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Development of a Model for Quantifying Erodibility of Soils in Eastern Nigeria

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Abstract: Erodibility is the most variable factor influencing water-induced gully erosion in soil, as it governs the soil's susceptibility to detachment by opposing the driving force of rainfall erosivity in the gully erosion process. Previous studies on erodibility in Eastern Nigeria have been conducted segmented, lacking a unified model for its quantification. Therefore, this study investigated erodibility and developed a model to quantify it in the region. The nine areas most at risk for gully erosion, one in each of the region's nine constituent states, were purposively sampled, with one gully from each area then selected through convenient sampling. Data collection instruments included observation, satellite imagery, and experimentation. A total of 81 soil samples—9 from each gully—were collected at depths of 0–30 cm, 30–60 cm, and 60–90 cm to determine the percentages of sand, silt, and clay used to quantify erodibility via Bouyoucos' Model. Multiple Linear Regression was employed for data analysis. Results indicated that the independent variables (%sand, %silt, and %clay) made significant contributions to the dependent variable (clay ratio/erodibility) across the gullies. Ten models were developed, one for each gully and one general model for the region, as the independent variables made a significant combined contribution ($R = .47$, $R^2 = .22$, $p = 0.00 < 0.05$ significance level) to the dependent variable. The regression equation produced a model for quantifying erodibility in Eastern Nigeria as follows: erodibility (clay ratio) = 129.04 – 179 sand – 2.237 silt – 9.189 clay. The study recommends: (i) prioritizing the quantification of erodibility in all gully erosion studies to enable the application of appropriate gully remediation strategies, and (ii) the use of the developed erodibility model by built environment professionals in approving development initiatives, among other applications.

Keywords: *Eastern Nigeria, Erodibility, Model, Gully erosion, Soil*

Conflicts of interest: None
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1. Introduction

Water-induced gully erosion happens across the globe with its accompanying adverse environmental and socio-economic consequences of enormous dimensions. Many physical (e.g. rainfall erosiivity, slope, soil type and erodibility) and anthropogenic (e.g. population increase, deforestation, agricultural practices and roads) factors influence water-induced gully erosion (Okuh and Osumgborogwu, 2019; Bellocchi and Diodato, 2020; Igwe, Ajadike, Ogbu, 2023a). Of all these factors, the erodibility phenomenon is of main importance because it performs a significant role in rill to gully erosion (Deng, Shen, Xia, Cai, Ding and Wang, 2018). For nearly two decades now, soil erodibility has been linked to the severity of water-induced gully erosion more than other factors of the phenomenon by many researchers (e.g. Bryan, 2000; Ezeabasili, Okoro and Emengini, 2014; AC-Chukwuocha, Ogbenna, Ogugua and Emenike, 2016; Ibeje, 2016; Song, Liu and Cao, 2020) across the globe and this makes its thorough investigation paramount in this research so as to develop a model for it.

Erodibility is a quantitative expression of the inherent susceptibility of a particular soil to erode at different rates when other factors that affect erosion are standardized (Idah, Mustapha, Musa and Dike, 2008). Less erodible sub-surface soils form V-shaped gullies with soil loss lower than that of more erodible sub-surface soils which form U-shaped gullies with more soil loss (Suresh, 2002). It refers to soil's resistance to detachment and transport of particles and aggregates and is defined by its resistance to two energy forces: the impact of raindrops on the soil and the shearing action of runoff between clods in grooves or rills (Isikwue, Abutu and Onoja 2012). Erodibility is an important index to measure soil susceptibility to water erosion as well as predict soil erosion (Borselli, Torri, Poesen and Iaquinta, 2012). It measures soil's ability to resist forces of runoff (Ozoko and Edeani, 2013).

Erodibility has been described as a principal parameter of erosion (Emeka-Chris, 2014). According to Ezeabasili et al. (2014), it is the susceptibility of soil to erosion and it depends on various soil properties: texture; soil aggregation; shear strength; infiltration capacity, permeability; organic matter content; soil profile; surface stoniness; chemical content; and detaching and transportation force. The soil properties that influence erodibility are: (i) those that influence water infiltration, water storage capacity and water movement throughout soil profile; and (ii) those that influence soil detachment and soil transportation by the effect of rainfall and runoff (Van Zijl, Ellis and Andrei, 2014). It is the vulnerability of soils to erosion (Obiora-Okeke, 2019). In the view of Minnesota Pollution Control Agency (2021), erodibility describes a measure of the inherent resistance of geologic materials (soils and rocks) to erosion. In the context of this study, erodibility is the sensitivity of a soil to be detached and transported, depending on the soil type, in soil erosion processes: rainsplash, sheet, rill and gully erosion.

