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ARTICLE

Spatial Patterns in Soil Chemistry and Granulometry in the Geomorphic Hazards' Vulnerable Land and the Need for Sustainable Utilizations

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ABSTRACT

This study evaluates the patterns in nutrients, grain size, and allied matters' distributions across geomorphic hazards vulnerable sites in Edo State to strengthen sustainable management efforts and boost land capability for agricultural uses. The specific objectives include determining the patterns of variations and relationships among the soil nutrients and allied parameters across distinct geomorphic hazards vulnerable sites. Soil samples were collected from 12 gullies and 3 flood-vulnerable sites using a soil auger and sediment corer, treated, homogenized, and analyzed in the laboratory for diverse parameters. The laboratory results were further analyzed using descriptive and inferential statistics. The grain size distributions reveal spatial fluxes, but with the unilateral dominance of sand particles. A test of multiple effects of variations in locations on nutrient endowments using Hotelling's Trace model gave a value of 13,868.621 and an F value of 3467.155 that is statistically significant at 0.013. Roy's Largest Root model offered a high value of 1850.015 and a high F value of 740.006, which is statistically significant at 0.000. The tests of variations between-subjects indicate that only phosphorus, calcium, and magnesium possessed high values that are statistically significant at a 0.05 confidence level. This study concluded that soil chemistry and granulometry in the geomorphic hazard vulnerable sites varied based on geographic locations, due to the uniqueness of the intervening human and natural agents. This study recommends the adoption of proactive people-oriented

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and site-specific engineering and supportive agronomic management strategies for enhanced land capability for sustainable crop production.

Keywords: Soil Chemistry; Nutrients; Granulometry; Geomorphic Hazards; Sustainable Land Use

1. Introduction

The global quest for sustainability in land capability for effective agriculture has attracted divergent levels of responsiveness through research and land use practices by agriculturalists, geographers, and allied Earth scientists in this Anthropocene Age. Yet, the expected outcomes are rather obscured by the varying magnitudes of geomorphic hazards at distinct geographic locations. Research evidence has shown that human exploitative excesses, such as unethical agricultural practices, mining, urbanization, and infrastructural development [1–5], are among the focal variables that exert pressure and negative feedback mechanisms on soil chemistry (quality) and land capability for optimum utilization in crop production across distinct spaces.

It is observed that most poor countries with a disproportionately high dependence on agricultural employment, rapidly expanding populations, and elevated levels of water stress also endure strong variability of rainfall uncertainties [6], which invariably affects land utilization and management. For instance, numerical assessment showed that productivity increases in response to wet anomalies and decreases with dry anomalies, on average, a 11 to 12 percent decrease in annual agricultural productivity globally [7]. A study has shown that 'our future ability to feed ourselves and live in a serene environment in this Anthropocene depends on our ability to reduce the rates at which the top-soils are currently eroding' [8], soil nutrients are depleting, and loss of cultivable land (e.g., class A & B) [9]. A clear understanding of hazard-driven soil nutrient losses and how they affect land helps with the design of sound strategies to control runoff [10].

Within the humid Tropical belts of West Africa and Nigeria in particular, excess rainfall events are directly linked with erosion and flood hazards. Other geomorphic hazards associated with upsurge rainfall scenarios consist of weathering, mass wasting, denudation, and sediment yield. The occurrences of highlighted hazards at the regional and local landforms have caused devastating impacts on human interactions, socio-economic activities, and the environment [11]. More succinctly, flood and erosion hazards had been identified among the top lethal geophysical and environmental hazards in the Tropics [1,12–15], affecting soil quality, nutrient endowment, food security, and biodiversity [3,16,17].

It is observed that most of the global challenges that humans face today (e.g., climate change, soil contamination, food security, water quantity and quality) are inextricably linked to land, the chemical reactions, and processes that occur over a range of spatial and temporal scales [17,18]. Retrospectively, though soil chemistry and granulometry remain among the top critical areas in landform and allied Earth science research in the Tropics, existing literature is skewed in context, method, and ideology; thereby necessitating the adoption of multidisciplinary approaches that combine field-laboratory-quantitative models to provide an expansive view of spatial fluxes in soil nutrients and granulometry across geomorphic hazards' vulnerable sites. Such knowledge and understanding usually provide clearer and more sustainable options for land resource management and utilization for viable agricultural production and boost food security.

In Brazil, the disaster risk response efforts reflect a robust approach to managing sediment yield and related hazards, while research reports on the past commitments indicate that prevention measures are critically under-implemented [19]. Empirically, 87 percent of municipalities have not integrated disaster risk response into their MPs despite the existing legal mandates [20]; the observed discrepancy reveals a gap between legislative intent and administrative practice, highlighting the need for more effective and comprehensive policy implementations [19–21].

The relationships between the city's historical development, modern urbanization, and natural topography create a complex environment where the effects of anthropogenic activities are pronounced [21–23]. Including extensive areas of quarrying, ridge removal, terracing, and valley filling, especially evident in locations like Malagrotta [22–24].

There is increased speculation that research efforts to identify and elucidate the intriguing relationships and variations between geomorphic hazards (flood and erosion), vulnerable land, and soil nutrient concentrations for tropical crops are rather limited. Such paucity can constitute severe constraints to the timely actualization of United Nations Sustainable Development Goal 15 Target 3, which envisages '*by 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world*' (UNSDG) [25,26]. The vitality of the stated goal and target suggests an urgent need for a study on soil nutrients in geomorphic hazards' vulnerable land at the local and State level as an index for measuring the level of commitments, before transcending to the regional and global scale. Hence, the impacts of degraded lands usually vary with locations and time.

Within southern China, the empirical assessment of four spatial scales indicated that the total determinants of gully were classified as lithology and soil > topography > human activities > climate > vegetation [27]. However, issues regarding spatial patterns in agricultural land and soil nutrient distributions were either eclipsed or received only passing attention. Hence, differences in the causative factors require multiple management approaches [1,11].

From the system approach, the anthropogenic and natural factors that drive land vulnerability to geomorphic hazards (erosion and flood) within the Tropics can be conceptualized using the hypothetical perspective as presented in **Appendix A**. The model provides support to existing literature [1,27], whose submissions point to the influence of intervening opportunities between and among the arrays of human and geological variables. Within the hypothetical model, stressors of land quality are the amalgam of human components such as level of land use, e.g., for farming, grazing, deep tillage, recreation, forestry, deep farm mechanization, vegetation cover, and allied characteristics; pattern of urbanization and socio-economic/infrastructural development, and engineering and construction works (e.g., road network/drainage construction, mining activities).

A further assessment of the item in **Appendix A** reveals that the natural agents encompass weather and climate elements, especially precipitation and wind, whose occurrences and magnitudes have exerted varying degrees of devastating consequences on people's lives and properties. Soil/rock texture, structure, parent materials, nutrients, and allied particle enrichments, the degree of permeability or non-permeability, and resistance or non-resistance to geomorphological processes. Surface configuration (i.e., slope profile, which can be constant, concave, or convex) directly influences the pattern of surface runoff that leads to erosion or surface accumulation that triggers flood hazard.

Geomorphic hazards destroy landform equilibrium, e.g., by removing the nutrients, soil, and vegetation materials [28], thereby creating some local and regional landforms at disequilibrium. Also, land remediation measures such as mechanical rolling, deep soil tilling, topsoil stripping, and backfilling often break the original state of the soil and may have impacts on the organic matter and fast-acting nutrient contents of the soil, as observed in Goudie [29]. According to Okafor [10] and Bower et al. [23], both hazard infestations and human intervention measures have major influences on the quality of the soil environment and the health of crops. The soil health includes a decrease in soil nutrients such as nitrogen, phosphorus, potassium, and organic matter, and a decrease in trace elements [30,31].

