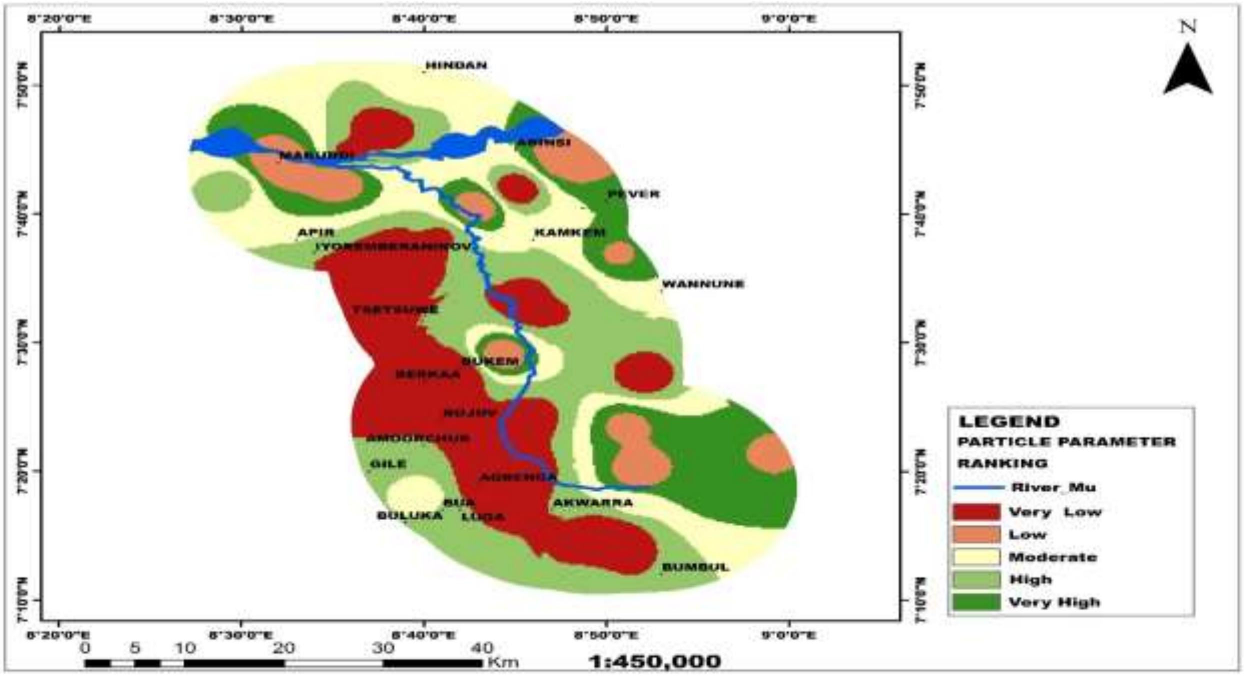

Figure 4: Soil particle density along river Mu
Source: Author's field Analysis, 2024.

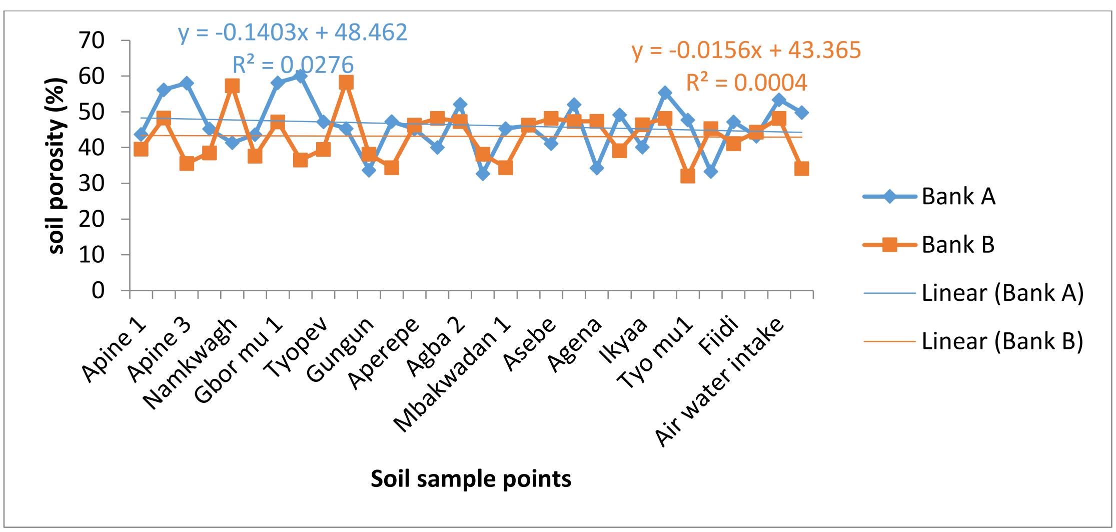

Figure 5: Soil porosity along the River Mu
Source: Author's field Analysis, 2024.

Results presented in figure 5 showed the soil porosity values (%) across 30 sample locations along Bank A and Bank B of River Mu. Soil porosity is a critical physical property that influences water

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retention, infiltration, aeration, and ultimately, the soil's susceptibility to erosion and sediment generation. Bank A has mean porosity at the upper course of 49.90%, middle course 43.58% and lower course 45.38% with a decreasing trend line (y = -0.1403x + 48.462)suggesting a weak declining trend with low explanatory power. The bank B recorded mean porosity at the upper course of 43.86%, middle course 42.87% and lower course 42.64% with the decreasing trend line (y = -0.0156x + 43.365) along the river course. Low soil porosity significantly affects sediment yield by increasing the vulnerability of soil to erosion. As the porosity is moderate along River Mu, moderate pore spaces are available for water infiltration, causing surface runoff during rainfall events. This increased runoff velocity, facilitates the detachment and transport of soil particles, thereby raising sediment yield. Moderate porosity soils have reduced water absorption capacity, leading to enhanced surface flow that mobilizes more sediment to River Mu. Khandouzi, et al (2019) demonstrated that soils with reduced porosity have fewer pores for water to infiltrate, which enhances runoff velocity and detaches more soil particles for transport downstream and this aligns with findings from River Mu, where moderate porosity along banks leads to increased sediment mobilization during high rainfall events.