A number of models have been evolved by researchers for computing erodibility. According to Rubianca, Bethanna, Deborah and Kelvin (2018), erodibility models aid land management by delineating areas vulnerable to forces of erosion, determining potential rates of erosion and its possible factors. In the literature, some relevant erosion models in form of regression equations for quantifying erodibility include: Bouyoucos' (1935) Model; Universal Soil Loss Equation (USLE) by Wischmeier and Smith (1978); Revised Universal Soil Loss Equation (RUSLE) by Hudson (1995); GIS and RUSLE-based Model; Wischmeier, Johnson and Cross' (1971) Model; Wischmeier, Smith and Uhlandi's (1958) Model; Erosion Productivity Impact Calculator (EPIC) Model; and Wischmeier and Smith's (1963) Model.

Using the Bouyoucos' (1935) model: Clay ratio = $\frac{\%\text{ sand} + \%\text{ silt}}{\% clay}$, Ezeabasili et al. (2014) quantified relative erodibilties of some soils from Anambra Basin, Eastern Nigeria in twelve locations with severe gully erosion and the values ranged from 0.21-24.64. Ibeje (2016) evaluated the erodibility status of soils in some areas of Imo and Abia states of Eastern Nigeria, making use of Wischmeier, Smith and Uhlandi's (1958) model: K = 2.77M1.14 (10-7) (12-a) + 4.28 (10-3) (B-2) + 3.29 (10-3) (y-3), where: M = (%silt-very fine sand) (100-%clay); a = organic matter (%); B = structural code (very fine granular = 1, fine granular = 2 coarse granular = 3 blocky platy or massive); Y= permeability class (rapid=1, moderate rapid = 2, moderate = 3, slow to moderate = 4, slow = 5, very slow = 6). K is normally classified in the following groups: very high > 0.45, high = 0.35-0.45, moderate = 0.25-0.35, low to very low < 0.25 based on classes of values of erodibility (Akinride and Obigbesan, 2000). Results indicated that erodibilty indices ranged from 34 (0.34) to 72 (0.72) at Arondizuogu and Isikwuato in Imo and Abia states respectively. Erodibility is the most variable factor influencing gully erosion because it provides the opposing force to the driving force of rainfall erosivity as the agent in a gully erosion process (Igwe. Ajadike and Ogbu, 2023b).

With GIS and RUSLE-based Model, AC-Chukwuocha et al. (2016) assessed erosion sensitivity of Owerri communities, Nigeria. The results of the study revealed that 57.56% of the area mapped ranked medium sensitivity to erosion and that Ohi with 87.3% of sand and 0.635% of organic matter had the highest erodibility index. Hanna and Marcin (2021) calculated the erodibility factor (K) in soils under varying stages of truncations in northern Poland, using the Erosion Productivity Impact Calculator (EPIC) Model and the outcomes of the research revealed that soil erodibility (K) ranged from 0.0172 - 0.0352 across soil profiles classified in four groups of varying degrees of truncation: completely eroded; strongly eroded; slightly eroded; and non-eroded forest. Abubakar, Ogbonna, Ogugua and Emeka (2021) investigated the effect of land uses on soil eodibility (index) and soil loss of Keana Geological Sediments of parts of Nasarawa State, Nigeria, using the Bouyoucos' (1935) Model. Results indicated mean value of erodibility (K) and predicted soil loss of 0.0492, 0.0460 and 0.0357; 7.77, 7.20 and 5.48 t ha-1 yr-1 for agricultural, forest and residential lands respectively. Oliveira, Nath and Pereira (2022) estimated erosion using the Bouyoucos' model which considers texture (soil samples containing sand, silt and clay) information collected from Mogi River's Margins, Municipality of Mogi Gaucu, SP, Brazil. The study determined areas of erosion as: high (> 50), moderate (49-5), low (4.9-1) and very low (0.99-0.1).

Although gully erosion occurs in all parts of Nigeria it is predominant in Eastern Nigeria, where it causes lots of environmental and socio-economic impacts of humongous dimensions like soil loss, sedimentation of low-lying areas and water bodies, loss of soil nutrients and low agricultural productivity and displacement of human populations. Despite these problems, all previous studies known to the researcher on erodibility of soils in Eastern Nigeria (eg. Emeka-Chris, 2014; Ezeabasili et al., 2014; Ibeje, 2016; Igwe and Egbueri, 2018) have been conducted using a piecemeal approach, focusing on localities, states and river basins, without covering the entire region which has common gully erosion problems. Additionally, no study known to the researchers in Eastern Nigeria has quantified the erodibility of soils for the region and developed a model for it as a scientific basis for understanding the reasons why there are variations in the gully erosion intensities and indeed problems from the Udi-Nsukka Plateau in the north to the coast of the Atlantic Ocean in the south. This study sees these as gaps to fill so as to add to the body of knowledge on gully erosion management. Hence, this study investigated erodibility in a comprehensive manner in the region and evolved a model for quantifying it as the bottom line for determining sustainable management strategies for gully erosion.