The preceding discourses depict limited literature in the context of the patterns in soil chemistry (nutrients) and granulometry in the geomorphic hazard vulnerable land in the humid Tropics and Nigeria in particular. The cardinal issues that provide direction for this study include: what are the distribution patterns of granulometry, particulate matter, and nutrients in distinct geomorphic hazards' vulnerable sites in Edo State? Do spatial patterns in geomorphic hazards' vulnerable sites have effects on soil nutrient concentrations in Edo State? Are there statistically significant variations between the locations of geomorphic hazards' vulnerable sites, soil nutrients, and allied materials' concentrations in Edo State?

2. Materials and Methods

2.1. Location and Rainfall

Edo state is located between Latitude 5°32′18″and 7°34′13″ North of the Equator, and Longitudes 4°54′07″ and 6°46′10″ East of Greenwich Meridian (**Figure 1**). Relatively, the study area is bounded by Kogi State on the North, Delta State on the South, Ondo State on the West and aspect of Delta State and River Niger on the East. The rainfall characteristics presented in **Figure 1** show spatial deviations with the highest annual scenarios 2400 mm and above recorded in Edo south geographic region, followed by Edo Central, while the least scenario is recorded in Edo North zone (**Figure 1**). Pattern is closing linked with vegetation.

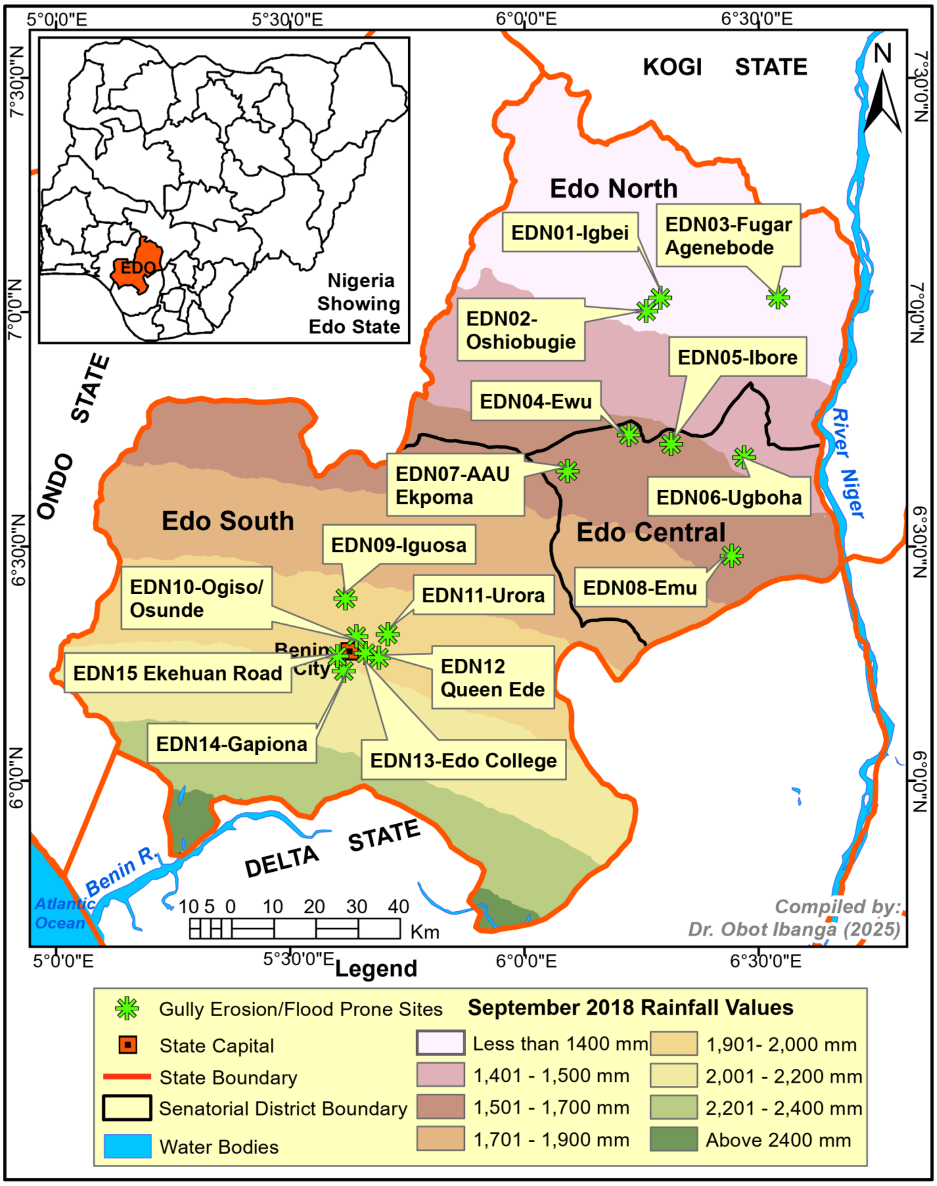


Figure 1. Edo State showing Hazards' Prone Sites and Rainfall as at September 2018.

Source: Author's Field Work.

2.2. Vegetation and Land Use

The vegetation in Edo State can be classified into three dominant groups. The southern belt is made up of three sub-classes comprising the saltwater and freshwater Swamps occupying a small portion of the riverine and estuarine axis of the Ovia Southeast and Ovia Southwest local Government areas. Some of the outstanding land use types in the area include farming, crop production, crude exploration, fishing, lumbering, hunting, and housing development. The vast land mass of the southern Edo ecological region, especially Benin City, Ikpoba-Okha, Oredo, and Egor, comprises the humid rainforest belt with alternate natural and derived forests. The land area provides unique opportunities for diverse agricultural practices, urbanization, housing, transportation, industrialization, military and paramilitary operations/services, infrastructural and amenities development.

The Edo Central is a transitional zone with mixed vegetation types, comprising more of rainforest vegetation and freshwater Swamps in Esan South and Esan West, while Esan Northeast is dominated by the traces of Guinea Savannah vegetation features. However, major socio-economic activities and land use types in the zone include distinct crop and allied agricultural production, housing, transportation, and infrastructural/amenities development. On the contrary, the Edo North is a zone with fairly homogenous Guinea Savannah vegetation that favours the growth of cereals, roots and tubers, fruits and vegetables. It is worth emphasizing that the disparities in vegetation and land use types across the eco-geomorphological zones in Edo State have a strong affinity with the uniqueness of the local climate, relief, soil, and geology.

2.3. Drainage, Relief, and Geology

The drainage and relief patterns across the distinct geomorphic hazards' vulnerable sites in Edo State depict elements of spatial variations and homogeneities as summarized in **Figure 2**, respectively. Generally, the drainage is dominated by dendritic patterns, which can be directly linked to the influence of normal erosion and geology (sedimentary formations) as reported in Ye and Wu [32]. By implication, the prevalence and vulnerability of geomorphic hazards in the study area are initiated by natural local geographic variables and accelerated by human indicators.