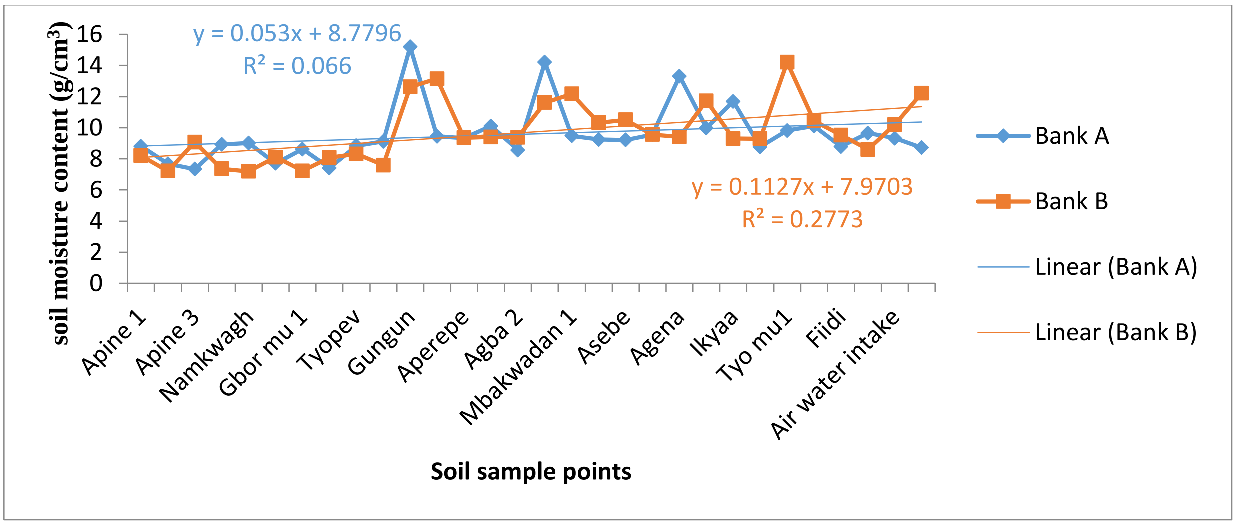

Figure 6: Soil moisture content along River Mu
Source: Author's field Analysis, 2024.

The results shown in Figure 6 illustrate the soil moisture content (g/cm³) across 30 sample locations on Bank A and Bank B along the River Mu. Soil moisture is a critical factor influencing soil cohesion, infiltration, surface runoff, and ultimately, erosion and sediment yield dynamics. On Bank A, the mean moisture content increases from 8.35 g/cm³ in the upper course to 10.44 g/cm³ in the middle course and slightly decreases to 10.02 g/cm³ in the lower course. Notably, there is spike in moisture content at the lower course at Ikyaa, with increase positive downstream trend line (y = 0.053x + 8.7796) explaining a modest 6.6% increase in moisture content moving downstream. Similarly, Bank B shows mean moisture content rising from 7.84 g/cm³ in the upper course to 10.81 g/cm³ in the middle course and 10.50 g/cm³ in the lower course, with significant moisture spikes at Tyo Mu 1 in the lower course. The downstream trend line for Bank B (y = 0.1127x + 7.9703) indicates a more pronounced increase in moisture content with distance downstream.

Moderate soil moisture levels enhance particle cohesion, particularly in clay-rich soils, which can reduce erodibility. However, when moisture content approaches saturation, soil shear strength decreases, thereby increasing the risk of erosion and mass wasting (Okogbue & Ezechi, 2020). Areas of high moisture without adequate vegetation cover tend to exhibit lower infiltration rates during storm events, generating more surface runoff and accelerating the detachment of soil particles. Episodic events such as localized saturation can trigger sediment pulses, influencing sediment transport in River Mu. Overall, soil moisture content shows an increasing trend downstream on both banks, contributing to higher sediment yield via cumulative saturation effects and progressive bank erosion. Soil moisture thus plays a dual role; it enhances soil cohesion at moderate levels but increases erosion susceptibility when saturation is exceeded. Nath and Goswami (2016) reported that river bank erosion is more severe in soils with weak cohesive strength, low clay content, and high permeability, conditions which are exacerbated by increased soil moisture. The study reported that shear strength decreases with elevated moisture content, a direct contributor to soil instability and erosion risk, aligning with the dual role of moisture in promoting cohesion at moderate levels but increasing erosion at saturation as found in River Mu. Haraz River (2013) demonstrate vegetation's role in modifying soil moisture effects on bank erosion by affecting water velocity and shear stress, which in turn influence sediment detachment and depositional patterns and this findings corroborated with soil moisture variations along riverbanks of Mu downstream.

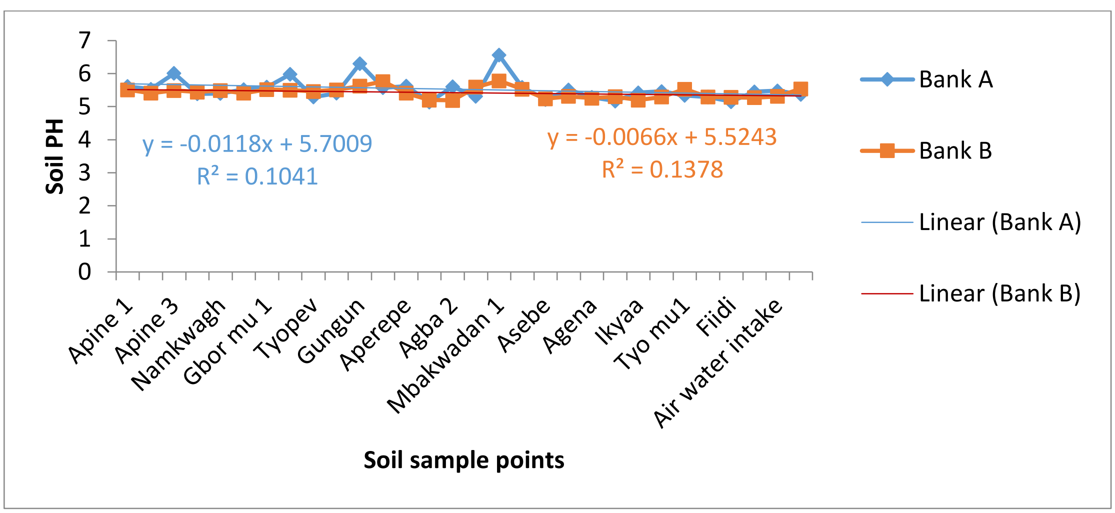

Figure 7: Soil PH along River Mu
Source: Author's field Analysis, 2024.

Results presented in figure 7 illustrates the variation in soil pH (1:1 soil-water ratio) across 30 sampling locations for Bank A and Bank B along River Mu. Soil pH is a fundamental chemical property that influences nutrient availability, microbial activity, metal solubility, and soil structure all of which affect erodibility and sediment yield (Brady & Weil, 2016). On bank A, mean pH at the upper course is 5.57, middle course 5.64 and lower course 5.34 while on bank B, the mean pH values at upper course is 5.47, middle course 5.46 and lower course 5.33. Both river banks shows a mild but noticeable decreasing trend in pH downstream of $y = -0.0118x + 5.7009$ ($R^2 = 0.1041$) which explains 10.4% increase on bank A and $y = -0.0066x + 5.5243$($R^2 = 0.1373$) which explains 13.7% on bank B. All the soil samples fall in the moderately acidic range (pH 5.0–6.0), which is common in tropical riparian zones. Acidic soils (pH < 6) often suffer from poor aggregation due to limited calcium and magnesium availability, elements essential for soil flocculation. The soils are dispersed particles and are more easily detached and transported, thereby increasing erodibility and sediment yield. Moderate pH values along the River channel inhibits microbial diversity and slows organic matter decomposition. This weakens aggregate stability and increases susceptibility to erosion during rainfall events. Since Bank A shows slightly higher variability and declining pH trend, the zones downstream have poorer structural resistance.