2. Materials and methods

2.1. Study area

The study was carried out in Eastern Nigeria, which is a region in Nigeria (Figure 1) where gully erosion is dominant, and its nine communities with large gullies located in Mgbarakuma, Ikot Ayan Itam, Oko, Igbogene, Ikot Nkebre, Ocha-Ekoli Edda, Abia, Ozu Urualla and Umuebulu II in Abia, Akwa Ibom, Anambra, Bayelsa, Cross River, Ebonyi, Enugu, Imo and Rivers states respectively. The communities are situated in the nine most gully erosion-risk areas with large gullies in Umuahia (Abia), Itu-Uyo (Akwa Ibom), Agulu-Nanka-Oko-Ekwulobia (Anambia), Yenagoa (Bayelsa), Calabar (Cross River), Ekoli-Nguzu Edda (Ebonyi), Udi-Nsukka (Enugu), Ideato-Orlu (Imo) and Oyigbo-Etche (Rivers) respectively according to National Geo-Hazards Monitoring Centre, Awka (NGHMCA) (2019). The region has a total land mass of 46,977km2. From the region's base population of 30,092,822 persons in 2006 (National Population Commission [NPC], 2010) and population growth rates for Nigeria ranging from 2.67-2.55% between 2007 and 2023 according to the United Nations (2023), the number of human beings in the region has been estimated to be 46, 809, 600 persons in 2023.

The region is located between latitudes 50 0′ 0″ N, 70 0′ 0″ N of the equator and longitudes 60 0′0″E, 90 0′ 0″E. It consists of the contiguous states of Abia, Akwa Ibom, Anambra, Bayelsa, Cross River, Ebonyi, Enugu, Imo and Rivers. It is bounded on the east by the Cameroon Highlands, west by the River Niger, north by Kogi and Benue states and the Atlantic Ocean in the south, along the Gulf of Guinea. It was formerly administered as Eastern Nigeria before the Nigerian-Biafran civil war that erupted in 1967 till 1970. From1967 to 1996, the region had metamorphosed politically, through its balkanization by various military juntas, who ruled Nigeria over the years, into its present nine constituent states (Figure 2).

Geologically, it is characterized by several mega structural features, notably the Calabar Flank, the Mamfe Embaymeul, the Anamba Basin, the Afikpo Syncline, the Abakaliki Anticlinorium, the Niger Delta, the Oban Massif and the Obudu Plateau (Bassey, 2012) as indicated in Figure 3. The geology of the area influenced gully formation and expansion as well as massive landslides that happened in several communities because the Ameki Formations, Nanka Sands, Ajali Sands and Coastal Plain Sands in the area are very susceptible to the forces of denudation anywhere they were exposed as sandy outcrops (Egboka and Orji, 2016). The region lies within the tropical rainforest and derived savanna belts, with abundant rainfall ranging from 4000mm on the coastal sea board in the south to below 1700m in the Udi-Nsukka Plateau in the north (United Nations Development Programme [UNDP], 1995), varying land forms, scarcely thick natural vegetation and many natural resources like huge crude oil/natural gas reserves, lead, limestone and gold. According to the UNDP, the mean annual maximum temperature ranged between 300C in Calabar and Port Harcourt to 330C in Enugu whilst the mean annual minimum temperature decreased from the interior to the coast, ranging from 290C to 210C.

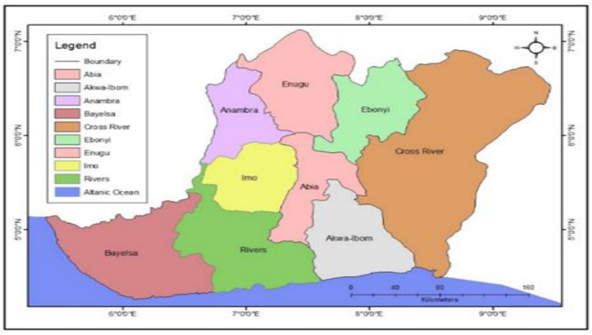

Figure 1: Map of Eastern Nigeria in the map of Nigeria
Source: National Geo-Hazards Monitoring Centre, Awka (NGHMCA), 2020

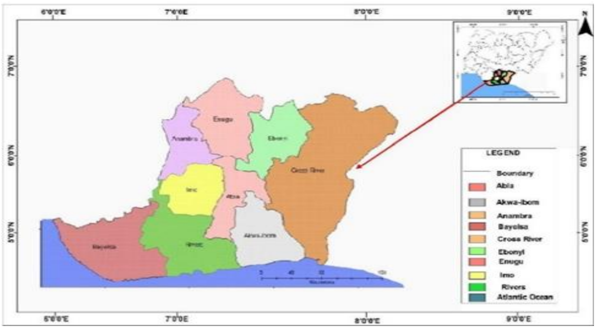

Figure 2: Map of Eastern Nigeria indicating her nine constituent states
Source: National Geo-Hazards Monitoring Centre, Awka (NGHMCA), 2020