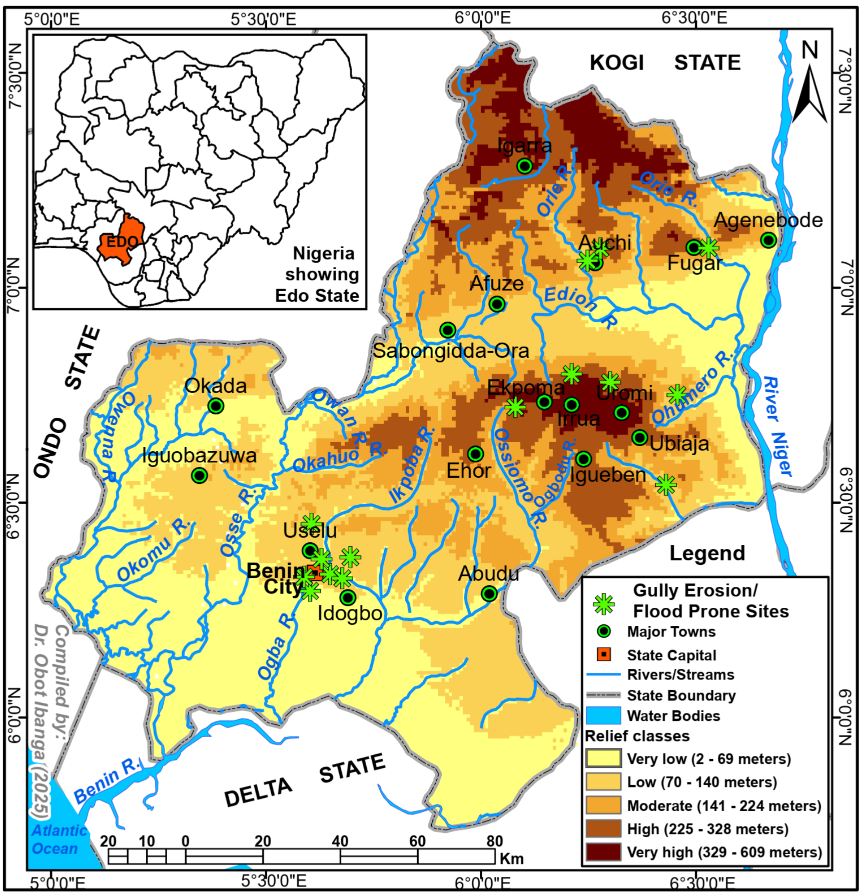


Figure 2. Relief and Drainage of Edo State.

Source: GIS Extraction from the Nigeria Geological Survey Agency Map Sheet 298 (2012).

The relief characteristics presented in **Figure 2** indicate that the highest range of 320–609 m above average mean sea level is associated with the boundary region of Edo North and Edo Central, where Rivers Orie, Edion, Owan, and Ohamero, Ossiomo divides exist. The elevations serve as divides for the highlighted Rivers and are highly vulnerable to diverse geomorphic hazards such as erosion, mass wasting, and weathering. On the contrary, the Edo South margin of the Benin River wetland and the Niger River wetland along Edo Central possess the lowest elevations of between 2 and 69 m above mean sea level, and are highly vulnerable to flood.

The geologic formations presented in **Figure 3** reveal dynamics in sequences across spaces. In Edo South, the erosional hazards' vulnerable sites have much affinity with the Coastal Plain Sand Deposits of Tertiary Times; those of Edo Central are converged within the Abeokuta Formation, while geomorphic hazards' vulnerability in Edo North is most dominant in the False-Bedded Rocks and Upper Coal (**Figure 3**). Retrospectively, younger geology formations (Coastal Plain Sand Deposits) are most vulnerable to geomorphic hazards in the State.

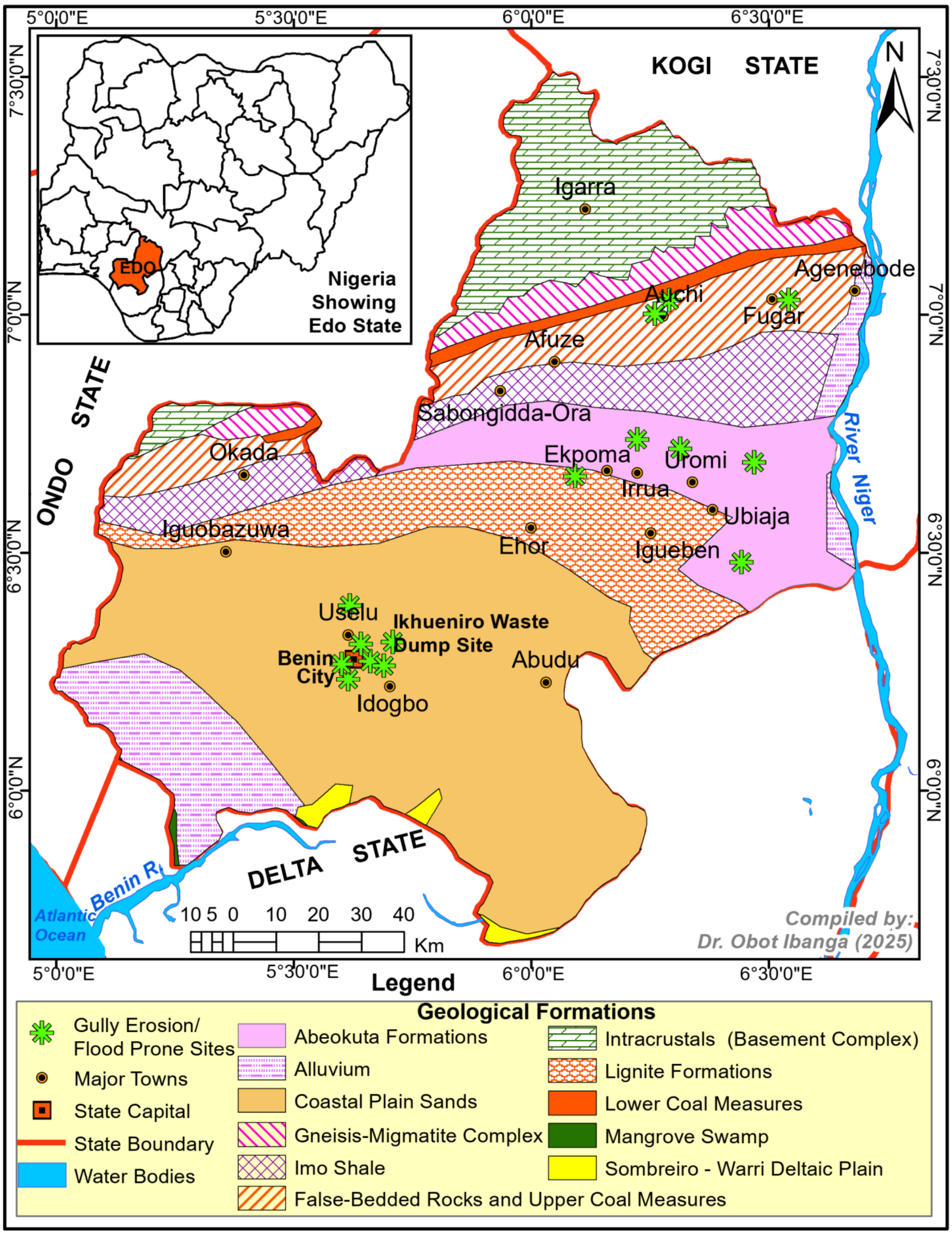


Figure 3. Geologic Formation of Edo State.

Source: GIS Extraction from the Nigeria Geological Survey Agency Map Sheet 298 (2012).

2.4. Reconnaissance Survey and Geomorphic Hazards' Sites' Demarcations

This study was preceded by a series of reconnaissance surveys backed by field work. Prior to soil sample collection, the study area was stratified into three distinct eco-geomorphological zones, comprising Edo South, Edo Central, and Edo North (see **Figure 1**) using geo-political boundaries and gully erosion/flood as indicators. A total of fifteen (15) hazards' vulnerable sites, comprising 12 gullies and 3 floods, with the recent catchment plans as enumerated in Ye and Wu [32] and **Figure 1**, respectively, were purposely selected. In each site, a set of soil samples was collected within the depth of 0–30 m using a soil core for granulometry and a soil auger for nutrients, and each coordinate was recorded using Global Positioning System (GPS) as described in recent studies [3,32–34]. The summary of soil granulometry, particulate matter, nutrients, and locations is presented in **Tables 1** and **2**, as well as **Figure 1**, respectively.

