



INTEGRATED MULTI-INDEX EVALUATION OF STRUCTURAL VULNERABILITY AND ENVIRONMENTAL QUALITY IN ERODING COASTAL SOILS OF BAYELSA STATE, NIGERIA

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ABSTRACT

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Soil structural stability is a key determinant of erosion resistance, environmental quality, and sustainable land use in coastal ecosystems. This study assessed the structural vulnerability and environmental quality of selected erosion-prone coastal soils in Bayelsa State, Nigeria, using an integrated multi-index evaluation approach. Soil samples (0–20 cm) were obtained from fifteen riverine communities located within Yenagoa, Ogbia, and Southern Ijaw Local Government Areas. Soil structural quality was assessed using dry-stable aggregates (DSA), water-stable aggregates (WSA), mean weight diameter (MWD), geometric mean diameter (GMD), potential structural deformation index (PSDI), water stability index (WSI), aggregate stability ratio (ASR), and aggregate stability index (ASI). The evaluated indices were subsequently integrated into an Environmental Quality Index (EQI) to enable comparison among the study locations. The results revealed considerable spatial variability in soil structural properties across the study locations. DSA and WSA values ranged from 33.08 to 63.30 % and from 31.61 to 43.09%, respectively, suggesting moderate susceptibility to structural degradation and water erosion. The wet mean weight diameter (MWD_w) and PSDI values suggested varying degrees of vulnerability to slaking and structural deformation under intense rainfall conditions. EQI ranking identified Tariladei, Ikpetiama, and Agbura as structurally resilient soils, whereas Amassoma, Igeibiri, and Angiama were more susceptible to degradation. The findings demonstrate that the multi-index approach is effective for evaluating soil structural condition and prioritizing conservation interventions in the dynamic coastal environments of the Niger Delta.

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INTRODUCTION

Sustainable soil management remains central to food security and environmental resilience for the projected 9.3 billion global population by 2050 (United Nations [U.N], 2024). Coastal ecosystems in the Niger Delta, particularly within Bayelsa State, represent some of the most ecologically sensitive yet anthropogenically pressured regions in West Africa. Soils in these environments play critical roles in nutrient cycling, agriculture, habitat provision, and filtration of

contaminants (Agbeshie *et al.*, 2025). However, rapid urbanization, unsustainable land use, sand mining and oil exploration have intensified environmental degradation (Figure 1) (Ogbonna *et al.*, 2020; Olukaejire *et al.*, 2024). The stripping of vegetation and topsoil through extractive and industrial activities has accelerated soil erosion (Figure 2) and destabilized soil aggregates (Onyeabor and Onyeabor, 2025; Bronick and Lal, 2005). These stressors are further aggravated by climate change events such as flooding, rising sea levels, and intense rainfall (Amaefule *et al.*, 2023), that pose a direct threat to soil structural integrity.



Figure (1a): Sand mining in the area



Figure (1b): Contaminated farm land



Figure (1c): Oil leak from a flow station in Bayelsa State

Figure (1). Land degradation as a result of human activities in the area.

In humid tropical environments, structural stability is a key determinant of erosion resistance (Igwe *et al.*, 2013). Soil aggregates influence water infiltration, moisture retention, aeration, microbial activity, and resistance to erosive forces (Yang *et al.*, 2025). Aggregate breakdown promotes nutrient depletion, crust formation, slaking, and increased runoff (Usman, *et al.*, 2025). These processes are more alarming under intense rainfall, seasonal flooding (Barthès and Roose, 2002), tidal influences and fluctuating groundwater levels that characterize coastal ecosystem (Dike *et al.*, 2024). Reliance on a single indicator may not fully represent the overall structural condition (Six *et al.*, (2000), hence, integrated assessment frameworks are

needed for a more comprehensive evaluation of soil structural condition (Agbeshie *et al.*, 2025).

Despite the critical environmental and agricultural roles of coastal soils, systemic evaluation of their structural integrity using integrated indices remains limited (Ashioba and Udom, 2023). Therefore, this study is aimed to assess structural vulnerability and develop an environmental quality index (EQI) of selected erosion-prone coastal soils in Bayelsa State, Nigeria. Specifically, the objectives were to determine selected structural indices, integrate these indicators into an EQI for site ranking and provide management recommendations based on the findings.



Figure (2). Soil erosion occurring on the area.

MATERIALS AND METHODS

Study Location

This study was conducted in three Local Government Areas of Bayelsa State, Nigeria: Southern Ijaw (4.4693° N, 6.0704° E), Ogbia (4.6251° N, 6.3176° E), and Yenagoa (4.9267° N, 6.3644° E). The soils of the area are underlain by unconsolidated Quaternary deposits derived from the Niger River and its tributaries. These deposits consist mainly of sand, silt, clay, and peat, with variations in depth and composition across locations (Joseph *et al.*, 2019). Geologically, the area is characterized by flat terrain with extensive freshwater swamps, meander belts, and alluvial floodplains. Clay shale predominates in the area, reflecting the typical wetland environment of the Niger Delta region (Reyment, 1965).