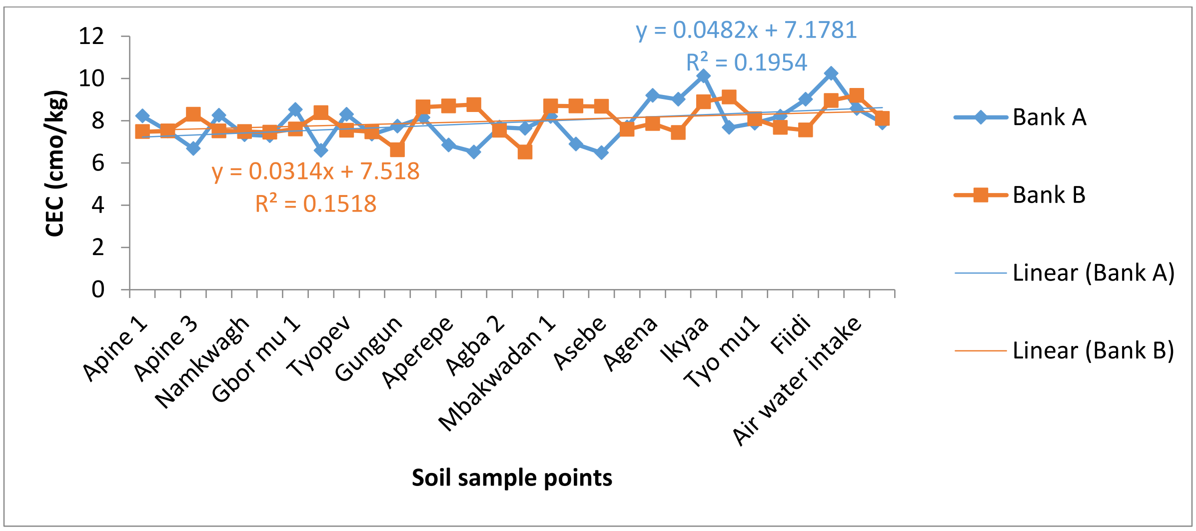

Figure 8: Cation Exchange Capacity (CEC) along River Mu
Source: Author's field Analysis, 2024.

Results presented in figure 8 illustrates the Cation Exchange Capacity (CEC) in cmol/kg across 30 soil sample locations for Bank A and Bank B along the River Mu. CEC is a critical indicator of soil fertility and structure. It reflects the soil's ability to hold and exchange positively charged ions (cations) like calcium, magnesium, potassium, and sodium, which are essential for soil health and vegetation stability. The mean CEC on Bank A at upper course is 7.61, middle course 7.38 and lower course 8.78 recording its highest values at Ikume and Fiidi with 9.01 while bank B shows the mean values at the upper course 7.68, middle course 8.05 and lower course 8.29 with the highest value at Buur 9.12. Both river banks A and B shows an increasing trend $y = 0.0482x + 7.1781$, and $y = 0.0314x + 7.518$ respectively showing increasing CEC down slope along River Mu and the cation exchange capacity along the channel is considered low. Cation exchange capacity (CEC) along River Mu ranges from 6-9 cmol/kg in the soil which is generally considered low and has several implications that affect soil erosion and sediment yield. Low CEC limits the soil's ability to hold and retain essential nutrient cations such as calcium (Ca2+), magnesium (Mg2+), potassium (K+), and sodium (Na+). This leads to nutrient deficiencies that weaken soil structure and plant health. Soils with low CEC tend to have low clay and organic matter content, which reduces their water and nutrient retention capacity. This poor nutrient retention increases soil vulnerability to erosion because such soils have less aggregate stability and structural resistance to detachment by rainfall impact. Reduced availability of calcium and magnesium due to low CEC impairs soil aggregation and flocculation, leading to more dispersed soil particles that are easily detached and transported by water runoff, thus increasing sediment yield. Low CEC soils are more prone to nutrient leaching and acidification, which further degrades soil fertility and biotic activity, reducing vegetation cover.

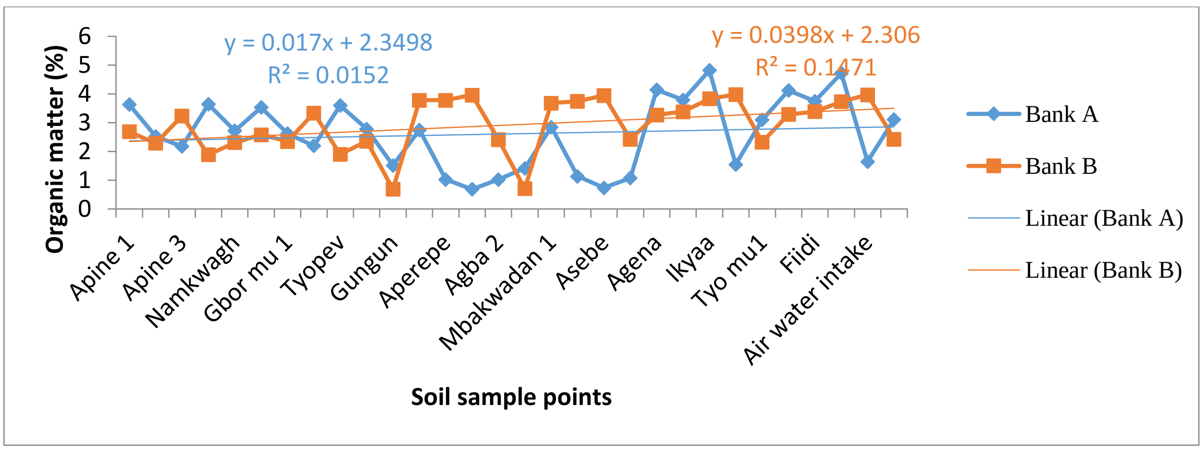

Figure 9: Organic matter content along River Mu
Source: Author's field Analysis, 2024.

Results presented in figure 9 shows the variation of organic matter (%) across 30 soil sample locations for Bank A and Bank B along the River Mu. The organic matter content of the soils are very important chemical characteristics of soils that influences the production of humus that help to bind the soil particles together, to enhance its cohesiveness and ability to withstand or resist the tractive force of runoff. It is a key factor influencing soil aggregation, structure, moisture retention, and biological activity all of which directly impact erodibility and sediment yield. Bank A shows more variability in the mean values at the upper course 2.94%, middle course 1.23% and lower course 3.47% with values fluctuating widely between 0.69% at Agba 1 to 4.82% at Ikyaa while Bank B shows more variability in the mean values showing the upper course 2.50%, middle course 2.91% and lower course 3.36% with values fluctuating widely between 0.69% at Gungun to 3.98% at Buur. Bank A shows regression trend line of $y = 0.017x + 2.3498$, while Bank B shows $y = 0.0398x + 2.306$, both shows increase in organic matter downstream and these organic matter content is considered low along River Mu. With this amount of organic matter content in the soils along River Mu, the soils will be moderately erodible, but more during periods of high intensity of rainfall in the area. This is because organic matter helps to build soil's resistance against shearing effect of surface wash; however, in periods of high intensity of rainfall, the soils would become loose, dislodged and carried down slope by overland flow.