Table 1. Descriptive Statistics of Granulometry and Particulate Matters in Edo State.

S/N	Location	Sand (%)	Silt (%)	Clay (%)	Texture Class	Organ Carbon (%)	Organ Mat. (%)	Bulk Dens (g/cm^3)	M_C (%)	H_C_S	ECEC (Cmol/kg)
1	AAU	87.60	7.40	5.00	LS	1.23	2.12	0.00	0.00	0.00	9.45
2	Edo Coll.	65.60	11.40	23.00	SCL	0.53	0.92	1.12*	6.66	0.068	7.07
3	Ekenwa	65.60	15.40	19.00	SL	0.57	0.98	0.820	7.15	0.059	7.46
4	Emu	91.60	3.40	5.00	Sand	0.33	0.57	0.891	6.50	0.022	6.96
5	Ewu	87.60	5.40	7.00	LS	2.86*	4.94*	0.840	2.59	0.072	15.78
6	Fugar	93.60*	3.40	3.00	Sand	0.30	0.52	0.839	2.47	0.022	5.08
7	Capiona	71.60	17.4*	11.00	SL	1.30	2.24	0.887	3.36	0.067	23.7*
8	Igbei	93.60*	1.40	5.00	Sand	0.73	1.26	0.790	3.76	0.032	6.23
9	Igbore	93.60*	3.40	3.00	Sand	1.50	2.58	0.728	6.53	0.024	10.99
10	Iguosa	65.60	9.40	25.0*	SCL	0.23	0.40	0.916	9.50*	0.074	6.47
11	Ogizo	81.60	11.40	7.00	LS	1.67	2.87	0.902	4.74	0.062	11.52
12	Oshobugie	85.60	7.40	7.00	LS	0.93	1.61	0.851	1.83	0.083*	9.46
13	Ugbola	81.60	7.40	11.00	SL	2.17	3.73	0.783	5.06	0.070	20.79
14	Urora	83.60	5.40	11.00	LS	1.63	2.81	0.793	4.82	0.066	8.12
15	Queen Ede	89.60	3.40	7.00	LS	1.13	1.95	0.900	4.36	0.082	8.23
	Sum	**1238**	**113.0**	**149.0**		**7.11**	**29.5**	**12.06**	**69.33**	**0.803**	**157.37**
	Mean	**82.53**	**7.53**	**9.93**	**LS**	**1.14**	**1.97**	**0.861**	**4.952**	**0.057**	**10.49**

Note: * represents the highest value of granulometry and particulate matter in recorded in each location.
Source: Author's Analysis.

Table 2. Descriptive Evaluation of Soil Nutrients' Concentrations in Hazards Vulnerable Sites.

Location	N (%)	P (ppm)	K (Cmol/kg)	Ca (Cmol/kg)	Mg (Cmol/kg)	Na (mg/kg)	pH	BS (%)	EA (Cmol/kg)
AAU	0.113	27.60	0.120	5.60	2.80	0.131	0.60	91.55	0.80
Edo Coll.	0.056	18.10	0.106	3.60	1.60	0.087	5.10	76.28	1.68
Ekenwa	0.070	13.80	0.117	3.60	2.00	0.146	5.00	78.59	1.60
Emu	0.028	8.50	0.124	3.20	2.80	0.113	5.20	89.61	0.72
Ewu	0.210	*38.70*	*0.164*	10.00	4.80	*0.174*	0.20	*95.93*	0.64
Fugar	0.028	7.30	0.120	2.80	1.20	0.078	5.40	82.64	0.88
Capiona	0.140	30.00	0.122	*15.20*	*7.60*	0.121	*7.10*	96.98	0.72
Igbei	0.084	17.50	0.126	3.60	1.60	0.104	6.40	87.16	0.80
Igbore	0.156	33.10	0.148	6.40	3.60	0.128	6.90	93.69	0.72
Iguosa	0.042	6.50	0.125	2.80	1.60	0.109	5.50	71.62	*1.84*
Ogizo	0.140	27.30	0.146	6.80	3.60	*0.174*	6.10	93.06	0.80
Oshobugie	0.098	21.60	0.140	5.60	2.80	0.122	6.30	91.56	0.80
Ugbola	*0.280*	28.90	0.157	14.80	4.80	0.148	6.60	95.74	0.88
Urora	0.154	34.20	0.148	4.80	2.00	0.131	6.10	87.18	1.04
Queen Ede	0.098	24.00	0.117	4.80	2.40	0.113	6.30	90.28	0.80
Mean	0.113	22.473	0.132	6.240	3.013	0.125	5.99	88.125	0.981

Note: N_Nitrogrn; P_Phosphorus; K_Potassium; Ca_Calcium; Mg_Magnessium; Na_Sodium; BD_Bulk_Density; Measuring Units: % = percent; mg/kg = Milligrams per Kilogram; Cmol/kg = Centimoles per Kilogram.
Source: Author's Analysis.

2.5. Soil Sampled Collection and Analytical Methods

A set of three soil samples was collected during the peak rainy season at (the upper, middle, and lower parts of) each geomorphic hazard vulnerable site using a handheld soil auger for nutrient analyses and a soil core for granulometry/particulate matter concentrations. The collected samples were carefully packaged in black polythene bags, labelled, and stored in the cooler before transported to the National Laboratory for soil, plants, and water in Umudike, Abia State, for detailed treatments, processing, and laboratory analyses. The rationale was to ensure strict compliance with the approved standards of the global best practices in soil sample treatments and analyses. However, the parameters analyzed in the laboratory include sand, silt, and clay for granulometry; while nutrients and allied particulate matters encompass nitrogen (N), potassium (K), phosphorus (P), calcium (C), potential hydrogen (pH), magnesium (Mg), sodium (Na), exchangeable acidity (EA), organic matter (OM), organic carbon (OC), effective cation exchange capacity (ECEC), hydrolytic conductivity (HCS), bulk density (BD), microbial content (MC).

2.6. Analytical Methods for Data

The data collected from distinct sources were analyzed using descriptive and multivariate statistics. The descriptive statistics, such as means, bar charts, graphs, and percentages, were used for comparative assessment of the proportion of variable concentrations in soils at distinct geomorphic hazards vulnerable sites. The multivariate Analysis of Variance (MANOVA), which is an embodiment of Pillai's Trace, Wilks' Lambda, Hotelling's Trace, and Roy's Largest Root models, was employed as a surrogate for multiple tests of variations among the sequence of parameters in the series. A linear regression model was used to evaluate the proportion of variance between subjects in soil nutrients within the geomorphic hazards' vulnerable sites, while univariate analysis of variance was adopted for the test of variance between subjects in the series. The statistical analyses were performed using the Statistical Package for Social Sciences (SPSS) version 22.0. A test of statistical significance was done at a 95 percent confidence level.

3. Results and Discussions

The data generated from distinct sources were analyzed descriptively and inferentially, and the results are chronologically presented in the discussions that follow.