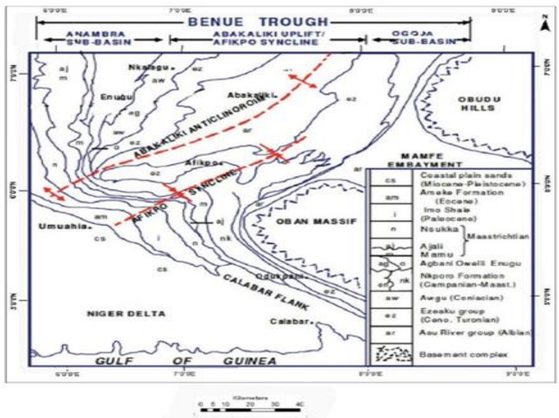

Figure 3: Geological map of Eastern Nigeria indicating the various mega structural features
Source: Adapted from Bassey, 2012

2.2. Sampling methods and data analysis

Two sampling technique were employed in the course of the research. Firstly, the nine most gully erosion-risk areas with large gullies were purposively sampled to depict the best gully erosion scenario of Eastern Nigeria. Secondly, the convenience sampling technique was used in selecting nine large and active gullies that were accessible and in close proximity to human settlements with proofs of failed remediation strategies. Each gully bears the same name with the community where it is located. The multiple linear regression was used in data analysis to establish the relationship between the independent variables % sand, % silt and % clay, and erodibility as the dependent variable so as to develop a model for quantifying the erodibility phenomenon in the region. The geographical locations of the investigated gullies were taken at points 5m away from the edges of the gullies at the head-scraps, using a GPS-76 Marine Investigator to show their co-ordinates. The elevations of the points above sea level were also taken by making use of the same instrument. The global locations and elevations of the gullies above the sea level taken at their head scraps are indicated in Table 1. The tape was used in measuring the lengths and widths (1m each) of the soil profile pits as well as their common depth (0.9m) from which soil samples were taken at depths of 0-30cm, 30-60cm and 60-90cm, measured using the same tape. Again, the distance of 5m from the edge of each gully at its head-scraps was taken using a five-metre long bamboo instead of a tape to avoid falling inside the gullies whose head-scraps where active gully erosion process occurs highest were the most unstable.

The experimental method was used for the generation of quantitative data from primary sources. A total of eighty-one (81) composite soil samples were collected from the nine investigated gullies. At each of the studied gullies, three soil profile pits measuring 1m x 1m x 0.9m were dug at a distance of 5m, measured using a 5-metre long bamboo from the three edges of the gully, one at the head-scrap and one at each of the two shoulders (sidewalls), 5m away from the head-scrap. The head-scraps and shoulders near to them were chosen because these are where gullying occurs highest in its upslope movement and sidewall expansion. Three soil samples were collected from each of the pits at depths of 0-30cm, 30-60cm and 60-90cm. The three layers were chosen at the top soil (0-30cm) that must be eroded before gullying starts, at the point where gully erosion begins from the sub-soil (30-60cm) and even beyond (60-90cm) as gullying continues for a proper understanding of mean soil erodibility from the top soil to two layers of the sub-soil. The collection of soil samples was conducted during the dry season between 10th-12th March, 2020 before the lockdown due to the Coronavirus disease, 2019 (COVID-19) pandemic, when the gullies' edges and their environs were considerably and seemingly stable and safe to a large extent. At each of these nine sampling locations, a digger and a shovel were used in creating the soil profile pits while a trowel was used in carefully collecting the soil samples at the various depths, starting from the last stratum (60-90cm) to avoid contamination by the upper ones (30-60cm and 0-30cm), then the second (30-60cm) so as to avoid contamination by the first (0-30cm), which would have been the case if the collection happened in a reverse order beginning from the first.

The samples were homogenized in a clear plastic plate and a composite soil sample was drawn from each. This process was repeated for all the experimental units in the laboratory. Each of the nine soil samples from Mgbarakuma (Abia); Ikot Ayan Itam (Akwa Ibom); Oko (Anambra); Igbogene (Bayelsa); Ikot Nkebre (Cross River); Ocha Ekoli-Edda (Ebonyi); Abia (Enugu); Ozu Urualla (Imo); and Umuebulu II (Rivers) were wrapped in threes according to the three layers and poured into nine separate small polythene bags labelled SSA, SSB, SSC, SSD, SSE, SSF, SSG, SSH, and SSI respectively. The nine small bags were then put into a big polythene bag. It is noteworthy that at the end of each day (10th and 11th March, 2020), the soil samples collected were preserved in the refrigerator in the hotels where the researcher lodged. Then on 12th March when the collection of the 81 soil samples was completed, they were all transported immediately to the laboratory of the Department of Soil Science and Technology, Federal University of Technology, Owerri for soil particle size distribution analysis.

The soil samples were air dried and standard laboratory methods were used in determining the soil properties following standard laboratory procedures (Gee and Or, 2002; Grossman and Reinesch, 2002). Soil particle size distribution was determined using the hydrometer method. Clay ratio indices which are the erodibilities of the soils at the gully erosion sites were computed by using figures of particle size distribution (%sand, %silt and %clay) to determine the levels of resistance of soils to gully erosion across the investigated gullies in the region. The clay ratio (erodibility) indices were computed using the aforementioned Bouyoucos' (1935) model.