Organic matter promotes aggregation of soil particles into stable structures that are more resistant to raindrop impact and overland flow. The higher OM content on Bank B suggests reduced erodibility compared to Bank A. low organic matter content is signal of weakened soil structure, which could increase susceptibility to detachment and sediment generation during high rainfall events. Soils rich in organic matter have improved infiltration rates, reducing the volume and velocity of surface runoff a key driver of soil erosion. The findings agrees with Lal, (2020) who submitted that soils with higher organic matter have better aggregate stability, improved infiltration, and reduced susceptibility to detachment by raindrop impact and surface runoff directly aligning with your description. The map of organic matter of the study area is shown in figure 10.

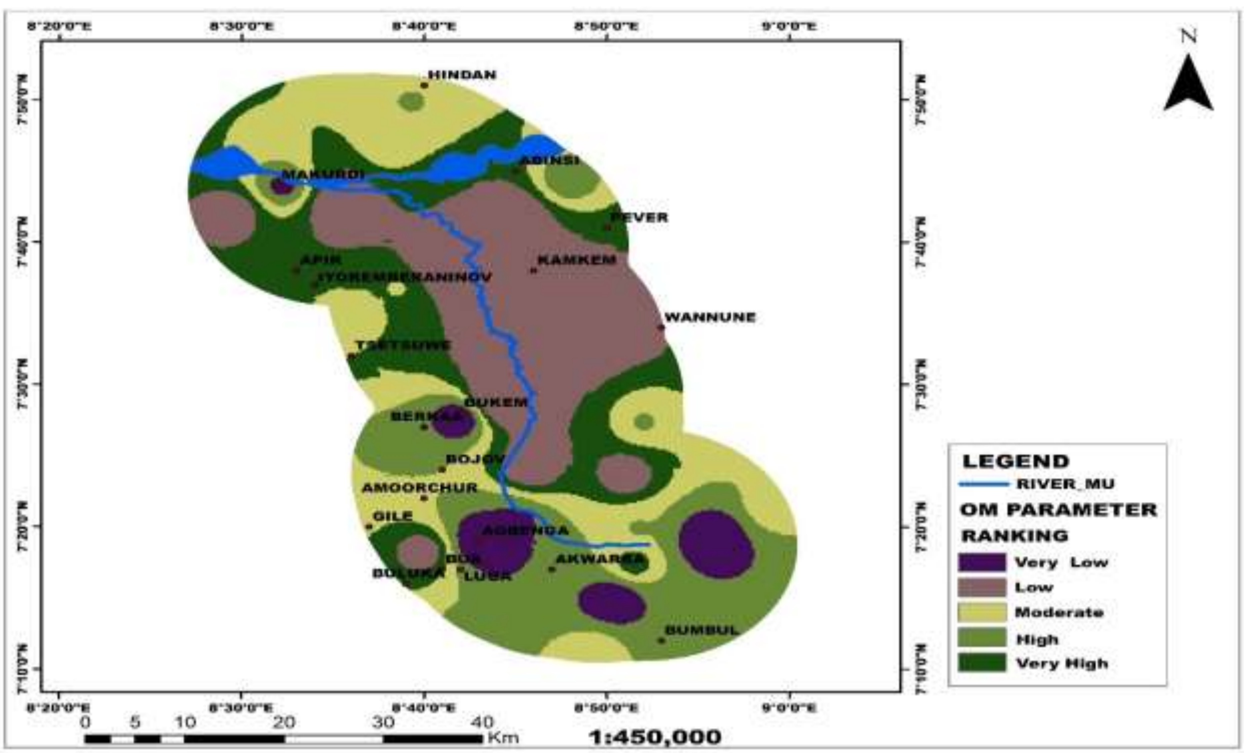

Figure 10: Organic matter content along River Mu
Source: Author's field Analysis, 2024.

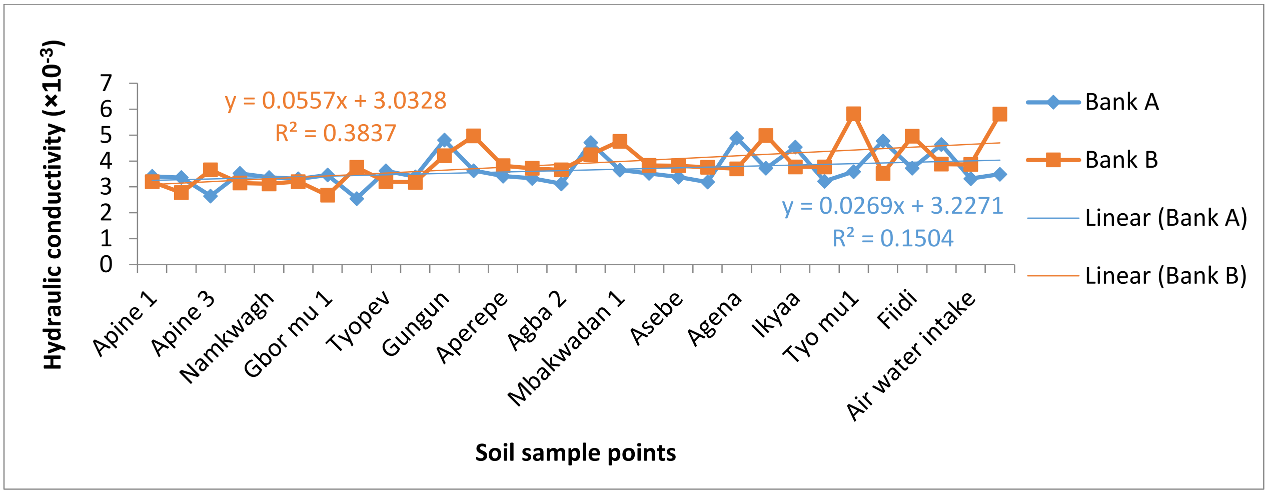

Figure 11: Hydraulic conductivity along River Mu
Source: Author's field Analysis, 2024.

Data presented in figure 11 displays the variation in hydraulic conductivity ($\times 10^{-3}$ cm/s) across 30 soil samples along River Mu. Hydraulic conductivity (HC) measures the soil's ability to transmit water, which directly influences surface runoff, infiltration, erosion potential, and sediment yield. Bank A shows more variability in the mean values at the upper course 3.26×10^{-3}, middle course 3.68×10^{-3} and lower course 3.10×10^{-3} with values fluctuating widely between 2.55×10^{-3} at Gbor Mu 2 to 4.89×10^{-3} at Ikyume while Bank B shows more variability in the mean values showing the upper course 3.19×10^{-3}, middle course 4.08×10^{-3} and lower course 4.41×10^{-3} with values fluctuating widely between 2.78×10^{-3} at Apine 2 to 5.82×10^{-3} at Buur. Hydraulic conductivity trends on bank A showed weak positive increasing trend ($y = 0.041x + 3.308$) while bank B showed increase positive trend ($y = 0.113x + 2.985$). Increased HC indicate sandy or well-aggregated soils with macrospores, which facilitate infiltration on Bank B while lower HC is associated with compacted or fine-textured soils (such as silts and clays), which are more erodible due to poor structure and crust formation. The hydraulic conductivity recorded along River Mu is generally low. Findings conforms with Ezeaku (2022) who studied Hydraulic conductivity and sediment delivery in selected riverbanks of central Nigeria and found that where HC is low, water tends to flow overland, detaching and transporting finer soil particles entraining them and subsequent sediment yield.