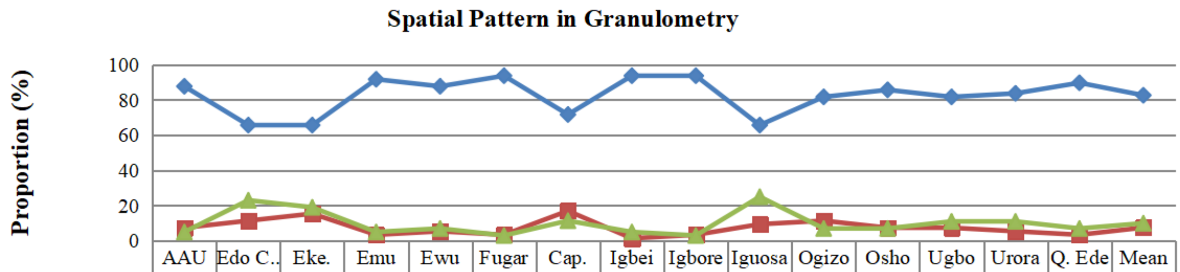
3.1. Descriptive Assessments of the Patterns in Granulometry and Particulate Matters

The results of the analyses of granulometry and particulate matter concentrations in soil within the geomorphic hazards' vulnerable sites are summarized in **Table 1**, **Figures 4** and **5**. The comparative evaluations of the patterns in the results indicate disparities based on the parameters, land use, and geographic locations. Contextually, the highest proportion of 93.60 percent for sand is recorded uniformly at Fugar, Igbei, and Igbore gully hazards vulnerable sites. Contrarily, the highest proportion of silt (17.40 percent) is recorded at the Capiona flood hazard vulnerable site, while the highest proportion of clay (19.40 percent) is associated with the Ekenwa gully erosion hazard's vulnerable site, as presented in **Figure 4** and **Table 1**. The results validate a report that the city's historical development, modern urbanization, and natural topography create a complex environment where the effects of anthropogenic activities are pronounced [20,23].

Further comparisons using extremely low concentrations of granulometry reveal that a value of 65.60 percent of sand is recorded homogenously at Edo College and Ekenwa gully hazard sites, respectively. For silt, a lowest value of 1.40 percent is recorded at Igbei hazard vulnerable site, while a least value of 5.00 percent for clay is registered at Ambrose Ali University gully site, Ekpoma. Retrospectively, the high silt contents in soils, coupled with fairly constant relief, impede water infiltration capacity and accelerate the level of land vulnerability to flood hazards. Contrarily, the high sand concentrations at Fugar, Igbei, and Igbore gully complexes can be associated with increased relief, geology, and human interferences through land use practices. The trend showed strong affirmation of Liu et al.'s [27] report on granulometry and particulate matter concentrations in the Kwa Iboe River Basin of southeastern Nigeria. The result also supports GHD's notion that, without intervention, geomorphological processes in the long term would damage water infrastructure, accelerate total suspended solids/bedload contributions to the downstream area of Toronto water treatment facilities, as well as increase risks to slope stability and public trails, loss of valley trees, and impacts to private property in Canada [27].

From the dimension of particulate matter concentrations, the results summarized in **Table 1** and **Figure 5** reveal differences in parameters across spaces. The organic carbon enrichment is most dominant in the Ewu hazard vulnerable site, with a value of 2.86 percent, while the highest value, 4.94 percent for organic matter content, is associated with the Ewu hazard vulnerable site. In the extreme low cases, the results in **Table 1** and

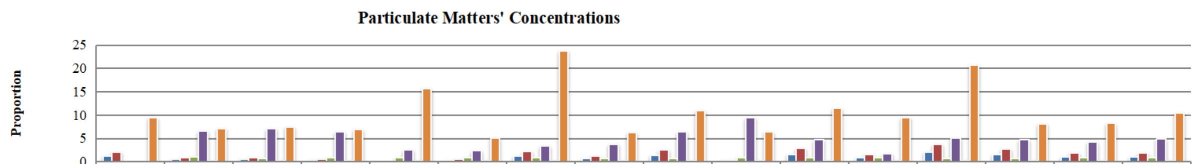
Figure 5 indicate that a least value of 0.23 percent for organic matter is recorded at Iguosa gully hazard site, while the least organic carbon content of 0.52 percent is registered at Fugar gully site.



	AAU	Edo C.	Eke.	Emu	Ewu	Fugar	Cap.	Igbei	Igbore	Iguosa	Ogizo	Osho	Ugbo	Urora	Q. Ede	Mean
Sand	87.6	65.6	65.6	91.6	87.6	93.6	71.6	93.6	93.6	65.6	81.6	85.6	81.6	83.6	89.6	82.53
Silt	7.4	11.4	15.4	3.4	5.4	3.4	17	1.4	3.4	9.4	11.4	7.4	7.4	5.4	3.4	7.51
Clay	5	23	19	5	7	3	11.4	5	3	25	7	7	11	11	7	9.96

Figure 4. Spatial Fluxes in Granulometry (Grain Sizes) across Hazards' Vulnerable Sites.

Source: Author's Analysis.



	AAU	Edo Coll.	Ekenwa	Emu	Ewu	Fugar	Capiona	Igbei	Igbore	Iguosa	Ogizo	Oshobugie	Ugbola	Urora	Queen Ede	Mean
O. C	1.23	0.53	0.57	0.33	0	0.3	1.3	0.73	1.5	0.23	1.67	0.93	2.17	1.63	1.13	1.14
OM	2.12	0.92	0.98	0.57	0	0.52	2.24	1.26	2.58	0.4	2.87	1.61	3.73	2.81	1.95	1.97
Bulk D	0	1.116	0.82	0.891	0.84	0.839	0.887	0.79	0.728	0.916	0.902	0.851	0.783	0.793	0.9	0.861
MC	0	6.66	7.15	6.5	2.59	2.47	3.36	3.76	6.53	9.5	4.74	1.83	5.06	4.82	4.36	4.952
HCS	0	0.068	0.059	0.022	0.072	0.022	0.067	0.032	0.024	0.074	0.062	0.083	0.07	0.066	0.082	0.057
ECEC	9.45	7.07	7.46	6.96	15.78	5.08	23.76	6.23	10.99	6.47	11.52	9.46	20.79	8.12	8.23	10.49

Figure 5. Spatial Fluxes in Particulate Matters' Distributions in Hazards' Vulnerable Sites.

Source: Author's Analysis.

The pattern of bulk density in the geomorphic hazard vulnerable sites depicts spatial fluxes, with a highest proportion of 1.116 percent recorded at the remediated Ambrose Ali University gully site, while the least value of 0.728 percent is associated with the Igbore hazard vulnerable site (**Table 1** and **Figure 5**). In the context of microbial contents, **Figure 3** indicates that a peak value of 9.50 percent is recorded at the Iguosa gully hazard site, while a threshold proportion of 1.83 percent is established at the Oshogbugie hazard vulnerable complex.

3.2. Descriptive Assessments of the Spatial Patterns in Soil Chemistry (Nutrients)

On the basis of soil nutrient concentration, the results of the laboratory analyses and their values are summarized in **Table 2**, **Figures 6–8**, respectively. From the results, it is clear that the patterns are highly dynamic, but with disparities based on geographic locations and parameters. Contextually, nitrogen enrichments in hazard-vulnerable sites were relatively moderate to low, with a peak value of 0.280 mg recorded at Ugbola and a least value of 0.028 mg recorded at the Fugar hazard-vulnerable site.

The climax value of the concentrations of phosphorus (22.473 ppm) is recorded consecutively at the Ewu gully hazard vulnerable site. Further comparisons of the results in **Table 2** indicate that the concentrations of calcium and magnesium were at their peaks at the Capiona flood hazard site, with the values of 15.20 and 7.60, respectively. The threshold values of 1.20 mg recorded at Fugar and their grand mean values for nitrogen, phosphorus, and potassium were 0.113, 38.70, and 0.164, respectively. On the contrary, the grand mean values for calcium and magnesium were 6.240 and 3.013, respectively (**Figure 6**), which suggests soil suitability for staple food crop production and very high prospects for sustainable and supportive agronomic remediation practices at each site as envisaged for the catchment management plan. A juxtaposition of the results with recent literature indicate that the differences in nutrient enrichments patterns portray in different locations closely conform the observation that human exploitative excesses such as agriculture, mining, urbanization, and infrastructural development[1–5], that exert pressure and negative feedback mechanisms on soil chemistry, decrease in soil nutrients such as nitrogen, phosphorus, potassium, and organic matter[30,31,35]. According to Yan et al.[31], promoting ecological agriculture and natural reserves is necessary.