Table 1: Locations and elevations of the investigated gullies across nine communities in Eastern Nigeria

S.N.	State	Gully site	Gully location	Elevation (m)
1.	Abia	Mgbarakuma	E07° 25' 17" N05° 28' 23"	144.6
2.	Akwa Ibom	Ikot Ayan Itam	E07° 59' 07" N05° 07' 17"	37.8
3.	Anambra	Oko	E07° 05' 08" N06° 02' 20"	267.6

4.	Bayelsa	Igbogene	E06º 24' 10" N05º 02' 41"	10.8
5.	Cross River	Ikot Nkebre	E08º 21' 30" N05º 03' 46"	64.2
6.	Ebonyi	Ocha-Ekoli Edda	E07º 50' 18" N05º 44' 44"	184.1
7.	Enugu	Abia	E07º 24' 53" N06º 20' 04"	428.1
8.	Imo	Ozu Urualla	E07º 03' 36" N05º 51' 45"	102.9
9.	Rivers	Umuebulu II	E07º 08' 35" N04º 53' 21"	15.5

Source: Researcher's field survey, 2020

3. Results and discussion

3.1. Physical observation of gullies

The physical observation of the nine investigated gullies in Eastern Nigeria in Table 1 from the Udi-Nsukka Plateau in the north to the coast of the Atlantic Ocean in the south indicated that they are large older gullies of humongous dimensions, exemplified by Oko and Abia gullies in Plates 1 and 2 respectively, creating many environmental and socio-economic problems like soil loss, sedimentation of low-lands and water bodies, distortion of the landscape and loss of agricultural lands, displacement of residents from their homes, destruction of plants which act as a sink for carbon dioxide (CO2), loss of sources of livelihood, among others. It was also observed that the hitherto stabilized older gullies were undergoing renewed expansion due to the destruction of the instituted conservation structures of concrete works of drains and biological measure of plants and grasses at the gullies by excessive flood water that enters the gullies' channels. Furthermore, observation revealed that emerging new gullies are springing up in all the communities with the existing older gullies. No doubt, both the older gullies and emerging new ones are now threatening the survival of the communities' environments and its people and by extension the entire region. This underscores and reinforces the need to develop a model that would be a scientific basis for managing gully erosion in the region, by delineating areas of high, medium and low vulnerabilities to the forces of gully formation and expansion.

Plate 1: Humongous distortion of the landscape and destruction of agricultural land by the Oko gully, Orumba North Local Government Area, Anambra State
Source: Researcher's field survey, 2020

Plate 2: A concrete work of drain torn by the excess flood water entering the Abia gully, Udi Local Government Area, Enugu State, wreaking havoc on agricultural lands and water bodies
Source: Researcher's field survey, 2020

3.2. Soil particle size distribution and clay ratios (Erodibility Indices)

The variations of the means of the soil particle size distribution (with their textural classes) and those of the calculated clay ratios (erodibility indices) are shown in Table 2. The proportions of sand at gullies were high, a form of domination in the soils of the region, ranging from 78.08% to 96.04%. This is in consonance with the contention of Agbai, Tate and Efenudu (2022) that sandy fraction dominates the soils of Akoko-Edo Local Government Area of Edo State, Nigeria. Both fractions of silt and clay that ranged from mean values of 2.40% to 10.39% and 1.53% and 12.87% respectively were very low. The high %sand, low % silt, low % clay fractions of soils of the region make the area generally susceptible to the forces of denudation. The means of clay ratio (erodibility) ranged between 6.70 and 69.71 across the investigated gullies from the south to the north of Eastern

Nigeria, implying that the soils of the northern part of the region are more erodible than those of the southern part which is a proof for the reason why the large gullies are found more in the north than in the south. The variability of soil texture (%sand, %silt and %clay) established by this study is in conformity with the opinion of Wang, Chen, Thang, Chen, Xianggian, Liu and Hu (2018) that percentage fractions of sand, silt and clay varied in Gorges Reservoir, China and the contention of Ogban (2021) who posited that variation occurred in total sand, silt and clay in University of Uyo Teaching and Research Farm, Akwa Ibom State, Nigeria. In a similar manner, the mean values of erodibility indices which were found to have varied across the gullies is in line with the assertion of Ibeje (2016) that there was variation in the erodibility indices of soils, ranging from 34 (0.34) to 72 (0.72) at Arondizuogu and Isikwuato respectively in Imo and Abia states, Eastern Nigeria in that order as well as the opinion of Hanna and Macin (2021) that erodibility varied across northern Poland, ranging between 0.0172 and 0.0352.