Soil Loss along River Mu Catchment

The soil loss was calculated using Revised Universal Soil Loss Equation in GIS. The Universal Soil Loss Equation (USLE), by (Weischmeier and Smith 1986) and its revised version (Renard et al, 1997) is the most commonly used model for estimating long term average soil loss. The Revised Soil Loss Equation (RUSLE) was adopted for the evaluation and estimation of the annual soil loss in the study area. The R factor (Rainfall-runoff erosivity), K factor (soil erodibiity), LS factor (slope length factor), S factor (slope steepness), C factor (land cover-management), P factor (conservation practice) and computed average annual soil loss was determined (A)

C factor

The Cover Management (C-Factor) represents the effect of vegetation cover and land management practices on soil erosion. Vegetation reduces the direct impact of raindrops, preventing splash erosion. This indicates how conservation practice affects the rate of annual soil loss in the various catchments showing the ratio of soil loss from land use under specified conditions to that from fallow and tilled land.The C factor map is shown in figure 12.

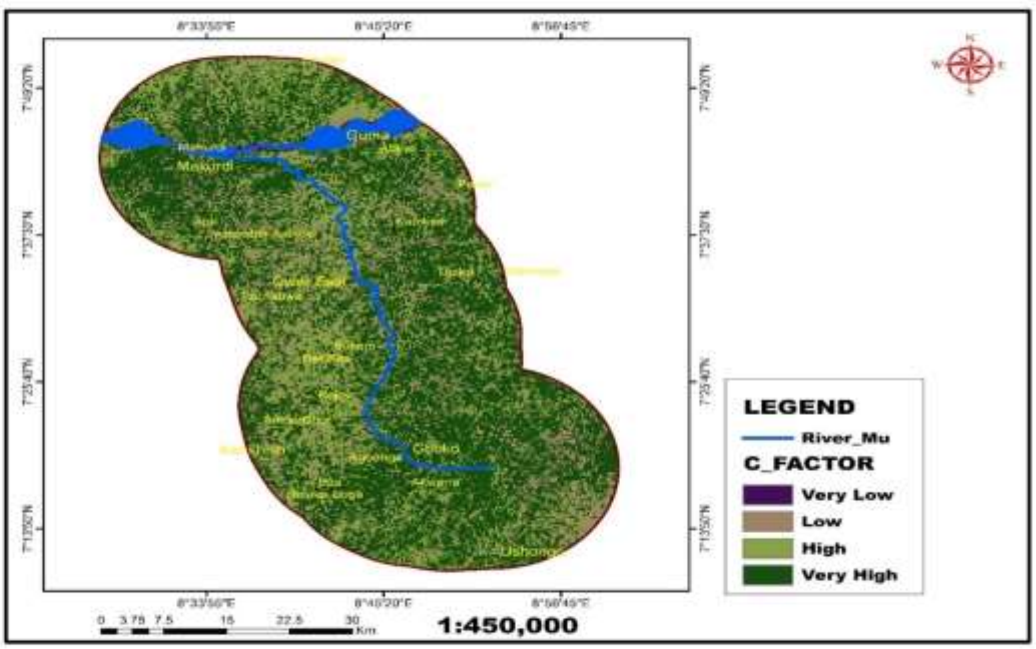

Figure 12: C Factor
Source: Author's field Analysis, 2024.

The C Factor distribution (Cover-Management Factor) across River Mu Basin as shown in figure 12, which is a key input in the Revised Universal Soil Loss Equation (RUSLE) model used to estimate soil erosion risk. It ranges from very low which is dense vegetation or well-managed land which will give low erosion and high which represents bare land or poorly managed areas that are vulnerable to erosion which will give high erosion. Low C factor indicates dense vegetation, forests, grasses, or less-tillage agricultural land. These areas resist erosion due to effective ground cover and they are found at each stage of the River course, Makurdi (lower course), Tse-Tsue (Middle course), Luga (Upper course). This means at this points, erosion and sediment yield will be low. Moderate C Factor which ranges from 0.3–0.6 represents seasonal farmland, moderately grazed zones, or transitional areas and they are susceptible to moderate erosion, especially during planting or dry seasons. High C Factor denotes bare lands, exposed soils, urban/built-up areas, or heavily degraded zones. Such areas are highly prone to sheet, rill, and gully erosion. These areas are found in Bua, Luga among others in the upper course, Apir, Yonevber Aninov in lower course of the River among others. These areas along the River basin will experience high erosion and sedimentation. The dominance of high C factor across the River Mu basin shows extensive land degradation, weak vegetation cover and poor land management practices. This indicates that much of the basin is highly vulnerable to soil erosion, contributing significantly to Sediment yield into River Mu, channel siltation, water quality degradation and loss of agricultural lands.

K-Factor

This quantifies how easily soil particles can detach and be transported. It depends on soil properties like texture, organic matter, and permeability. The K-factor (soil erodibility)is crucial in understanding how different soils respond to erosive forces.

The soil erodibility was computed using equation.

$$K = 2.8 \times 10 - 7 \times (12 - OM) \times MI.14 + 4.3 \times 10 - 3 \times (s - 2) + 3.3 \times 10 - 3 \times (P - 3) \dots \dots (1)$$

Where;
K = Soil erodibility factor.
OM = percent of organic matter content.
P = soil permeability code.
s = soil structure code.
M = particle size parameter.
M= (%silt+ % very fine sand) * (100-%clay)
The estimated K factors range from to 0.357 to 0.274

The computation was carried out in excel and imported in to the ArcGIS environment to create a shapefile and using the coordinates of the obtained soil samples, the derived K factor values were interpolated and the result generated. The K factor map is shown in figure 13.