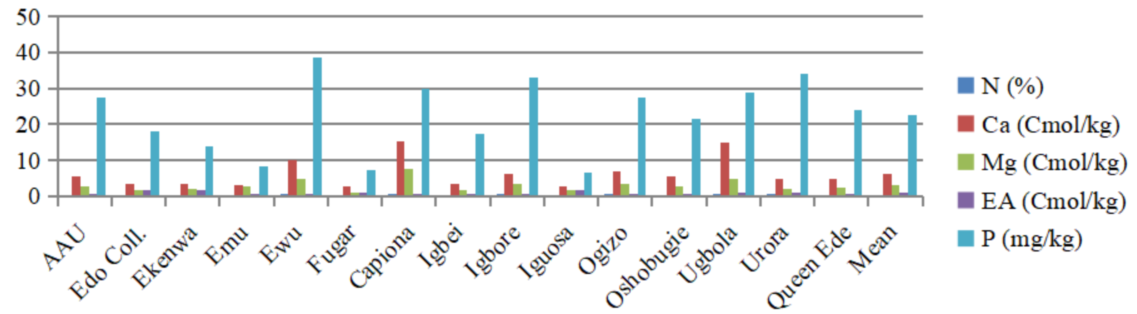


Figure 6. Analyses of the Fluxes in N, Ca, Mg, EA, and P in Hazards' Vulnerable Sites.

Source: Author's Analysis (2025).

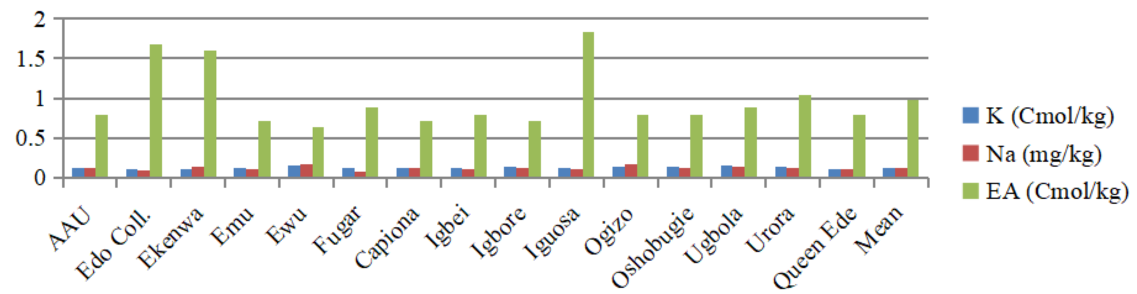


Figure 7. Analyses of Spatial Fluxes in K, Na, and EA in Geomorphic Hazards' Vulnerable Sites.

Source: Author's Analysis.

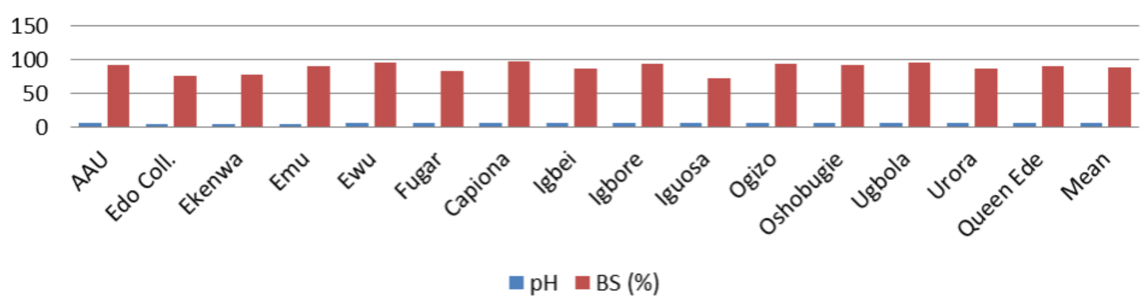


Figure 8. Analyses of the Fluxes in pH and BS Patterns in Geomorphic Hazards' Vulnerable Sites.

The results of the analyses of selected soil chemistry presented in **Figure 7** reveal spatial fluxes, with the most lethal value of 0.174 Cmol/kg for sodium is recorded homogenously at Ogizo and Ewu geomorphic hazards' vulnerable sites, while the most focal value of 0.164 Cmol/kg for potassium is recorded at Fugar geomorphic hazard vulnerable sites, respectively (**Table 2**). On the contrary, the lowest values of 0.078 Cmol/kg and 0.117 Cmol/kg are recorded for sodium and potassium at Fugar and Ekennwa gully vulnerable complexes as indicated in **Figure 7**. The low to moderate patterns in most soil nutrients' concentrations in the geomorphic hazards' vulnerable sites in Edo State conformed to World Science Forum [17] and Stewart et al. [18] notions that physical hazards affect soil quality, nutrient endowment, food security, and biodiversity.

The results of pH for soils in geomorphic hazards' vulnerable sites are summarized in **Table 2**, and **Figure 8** depicts disparities. Comparatively, the pH concentrations in geomorphic hazard vulnerable soils converge between a value of 7.10 for the highest recorded at Capiona flood vulnerable site and 5.00 for the lowest value recorded at Ekenwan gully site. However, the grand average concentration value of 5.99 recorded for the state clearly attests the dominance of slightly acidic to fairly neutral pH. Contextually, the fairly acidic soils at the Ekenwa, Emu, Ambrose Ali University (AAU), Iquosa, and Fugar geomorphic hazards vulnerable sites reveal increase potential deficit of primary nutrients such nitrogen, phosphorus, potassium, and manganese in the soil if proper remedial measures are not introduce by farmers and allied geomorphic hazard vulnerable land users to boost their future sustainability and protection. On the contrary, only the Capiona site exhibits a trace of fairly alkaline characteristics with a high value of 7.10 in the series (**Figure 8**). The oscillations in the results showed a relative affinity to Meena et al. [11] and Han et al. [30], observation that both geomorphological hazards' infestations and human intervention measures have major influences on the quality of the soil environment and the health of crops.

3.3. Test of Multiple Effects of Variations among Parameters in Hazards' Vulnerable Sites

To evaluate the pattern in soil nutrients and allied materials' variations across distinct geomorphic hazards' vulnerable sites in Edo State, MANOVA was employed and the results presented in **Table 3** revealed deviations based on complex statistical (Pillai's Trace, Hotelling's Trace, Wilks' Lambda, Roy's Largest Root, and ANOVA) models used and the corresponding results are chronologically presented in the discourses that follow.

Table 3. MANOVA Tests of Effect of Spatial Dynamics in Soil Nutrients Concentrations.

Test	Model	Value	F	Hypothesis df	Error df	Sig.
Hazard vulnerable sites	Pillai's Trace	3.158	1.500	40.00	16.000	0.192
	Wilks' Lambda	0.000	3.109	40.00	5.647	0.086
	Hotelling's Trace	13,868.621	3467.155	4.00	1.000	0.013*
	Roy's Largest Root	1850.015	740.006^{c}	10.00	4.000	0.000*

Note: a. Design: Intercept + Geomorphic hazard vulnerable sites; b. Exact statistic; c. The statistic is an upper bound on F that yields a lower bound on the significance level; * represents the highest value of granulometry and particulate matter in recorded in each location.

In the context of the degree of dynamism in sample size (test of homogeneity) among the groups of independent variables (geomorphic hazard vulnerable sites) on the multiple combinations of the seven dependent variables (soil nutrients and allied parameters) across Edo State, Pillai's Trace model was used. The model's results, presented in **Table 3**, offered a value of 3.158, but a relatively low F value of 1.500, which is statistically insignificant at 0.05. Thus, validating the uniformity of the group sizes. It is therefore declared that fluxes in geomorphic hazards' vulnerable sites in Edo State depict variations in soil nutrients/allied matters, but not contextually significant. This finding differs from Umo [4], Umo et al. [6], Grice and Iwasak [36], and Warne [37], dimensional affirmations of statistical significance variations. Such disparities in their findings can closely be attributed to differences in ideology, research interest, contexts, and/or method.