Table 2: Mean soil particle size distribution at the gullies and clay ratio (erodibility)

Gully	Stratum	%Sand	%Clay	%Silt	Textural class	Clay ratio (erodibility) indices
	0-30	84.52	7.20	8.28	LS	12.89
Mgbarakuma	30-60	83.80	14.92	1.28	LS	5.70
	60-90	81.52	13.20	5.28	LS	6.58
	Mean	83.28	11.77	4.95	LS	8.39
	0-30	83.08	7.20	9.72	LS	12.89
Ikot Ayan Itam	30-60	83.08	5.20	11.72	SL	18.23
	60-90	72.08	19.20	8.72	SL	4.21
	Mean	79.41	10.53	10.05	SL	11.78
	0-30	97.52	2.20	0.28	S	44.46
Oko	30-60	95.52	1.20	3.28	S	82.33
	60-90	95.08	1.20	3.72	S	82.33
	Mean	96.04	1.53	2.43	S	69.71
	0-30	85.52	7.20	7.28	LS	12.89
Igbogene	30-60	81.52	4.20	14.28	LS	22.81
	60-90	87.52	6.20	6.28	LS	15.13
	Mean	84.95	5.97	9.28	LS	16.94
	0-30	79.53	13.20	7.27	SL	6.58
Ikot Nkebre	30-60	82.52	13.20	4.28	SL	6.58
	60-90	84.08	12.20	3.72	LS	7.20
	Mean	82.04	12.87	5.09	SL	6.79
	0-30	96.08	1.20	2.72	S	82.33
Ocha-Ekoli Edda	30-60	95.08	3.20	1.72	S	30.25
	60-90	95.08	1.20	3.72	S	82.33
	Mean	95.41	1.87	2.72	S	64.97
	0-30	94.08	3.20	2.72	S	30.25
Abia	30-60	90.08	6.20	3.72	S	15.13
	60-90	90.08	7.20	2.72	S	12.79
	Mean	91.41	5.53	3.05	S	19.39
	0-30	86.08	5.20	8.72	LS	18.23
Ozu Urualla	30-60	84.08	6.20	9.72	LS	15.13
	60-90	85.08	8.20	6.72	LS	11.20
	Mean	85.08	6.53	8.39	LS	14.85
	0-30	86.08	9.20	4.72	LS	6.89
Umuebulu II	30-60	64.08	13.20	22.72	SL	6.58

60-90	84.08	12.20	3.72	LS	6.65
Mean	78.08	11.53	10.39	LS	6.70

S=sand, LS=loamy sand, SL=sandy loam
Source: Researcher's field survey, 2020

3.3. Development of a model for quantifying erodibility using multiple linear regression

The multiple linear regression analysis was conducted at 0.05 level of significance so as to determine the contributions of the independent variables (%sand, %silt and %clay) to the dependent variable (clay ratio/erodibility) and evolve nine erodibility models for the nine studied gullies as well as one erodibility model for the region as shown in Table 5. At Mgbarakuma gully, % sand, % silt and % clay indicate 99% contribution, adjusted to 98% influence which is significant because p = 0.00 < 0.05. The contributions of the three variables are all negatively significant to the present value of clay ratio. The implication is that as either % sand or % silt decreases, the clay ratio also decreases. But as %clay decreases, clay ratio increases. The regression equation is as expressed in a relationship: Clay ratio (erodibility) = 42.29-0.267 sand-179 silt-0.971 clay.

At Ikot Ayam Itam, % sand, % silt and % clay show 92% influence, adjusted to 85% contribution which is significant because p = 0.00 < 0.05. The %sand and % clay are negatively significant to clay ratio while % silt is positively significant to it. Therefore, as % sand decreases and % silt fraction increases, the clay ratio also decreases and increases respectively while as % clay decreases, the clay ratio increases. The regression equation is given as: Clay ratio (erodibility) = 16.796-1797 sand + 0.60 silt-233.74 clay. At Oko, %sand, %silt and % clay indicate 90% influence, adjusted to 81% contribution which is significant because p = 0.00 < 0.05. The % sand is positively significant to the clay ratio, but % silt and % clay are negatively significant to it. This simply means that as percentage sand fractions increases, the clay ratio also increases, as % silt gets low, clay ratio decreases. Nonetheless, as %clay decreases, clay ratio increases. The regression equation is given as: Clay ratio (erodibility) = -752.76 + 12.93 sand – 1797 silt – 233.74 clay. The negative value for the constant simply means that the expected value of the dependent variable (clay ratio/erodibility) will be less than 0 when all independent/predictor variables are set to 0.

At Igbogene, %sand, %silt and %clay show 91% contribution, adjusted to 83% influence which is significant since p = 0.00 < 0.05. Like at Oko, the % sand is positively significant to the clay ratio and both %silt and %clay are negatively significant to the clay ratio. It implies that as %sand increases, the clay ratio rises, but as %silt decreases, clay ratio also decreases while as %clay lowers, clay ratio increases. The regression equation is expressed as: Clay ratio (erodibility) = 24.54 + 0.236 sand-1797 silt-4.212 clay. At Ikot Nkebre, %sand, %silt and %clay indicate 99% influence, adjusted to 98% contribution which is significant because p = 0.00 < 0.05. Only one variable: %sand is positively significant to the clay ratio while both %silt and %clay are negatively significant to the clay ratio. This implies that as % sand increases, clay ratio also increases but as % silt decreases, clay ratio decreases as well. As % clay decreases, clay ratio increases. The regression equation is expressed as: Clay ratio (erodibility) = 14.408+ 0.006 sand-1797 silt-0.619 clay.