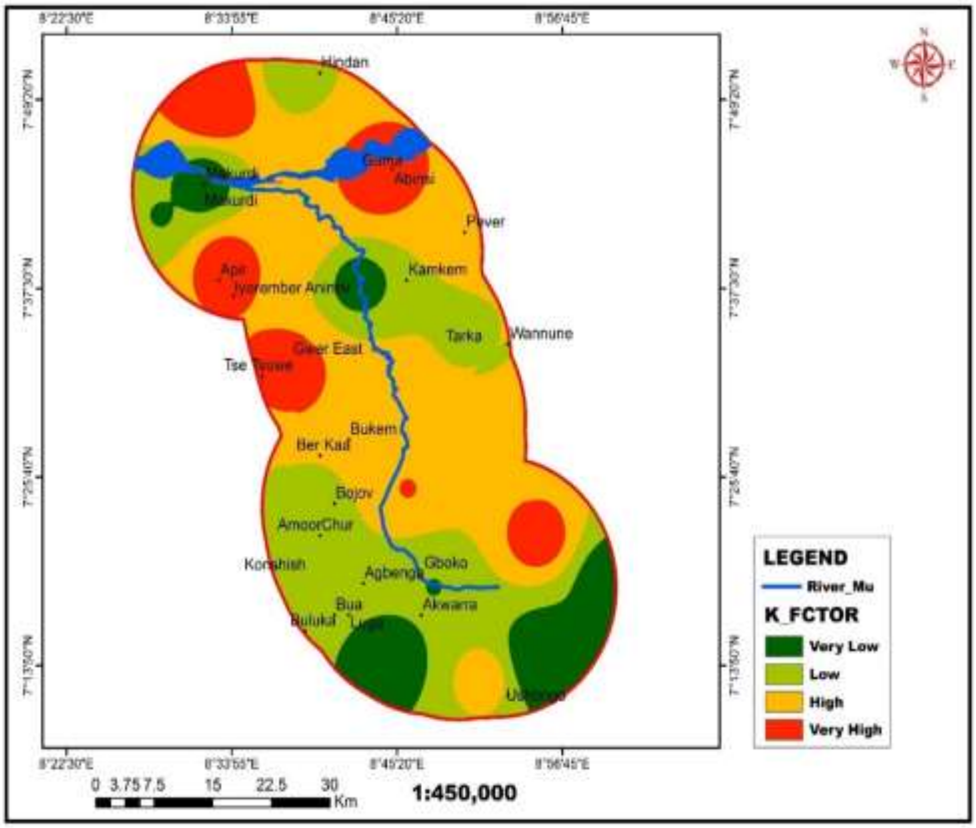

Figure 13: K Factor Map
Source: Author's field Analysis, 2024.

The K factor distribution map along River Mu as shown in figure 13, indicated spatial variability in soil erodibility within the watershed. This map is vital in soil erosion studies and watershed management as it informs land use planning, conservation practices, and agricultural decision-making. K Factor (soil erodibility factor) measures a soil's susceptibility to erosion by rainfall and runoff. It is a key parameter in the Universal Soil Loss Equation (USLE) and its derivatives like RUSLE. Low K factor indicate less erodible soils, possibly due to higher organic matter, soil structure stability, or lower silt content. High K factor suggest more erodible soils, often with fine textures, poor structure, or low organic content. The highest K factor are observed in the south eastern and north western parts of the basin (such as, Makurdi, and Bumbul), suggesting these areas are more prone to erosion.

The LS Factor

This is a combination of two topographic factors, Slope length and slope steepness. It describes the impact of topography (slope length and the steepness) on soil loss. i.e, the longer the slope length the greater the amount of cumulative runoff and also the steeper the slope of the land the higher the velocities of the runoff which contribute to erosion. Hence, the implication of the LS Factor implies that, the longer the slope length the greater the amount of cumulative runoff. Equation 12 was used in LS Factor and figure 14 showed the LS Factor.

$$LS = ((FA \times cs/22.1)\text{^}0.2) \times (0.065 \times 0.045 \times s + 0.0065 \times s^2)) \ldots\ldots\ldots\ldots\ldots..(2)$$

Where;
FA= Flow Accumulation
s =slope
cs =cell size

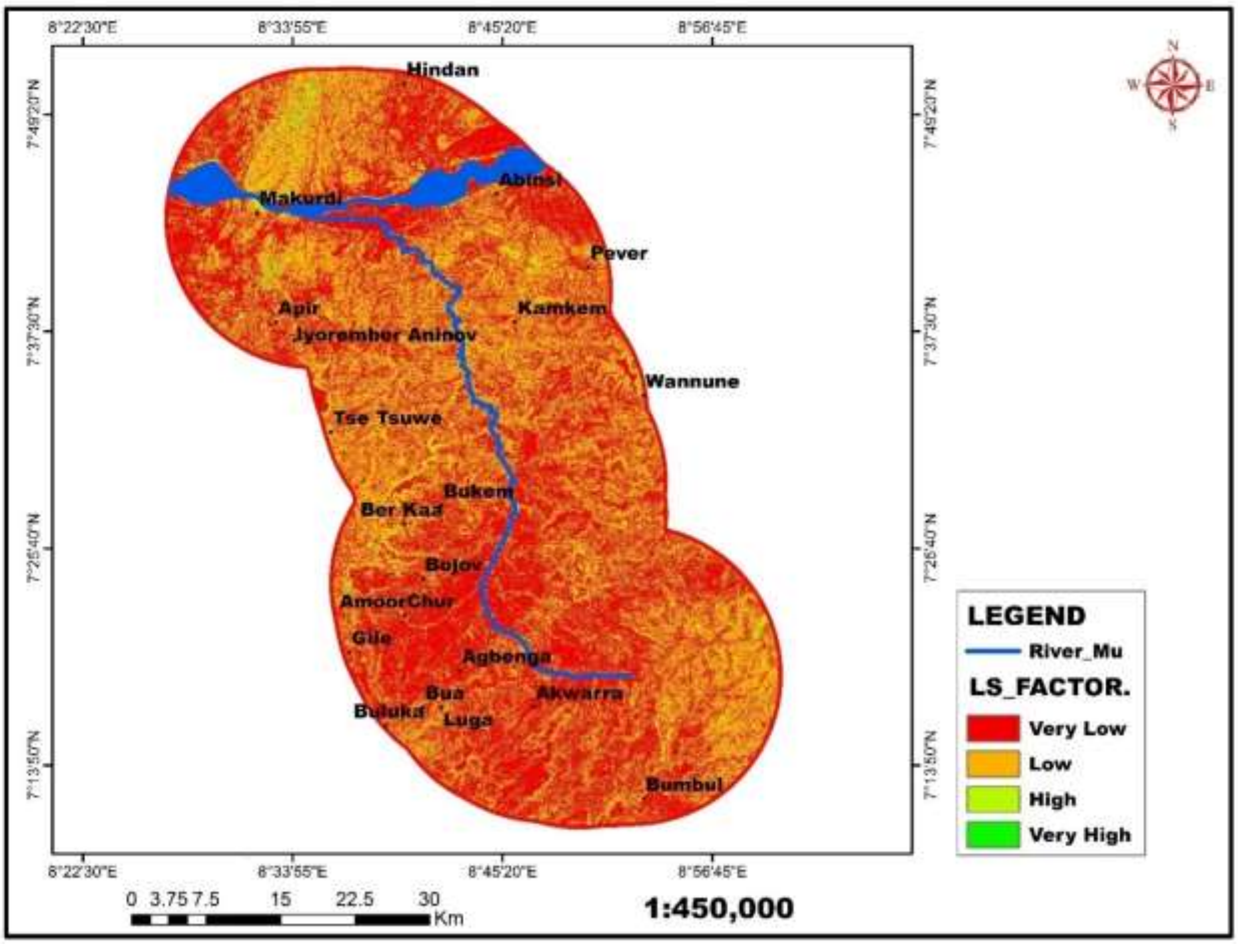

Figure 14: LS Factor
Source: Author's field Analysis, 2024.

The LS factor (Slope Length and Steepness factor) along River Mu as shown in figure 14, is a critical component of the Revised Universal Soil Loss Equation (RUSLE). It illustrates how topography contributes to soil erosion risk, with higher values indicating areas more prone to

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erosion due to slope characteristics. Low values represent flat or gently sloping land which has minimal risk of topographically induced erosion while high values occur in steep and/or long slopes, which increase runoff velocity and erosive power. Higher LS factor are visible along the valley sides, escarpments, and upper watershed zones, particularly around parts of Gboko. Lower values are more prevalent in valley bottoms and flat plains in the lower course of the River (Tyo Mu to Mu mouth). The implication is that more soil is loss at the upper course of the River than lower course of the River.