From the dimension of maximum matrix operation, Hotelling's Trace was adopted as a surrogate for the test of variations in the arrays of independent and dependent variables in Edo State. The Hotelling's Trace model gave a very high value of 13,868.621. A test of multiple effects of dynamism gave a very high F value of 3467.155, which is statistically significant at a 0.05 confidence level. The results led to an inference that spatial variations in geomorphic hazards' vulnerable sites have statistically significant effects on soil nutrient concentrations in Edo

State. The established pattern in the results collaborated with Umo and Enwereuzor [34] report in the humid tropical Rivers of Southeastern Nigeria, amidst the disparities in locations and contexts.

Wilk's Lambda model was employed to determine the proportion of variance in nutrients and allied materials' distributions on the linear combination of the dynamics in geomorphic hazards' vulnerable sites in Edo State. The results presented in **Table 3** depict disparities based on the statistical context. The Wilk's Lambda model gave a perfect calculated value of 0.000, which strongly affirmed Umo [4], Umo et al. [6], and Nath and Pavur [38] observations that a value of zero implies that there is no variance that is not explained by the independent variables. The result implies that both groups of variables contribute to the model's stability. A further probe of the result using Wilk's Lambda test of multivariate (combined) effect gave a low F value of 3.109, which is statistically insignificant at a 0.05 confidence level. It is therefore deduced from the result that oscillations in geomorphic hazards' vulnerable sites have no statistically significant multiple effects on the pattern in spatial enrichments of soil nutrients and allied materials concentrations in Edo State.

In another dimension, Roy's Largest Root is used to assess the association (strength of influence) among the arrays of (independent and dependent) variables because of its focus on the proportion of overlapping variance (influence) among the independent factors and the first linear combination of the dependent variables [3,5]. The model results presented in **Table 3** gave a high value of 1850.015 and a corresponding very high calculated F value of 740.06, which is statistically significant at a 0.000 confidence level. It is therefore established that variations in geomorphic hazards' vulnerable sites have statistically significant overlapping effects on the linear concentration of nutrients and allied material parameters in soils in Edo State.

3.4. Determination of the Proportion of Variances between Subjects in Hazards' Sites

In elucidating the effect variations between dependent variables (nutrients and allied parameters) on gully erosion and flood vulnerable sites (independent variables), regression models were used, and the results presented in **Table 4** depict disparities. The dimensional assessments of the result of the regression model reveal that phosphorus exhibited the highest Type III Sum of Squares value of 1057.529 and a corresponding highest mean squares value of 105.763, with a highest positive regression coefficient of 0.982. The model expresses 98.2 percent of the total variance in geomorphic hazards' vulnerable sites on the linear combinations of phosphorus concentrations in soil within the study.

Table 4. Test of Effects of Variations between Variables across Eco-geomorphologic Sites.

Source	Dependent Variable	Type III Sum of Squares	Df	Mean Square	R Square	F	Sig.
Corrected Model	Nitrogen	1.013^a	10	0.101	0.681	0.855	0.62
	Phosphorus	1057.629^b	10	105.763	0.982	21.041	0.03*
	Potassium	0.003^c	10	0.000	0.630	0.680	0.72
	Calcium	219.640	10	21.964	0.966	11.390	0.02*
	Magnesium	36.803	10	3.680	0.914	4.271	0.04*
	Sodium	0.180	10	0.018	0.213	0.109	0.99
	Organic_Content	5.783	10	0.578	0.847	2.207	0.23
	Organic_Matter	20.805	10	2.080	0.900	3.606	0.11

Note: a. Design: Intercept + Geomorphic hazard vulnerable sites; b. Exact statistic; c. The statistic is an upper bound on F that yields a lower bound on the significance level; * represents the highest value of granulometry and particulate matter in recorded in each location.
Source: Author's Analysis.

Calcium also possesses a high Type III Sum of Squares value of 219.640 with a high mean square of 21.964 and a very high positive regression coefficient of 0.966. The model accounted for 96.6 percent of the total variance explainable by changes in geomorphic hazards' vulnerable sites on the linear combination of calcium concentrations in soil within the study area. Further statistical assessment based on magnesium gave a high Type III Sum of Squares value of 36.803 with a mean square value of 3.680 and a very high regression coefficient of 0.914. The high coefficient of 0.914 implies that 91.4 percent of the total explainable variance in geomorphic hazards' vulnerable sites is attributed to the fluxes in magnesium concentrations in soil within the sampled locations in Edo State.

Contextually, organic matter in soil within the geomorphic hazards vulnerable site gave a high Type III Sum of Squares value of 20.805, with a mean square value of 2.080, and a very high positive regression coefficient of 0.900 in the series. This implied that a total of 90.0 percent of the proportion of variance in geomorphic hazards' vulnerable sites can be accounted for by spatial fluxes in magnesium concentrations in soils. A further juxtaposition of the results of regression models reveal that organic content and nitrogen concentrations in soil under geomorphic vulnerable sites in offer moderate Type III Sum of Squares values of 5.783 and 1.013, with mean square values of 2.080 and 0.101 and the high positive regression coefficients of 0.847 and 0.681 respectively. That means, while organic content in soil accounted for a total of 84.7 percent of the variance; nitrogen expressed 68.1 percent of the total of explainable variance in the sequence.

A further probe of the results in the context of potassium and sodium concentrations in soils yields the type III sum of squares values of 0.003 and 0.180, with the mean square values of 0.000 and 0.018. Their regression coefficients gave varying values of 0.630 and 0.213 in order, as reflected in **Table 4**. It is thus inferred from the results that, while potassium concentrations in soil accounted for 63.0 percent of the explainable variance, sodium concentrations in soil only expressed 21.3 percent of the proportion of variance in geomorphic hazards' vulnerable sites.

3.5. Tests of the Effects of Variations between Subjects in the Hazards' Vulnerable Sites

To test whether significant variations exist between each dependent variable on the linear combinations of each independent variable, an univariate ANOVA model was employed, and the results are summarized in **Table 4**, which depicts disparities based on the parameters tested for. The case-bound evidence drawn from **Table 4** reveals that only phosphorus, calcium, and magnesium possessed high calculated ANOVA values of 21.041, 11.390, and 4.271, respectively. Each calculated value is statistically significant at a 0.05 confidence level. It is therefore inferred from the results that there are statistically significant variations between the location of distinct geomorphic hazards, vulnerable sites, and the concentrations of phosphorus, calcium, and magnesium.

On the contrary, other viable nutrient parameters, notably nitrogen, potassium, sodium, organic matter, and organic content concentration in soil, were statistically insignificant amidst their vitality in staple crop productivity in soil. It is worth emphasizing that the statistical insignificance of the highlighted parameters does not necessarily mean that their spatial concentrations across the sampled geomorphic hazards' vulnerable sites in Edo State were below the threshold requirements for optimum plant growth and land capacity for sustainable agricultural production, but could be due to chance.

3.6. Implication of Findings of Geomorphic Hazard Vulnerable Site Utilization

The preceding discourses indicate that silt and clay contents were comparatively high in soils within the flood hazard vulnerable sites, coupled with fairly constant relief impede, whereas the sand class remained most focal in gully vulnerable sites. The highlighted attributes impede the water infiltration capacity of the soil and surface runoff, thereby accelerating the level of each site's vulnerability to flood hazards. The implication is that geomorphic hazards vulnerability in Edo State can partly be linked to localized natural forces, especially climate change-induced rainfall uncertainties, surface configuration, vegetation cover, and geology, as illustrated in literature across distinct locations [38–40]. But the bullying impacts of geomorphic hazards on the sustainable land protection and utilization are orchestrated by varying proportions of anthropocentric parasitism, such as land use practices for farming, urbanization, housing, road infrastructural development, grazing, lumbering, and hunting activities. A similar pattern collaborated Montgomery's observation that Rome possesses valuable geomorphological scenery for research because of its diverse array of anthropogenic landforms [41].