At Ocha-Ekoli Edda, %sand, %silt and %clay show 66% influence, adjusted to 44% contribution which is significant since p = 0.00 < 0.05. The three variables: %sand, %silt and %clay are negatively significant to the clay ratio. The implication is that as both % sand and % silt decrease, the clay ration decreases as well. However, as %clay decreases, the clay ratio rises. The regression equation is expressed in a relationship: Clay ratio (erodibility) =343.03-1997 sand-27.19 silt-86.398 clay. At Abia, % sand, % silt and % clay show 94% contribution, adjusted to 88% influence which is significant because p = 0.00 < 0.05. All the three independent variables: % sand, % silt and % clay are negatively significant to the clay ratio. Therefore, as % sand and % silt variables are decreasing the clay ratio is also decreasing, but as %clay decreases, clay ratio rises. The regression equation is clearly expressed in a relationship: Clay ratio (erodibility) = 50.05-1797 sand-2.106 silt- 3.977 clay.

At Ozu Urualla, % sand, % silt and % clay have 93 % influence, adjusted to 87% influence which is significant since p = 0.00 < 0.05. The contributions of the three variables are all negative to the value of clay ratio. Therefore, as the percentage value of either sand or silt is decreasing, clay ratio also decreases. But as the %clay lowers, clay ratio rises. The regression equation is expressed in a relationship: Clay ratio (erodibility) = 166.48-1.522 sand-27.19 silt-2.848 clay. At Umuebulu II, %sand, %silt and %clay indicate 97% contribution, adjusted to 94% influence which is significant as p = 0.00 < 0.05. The contributions of all the independent variables: %sand, % silt and %clay are all negatively significant to the value of clay ratio. The implication is that as the percentage values of both % sand and % silt decreases, the clay ratio decreases. But as % clay decreases, clay ratio rises. The regression equation is expressed as: Clay ratio (erodibility) = 17.13-179 sand-0.007 silt-0.761 clay.

The research investigated the contributions of the independent variables to the dependent variable (Table 3) so as to develop a model for quantifying erodibilities of soils linked to the severity of gully erosion by researchers (e.g. Bryan, 2000; Ibeje, 2016; Song et al., 2020). It is crucial to note that the hypothesis which addressed the development of a model for quantifying erodibility suggests that the independent variables: %sand, %silt, and %clay make significant contributions to the dependent variable which is clay ratio (erodibility) at gully sites in the region (R = 47, R2 = 22, p = 0.00 < 0.05 significant level). It was revealed that the independent variables made significant contributions to the dependent variable at all the nine investigated gully erosion sites. Nine models were evolved, one for each gully. Put together, the independent variables made significant combined contributions to the dependent variable in a regression equation thus: clay ratio (erodibility) =129.04 – 179 sand – 2.237 silt – 9.189 clay as a model for quantifying soil erodibility in Eastern Nigeria (Table 3). The combined % sand, %silt and %clay indicates 47% contribution, adjusted to 22% influence which is significant because p = 0.00 < 0.05. The contributions of all the three independent variables: %sand, % silt and % clay are all negatively significant to the combined value of clay ratio (erodibility). The simple implication is that as combined %sand or %silt decreases, the value of combined clay ratio decreases as well. However, as the combined %clay decreases the combined value of clay ratio increases. It is noteworthy that %clay has a negative significant relationship with clay ratio at all the nine investigated gully sites since p = 0.00 < 0.05. Therefore, as %clay fractions decreases at all the gullies, the clay ratio rises and the soils become more susceptible to gully erosion.

Table 3: Multiple linear regression models

Predicting equation	**R**	**R^2**	**Sig.**
Mgbarakuma			
Clay ratio = 42.29 -0.267 sand -179 silt -0.971 clay	0.99	0.98	0.000019
Ikot Ayan Itam			
Clay ratio= 16.796 -1797 sand +0.60 silt -0.953 clay	0.92	0.84	0.00421
Oko			
Clay ratio= -752.76 +12.93 sand -1797 silt -233.74 clay	0.90	0.82	0.005984
Igbogene			
Clay ratio= 24.54 +0.236 sand -1797 silt -4.212 clay	0.91	0.83	0.004758
Ikot Nkebre			
Clay ratio=14.408 +0.006sand -1797 silt -0.619 clay	0.99	0.98	0.000006
Ocha-Ekoli Edda			
Clay ratio=343.03 -1797 sand -27.19 silt-86.398 clay	0.66	0.44	0.00811
Abia			
Clay ratio= 50.05-1797 sand -2.106 silt -3.977 clay	0.94	0.88	0.001582
Ozu Uruaka			
Clay ratio=166.48 -1.522 sand -179 silt -2.848 clay	0.93	0.86	0.002239
Umuebulu II			
Clay ratio=17.13 -179 sand -0.007 silt -0.761 clay	0.97	0.94	0.000271
Combined			
Clay ratio= 129.04 -179 sand -2.237 silt -9.189 clay	0.47	0.22	0.000050