P Factor Map

This is the ratio of soil loss using a specific support practice to the corresponding loss with upslope and down slope. It reflects the effects of practices that will reduce the amount and rate of water runoff and thus reduce the amount of erosion. Common support practices that reduce the rate of soil loss are, cross slope cultivation, contour farming, strip cropping, terracing, and grassed waterways. The P factor map is shown in figure 15.

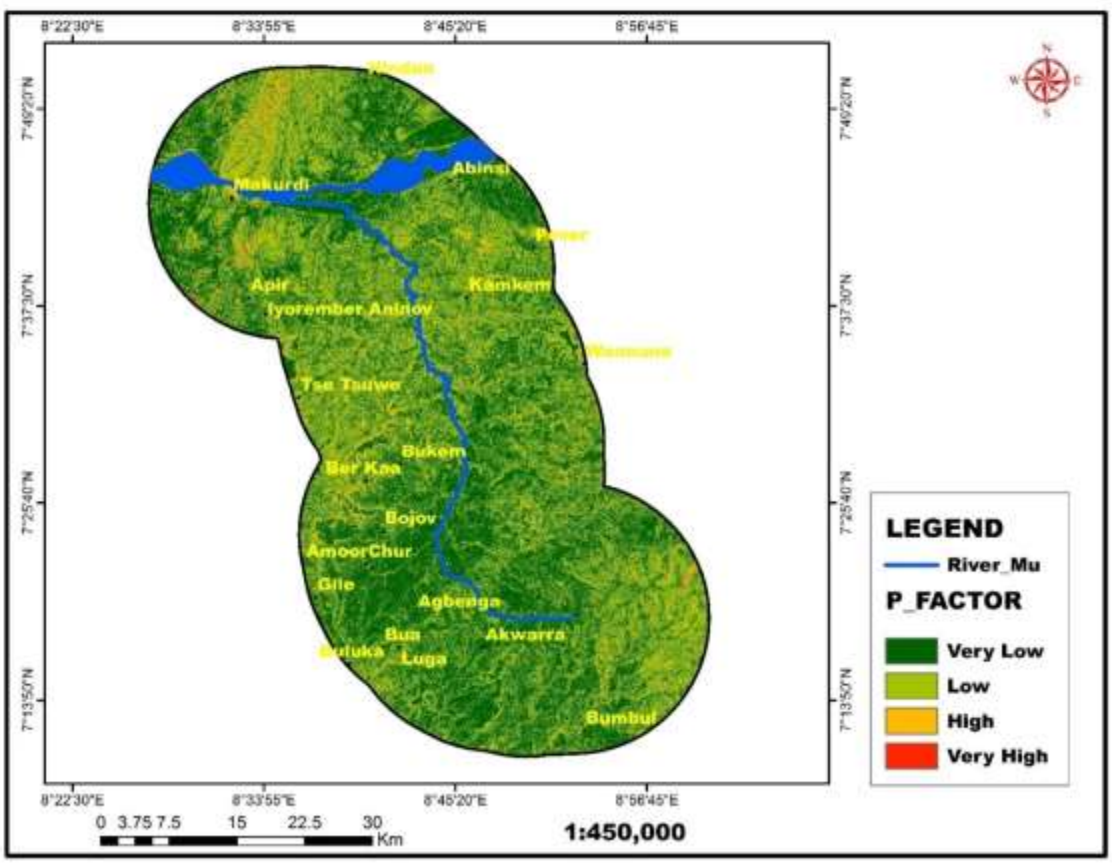

Figure 15: P Factor Map
Source: Author's field Analysis, 2024.

The P factor map as shown in figure 15 was derived from the land use/ land cover and support factors and assigned with values ranges from very low to very high, in which the highest value is assigned to areas with no conservation practices (open areas and grasslands), and minimum values given to built-up land and plantation area with contour cropping. The land use is converted to polygon and in the attribute table a new cell is created where values for the P factors are entered. The P factor range from low to high. Low P factor indicate the presence of erosion control practices, which reduce soil loss significantly. High P factor signify absence or ineffectiveness of conservation measures, leading to higher potential soil loss. Areas with high P factor (such as, Makurdi in the lower course and scattered uplands) are likely under conventional tillage, slope farming, or unmanaged lands. Lower P values appear in the valley bottoms and agricultural plains, such as parts of Gboko, Tarka among others in the lower course suggesting the use of support practices like contour ridging, or controlled runoff systems. The P factor directly affects sediment yield by determining how much of the eroded soil reaches the stream system. Higher P values mean less resistance to erosion, contributing to higher sediment yield into rivers, especially in regions already having high K and LS factors. When P is high + LS is high + K is high, sediment yield increases exponentially. Lower P factor areas, where conservation practices are present, act as sediment traps, minimizing downstream sediment delivery.

R Factor

R-Factor (Rainfall Erosivity) measures the impact of rainfall on soil erosion. In tropical and Mediterranean regions, models based on average annual precipitation (AAP) are commonly applied. For instance, in Nigeria and India, various models were developed to estimate R Factor using annual or seasonal rainfall data, which can significantly affect soil loss. Rainfall erosivity is the first factor required in the equation. The R factor is based on rainfall impact in the form of kinetic energy, and it also projects the rate and quantity of run-off which is directly interconnected with a particular precipitation event. Rainfall erosivity is calculated using the mean annual rainfall

$$\mathrm{R} = 8.12 + 0.562P \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (3)$$

The R factor map is presented in figure 16.

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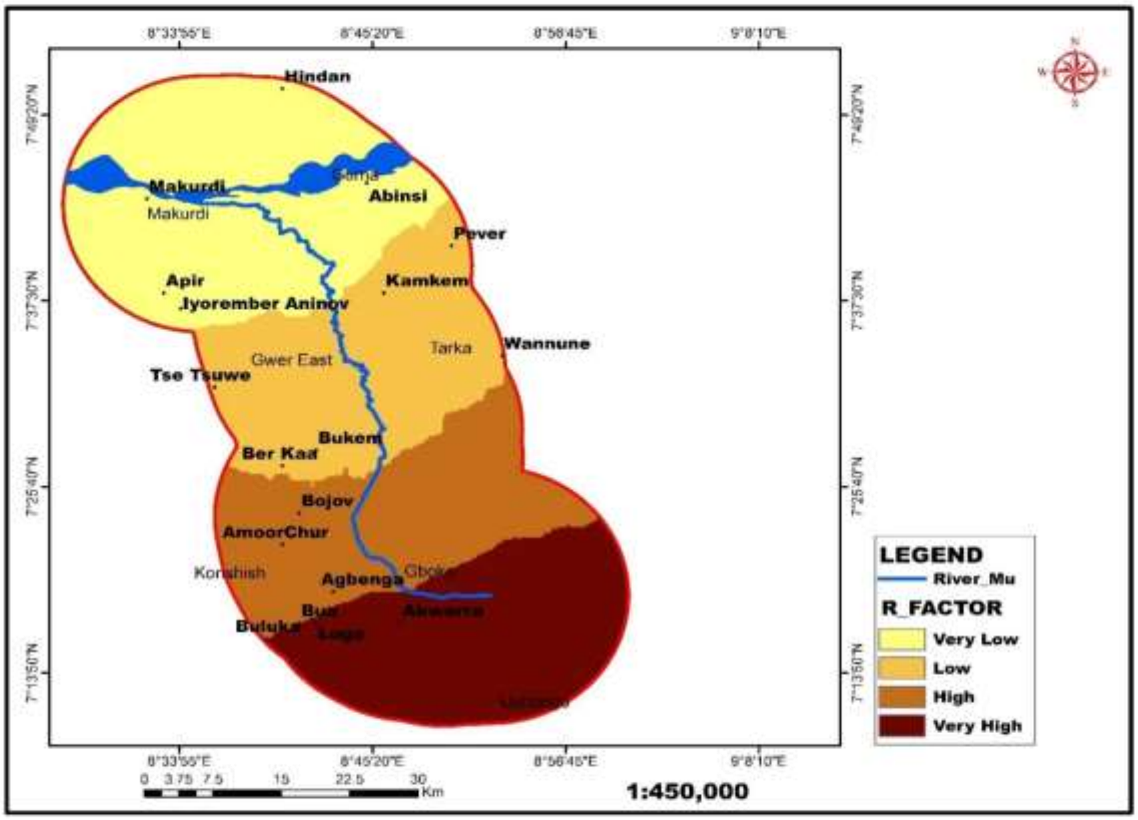