However, research linkages of an array of human-nature interactions, as well as rural people's understanding of the future impacts, are relatively low [42–44]. Further comparisons of perspectives from the literature indicate that integration of timber, horticultural crops, and multipurpose tree species within a unified spatial and temporal framework [45], to increase smallholder production for augmented social, economic, and environmental advantages [46]. Collaboratively, it is established that the agroforestry model is essential for farmers' well-being and ecological sustainability and restoration of degraded land forests, and supplying bioenergy [47]. Similarly, recent researches with keen interest on policy framework attest that the incorporation of multiple types of landscape management and nature protection will be sustainable if it is designed carefully to reflect the local context and institutional set-up [48–50].

The evaluation of patterns in nutrient concentrations clearly shows that generalized moderate mean contents within the Food and Agriculture Organization stipulated standards, with specific references to primary nutrients, notably nitrogen, phosphorus, potassium, calcium, and magnesium. The implication is that soil within the geomorphic hazards vulnerable zones in Edo converges between class A and B land with the dominant mean aggregate of Loamy-sand classification (**Table 1**), attesting their moderate to high suitability and utilization for diverse tropical agriculture such as cereals, root and tubers. However, increased vulnerability to erosion or flood hazards suggests the need for more proactive and issue-specific supportive remediation and conservation practices in the existing geomorphic hazards' vulnerable sites to avert gully rejuvenation. Such actions can boost sustainable management and utilization for staple crop production (e.g., cassava, yam, cocoyam, water yam, plantain, banana, tree crops, fruits, and vegetables) with outstanding historical benefits of sustaining the State and regional population.

4. Conclusions

The sequences of field survey and laboratory analyses indicated clearly that the occurrences and vulnerability of distinct sampled sites to gully erosion or flood hazards in Edo State are the amalgam of nature and human agents. However, the degree of vulnerability of each geomorphic hazard site differed across geographical locations due to the past, ongoing, and/or proposed remediation and mitigation (engineering and agronomic) efforts, as well as proactive community education and participation as envisaged in Ezemonye et al. [33] for the State. Such participatory actions, according to Harmáčková et al. and Odunuga et al. [50,51], will be useful in protecting farmers' livelihoods and the ecosystem.

The established pattern in the results are indications that the different past and continuing actions initiated and executed by the governments, donor agencies, communities, groups, and individuals to avert, manage, and/ or control geomorphic (erosion and flood) hazards at distinct sites had played vital role in facilitating the actualization of the United Nation Sustainable Development Goal 13, targets 1–3 that focus on climate change impact mitigations in the State. Similarly, Goal 15, Target 3, which focuses on the protection of ecosystems, land degradation, and biodiversity loss, is yielding positive impacts in Edo State, as shown in the patterns (homogeneities and diversities) of soil chemistry and granulometry. The recent adoption of distinct methods in different locations to actualize a sustainable watershed and catchment management plan for Edo State has boosted landforms, watersheds, and biodiversity protections in the hazard risk zones. This supports Ranjan et al. [42] observation that regenerative agriculture, which aims not only to alleviate ecological degradation and allied environmental problems, but also revitalize ecosystems and improve the well-being of communities.

This study established that the dispersals of soil nutrients and allied parameters between and among the hazards' vulnerable sites of geomorphic differed. Comparatively, a test of spatial variations led to the conclusion that some proportions of dynamism in geomorphic hazards' vulnerable sites have statistically insignificant effects on nutrients and allied matters' concentrations in Edo State (with respect to Pillai's Trace and Wilks' Lambda models). The results can be attributed to an increase in the promotion and sustainability of existing viable issue-based and place-centered remediation actions through collective commitments to boost natural soil nutrients enrichment and hazard-vulnerable land capability for sustainable selective agricultural production. The perspective is crucial given Thanuja et al.'s suggestion of the need for researchers to prioritize the integration of policy-driven interventions to enhance accessibility, and explore technological advancements that promote sustainable organic food consumption [49].

4.1. Recommendations

In consideration of the findings reached and the conclusion drawn in the course of this study, it is therefore recommend that:

(i) The past and ongoing geomorphic hazards (gully erosion and flood) impact mitigations and remediation efforts in most locations, such as Father Ede gully, Ekenwan gully, Urora flood, Gapiona flood, Iquosa gully, and Ambrose Ali University gully, are yielding positive results, especially the engineering and selective agronomic measures adopted. Yet, there is an urgent need for the proactive promotion and sustainability of community-based and place-centered geomorphic hazards, climate change education, and impacts mitigation/remediation through conversion of such vulnerable sites to viable demonstration farms.

(ii) Government, donor agencies, and the community should synergize and direct more efforts to community-based capacity building, promotion of conservative agricultural land use, and other developmental purposes in the geomorphic hazards' (e.g., erosion and flood) vulnerable sites to reduce the negative impacts on landforms (ecosystem) and people. Conservative land uses (e.g., biological, mechanical methods) hold high potential to boost ecosystem services, reduce biodiversity loss, aid natural soil nutrient replenishments, reduce surface water pollution, mitigate extreme oscillations in climatic variables, and prevent silting of rivers and/or their tributaries.

(iii) There are existing Rules, Regulations, and Laws guiding people's utilization of land, forest, and allied ecosystem resources at the international, regional, National, and local levels. Within the gullies and flood-vulnerable and remediated sites in Edo State, there is an urgent need for strict follow-up to monitor community compliance and implementation of those guidelines. Such actions will help to avert the people's exploitative excesses on land and allied resources, while offenders need to be punished accordingly, to deter others from indulging in such unlawful acts.

4.2. Limitations and Suggestion for Further Studies

The study focuses on fifteen major geomorphic hazards' vulnerable sites in Edo State only, thereby creating a need for future researchers to integrate both minor and major geomorphic hazards' vulnerable sites. Such actions will offer alternative avenues of statistical modelling and result in the generalization of the dynamics in nutrients, granulometry, and particulate matter.

Dimensionally, this study employs a descriptive design that presents an overview of phenomena during the peak rainy season only. There is a need for future researchers to adopt a cross-sectional/longitudinal design in sample collection across climatic seasons, backed by more quantitative and geospatial analyses to strengthen the understanding of hazard-driven dynamics at the regional scale.

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Conflicts of Interest

The author declares no conflict of interest.

Appendix A

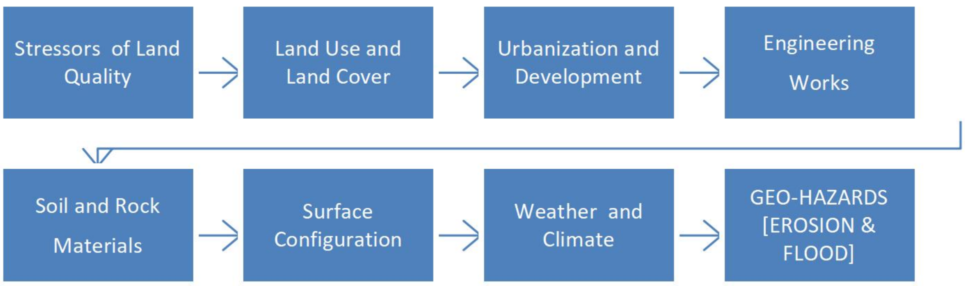

Figure A1. Hypothetical Model of Drivers of Land Vulnerability to Geomorphic Hazards.

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