Source: Researcher's field survey, 2020 (Significant level: 0.05)

There is a direct correlation existing between the properties of soils and severity of gully erosion in the region. The northern part of the region, with higher values of sand fractions than the southern part, has more number of gullies than the southern part. Additionally, soils of the north have higher values of the erodibility indices than those of the south. The implication is that soils in the north are more easily dispersible than those in the south, which accounts for the reason why more number of large and terrifying gullies are found in the northern part than in the southern part. Therefore, the severity of gully erosion and its associated problems are more in the north than in the south. The practical implication of the developed model is that it will be used for quantifying erodibility indices of soils in Eastern Nigeria and other tropical climes. Furthermore, the model as the first of its kind for the region, will be the basis of comparison with any other model (s) that may be evolved in future by researchers in the region.

The developed model lends itself for use in soil conservation and gully erosion management. Wherever the model is applied and the erodibility indices found to be high, it means that an appropriate soil conservation and gully erosion strategies would be either developed or existing ones from elsewhere adopted. For example, an area with high erodibility indices and as such severe gully erosion incidences needs soil conservation practices that must drastically reduce the detachment of soil particles, exemplified by mulching and organic manure which bind soil particles together. For gully erosion management in such an area, sanctuaries should be created around gullies where the biodiversity will remain without exploitation for many years and whenever it starts must be done on a strictly regulated basis to avoid over exploitation. The results of this study are in conformity with that of Abubakar et al. (2021) which revealed variations in the values of computed erodibilty indices of soils collected from three different land uses in Keana Geological Sediments of parts of Nasarawa State, Nigeria. Similarly, the findings completely align with that of Oliveira et al. (2022) that determined areas of erosion as high and low in the Mogi River's Margins, Municipality of Mogi, Gaucu, SP, Brazil through the computation of erodibility indices of soils.

One major novel contribution by this study to the field of gully erosion is the development of nine erodibility models, one for each gully and its underlying river basin and a general one for the entire region. Each of the nine models should be used for quantifying erodibility within the river basin under which the respective gullies are located. The general model is applicable only when erodibility of soils is to be quantified across the entire region. Another novel contribution of this study to the body of knowledge in gully erosion is that it has used the quantified erodibility indices to establish, in scientific terms, that areas with high values of erodibility have more severe gully erosion incidences and indeed problems than areas with low erodibility values. Examples of such severe problems include humongous soil loss, loss of agricultural lands, heavy sedimentation of low-lands and water bodies and damage of roads/footpaths observed in the course of the study.

4. Conclusion

The erodibility of soils in Eastern Nigeria has been quantified and its values found to be high in the northern part of the region than in the southern part, which is a proof that soils in the north are more erodible than those in the south. This accounts for the reason why there is more number of large gullies in the states in the north (e.g. Anambra, Enugu and Abia) than those in the south (e.g. Akwa Ibom, Bayelsa and Rivers). The nine models developed, one for each of the investigated gully erosion sites, were combined into one as the 10th model: Clay ratio (Erodibility) = 129.04 -179 sand – 2.237 silt – 9.189clay for the entire Eastern Nigeria is novel as a scientific basis for the quantification of the phenomenon and also the determination of appropriate remediation strategies at the gullies. This study concludes that the variations of the quantified erodibilities of soils across the geographical space of Eastern Nigeria call for the application of different and appropriate remediation strategies from the Udi-Nsukka Plateau in the north to the coast of the Atlantic Ocean in the south to lower the problems occasioned by gully erosion.

Based on the result of the study, it is recommended as follows:

a. Erodibility has been linked to the severity of gully erosion in Eastern Nigeria by this study because it has high values in the northern part of the region where large gullies of bigger dimensions exist and low values in the southern part with large gullies of lesser dimensions. Owing to this, it is recommended that quantification of erodibility be prioritized in all gully erosion studies so as to understand, in scientific terms, areas of high and low sensitivity to gully erosion incidences for the application of appropriate remediation strategies.

b. The erodibility model: 129.04–179sand-2.237silt–9.189clay evolved by the study is recommended for use by built environment professionals like environmental management practitioners, planners, consultants, development experts, geologists, hydrologists, among others, who do business of approving development initiatives. The knowledge of the erodibility statistic based on this model and its application on decision making will result in more environmental and socio-economic benefits as well as serve as a platform for future research on erodibility in Eastern Nigeria and other tropical regions.

c. The application of remediation strategies at gully erosion sites in the region should be based on the knowledge of the erodibility status of soils found by this study. The northern part of the region with more gullies than the southern part due to high values of erodibility requires more vegetation at the gullies in form of sanctuaries where logging, animal poaching, hunting plus collection of firewood or even fodder are prohibited for many years and highly regulated and monitored anytime they begin.

d. Efforts should be directed towards improving the soil quality at gullies, particularly in the northern part of the region where erodibility indices are higher than those in the southern part. This is achievable through the use of measures like plant charcoal, mulching and compost which would bind the high and loose sand fractions of soils at gullies in the northern part of the region to lower this high erodibility status.

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