Figure 16: R Factor Map

Results presented in figure 16 shows the rainfall erosivity of the study area. Result shows from very low R factor to very high R factor. The upper course of the River extending to the middle course have higher rainfall erosivity, while lower course (Makurdi, Guma, Apir) have low rainfall erosivity. This suggests that soil erosion potential is higher in the upper and middle course of the River Mu catchment due to more erosive rainfall on high slopes. The higher R values in the upper catchment suggest a need for erosion control measures like, vegetative cover, terracing, modern farming and reduced mining. Lower R factor in the lower course of the River (Makurdi, Apir) which suggest less erosive rainfall, less intensive soil conservation efforts. Increased rainfall erosivity in the upper course of the river results in higher sediment yield, which affects, water quality, reservoir siltation and agricultural productivity

Soil loss

Soil loss is a critical environmental concern affecting many river catchments around the world, and the River Mu Basin in Benue State, Nigeria, is not an exception. Understanding soil loss dynamics in the River Mu catchment is essential for sustainable land and water management. Quantitative assessment using Revised Universal Soil Loss Equation (RUSLE) has become instrumental in evaluating the spatial and temporal patterns of soil erosion in the area. It

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highlighted key factors such as rainfall erosivity (R-factor), soil erodibility (K-factor), topography (LS-factor), land cover and management (C-factor), and conservation practices (P-factor). Soil loss map is shown in figure 17.

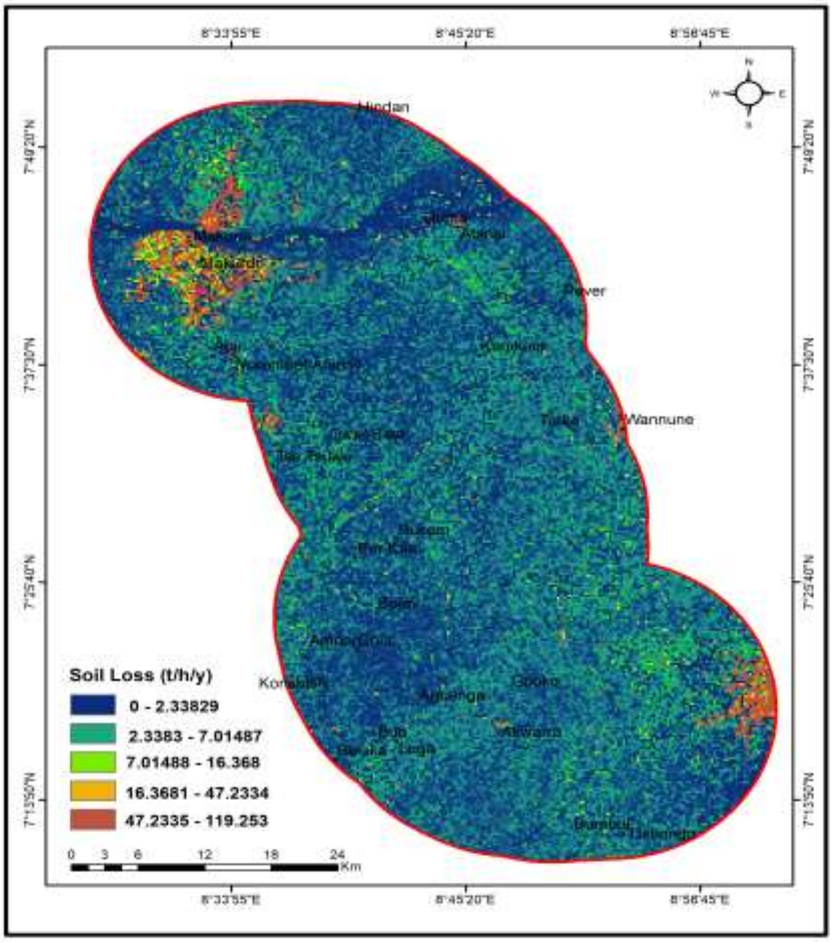

Figure 17: Soil Loss map

The analysis was carried out to estimate annual soil loss on a pixel-by-pixel basis and the spatial distribution of the soil erosion in the study area as shown in figure 17. Very low, Low, moderate, high and very high erosion classes based on the rate of erosion (t/ha/year), was defined, i.e., More erosion corresponds to very high erosion and least rate of erosion corresponds to low erosion. The highest soil loss ranges from 47.236 - 119.253 t/ha/y is concentrated in specific zones, particularly around the middle and upper course of the River and this showed that sediment is generated at the upper and middle course of the River more than the lower course of the River. Lower soil loss ranges from 0 - 2.382 t/ha/y is less prevalent and scattered throughout along River Mu. This shows that the catchment is characterized by flat terrain but rock outcrops and high elevations in places.

It is generally observed that most part of the catchment area is found in the very low erosion category, while, very high erosion occurs only in a few regions particularly in built-up areas and where steep slopes with barren land exists.

CONCLUSION AND RECOMMENDATIONS

The study concludes that soil fertility and stability are generally low, with Cation Exchange Capacity (CEC) ranging between 6–9 cmol/kg, indicating weak nutrient retention and poor soil aggregation. Upstream sandy soils were found to be highly erodible, while downstream clay and silt soils enhanced deposition but posed risks of siltation and channel instability. Soil porosity, cohesion, organic matter, and conductivity significantly influenced erosion vulnerability, with low organic matter and weak structure predisposing soils to detachment and transport. Based on the findings the study recommends to promote the use of organic amendments such as compost, manure) to improve soil organic matter, CEC, and aggregate stability, encourage conservation agriculture and agroforestry practices to strengthen soil structure and enhance vegetation cover and introduce bank stabilization measures using vegetation buffers, vetiver grass, and afforestation to reduce riverbank erosion.

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