The study area is characterized by a humid tropical monsoon climate with a bimodal rainfall distribution. Peak rainfall periods occur from April to July and from September to November, while annual precipitation exceeds 2,500 mm (Okoro and Oforu, 2025). Mean annual temperature ranges between 25°C and 32°C and is influenced by the proximity of the Atlantic Ocean.

Land use within the study area, is influenced by both natural and anthropogenic factors. Major human activities include crude oil exploration, deforestation, agriculture, and urbanization. The local population predominantly

depends on subsistence farming and fishing for livelihood. Major crops cultivated in the area include rice, yam, cassava, plantain, and sugarcane.

Field Study

Prior to soil sampling, a reconnaissance survey was conducted in the field to locate the site using the location map (Figure 3). Soil samples (0 - 20 cm) were collected from cassava-based farms to minimize land-use variability. Fifteen communities (five per LGA) were sampled with three replicates per location resulting in 45 composite samples. Collected samples were properly labeled, air-dried, transported to the Soil Science laboratory at the Federal University of Technology Owerri, for analysis. A stratified random sampling design was adopted for data collection across the three strata (LGAs). The essence of the stratification was to capture spatial variability in soil and environmental characteristics across the state.



Figure (3). Location map of the study area.

Laboratory Analyses

Determination of dry- and water-stable aggregates

Aggregate stability was evaluated using standard wet and dry sieving procedures following the methods of Nimmo and Perkins (2002) and Kemper and Rosenau (1986). Dry and wet greater than 0.25 mm were quantified as the proportion of aggregates mass retained after mechanical agitation under air-dry and submerged conditions, respectively. The WSA was classified into low (<30%), moderate (30-50%), and high (>50%) categories. High percentages of WSA indicate higher resistance to rainfall impact, improved infiltration rates, and stable soil structure, while low percentages (<30%) indicate susceptibility to crusting, erosion, and poor hydrological functioning (Le Bissonnais, 1996; Nimmo, 2004; Bronick and Lal, 2005). Dry and wet mean weight diameters (MWD) were calculated following the procedure outlined by Kemper and Rosenau (1986) using the expression:

$$MWD = \Sigma (Di \times Wi), \dots (Eq. 1)$$

Where Di represents the mean diameter of each aggregate size fraction and Wi denotes the proportion of aggregates retained in each fraction

Potential Structural Deformation Index (PSDI)

PSDI, which provides a measure of the extent of aggregate structural breakdown due to water stress was computed with:

$$PSDI (\%) = 1 - [MWD_w / MWD_d] \times 100 \dots (Eq. 2)$$

As described by Igwe and Nwokocha (2005). Agbede, (2009) ranked PSDI values below 25% as a low risk of deformation, 25–35% as moderate susceptibility, and values over 35% suggest high vulnerability to structural breakdown.

Aggregate Stability Index (ASI)

Which quantifies aggregate stability based on weight distribution across sieves (Nimmo and Perkins, 2002) was computed using the procedure of (Kemper and Rosenau, 1986) as the ratio of WSA to DSA. According to (Loaiza- Usuga, et al., 2025), the ASI is considered to have high stability if it is above 70%, moderate stability if it is between 50-70%, and poor if it is below 50%.

Water Stability Index (WSI)

The Water Stability Index (WSI), which evaluates the resistance of soil aggregates to breakdown under wet conditions, was calculated according to the method of Franzluebbers *et al.* (2000) using the expression:

$$WSI = (WSA / DSA) \times 100 \dots (Eq. 3)$$

Where WSA represents water-stable aggregates and DSA represents dry-stable aggregates. According to Igwe *et al.* (2013), WSI values greater than 85% indicate very stable soils, values between 70–85% indicate moderate to high stability, while values below 70% suggest low structural stability.

Aggregate Stability Ratio (ASR)

The Aggregate Stability Ratio (ASR) was used to evaluate the proportion of water-stable aggregates relative to dry-stable aggregates following the procedure described by Pieri (1992) using the expression:

$$ASR = \frac{\text{Weight of water stable aggregates}}{\text{Weight of drystable aggregates}} \dots \text{(Eq. 4)}$$

ASR values commonly range from 0 to 1, with higher values indicating greater resistance of soil aggregates to structural breakdown and improved soil stability (Okeke *et al.*, 2019).

Environmental Quality Index (EQI)

All aggregated related parameters were standardized and normalized to remove scale differences. The normalized values were integrated into an additive model to produce an Environmental Quality Index (EQI) (Pieri 1992) for each site.

$$EQI = \frac{X_1 + X_2 + \dots + X_6}{6} \dots \text{(Eq. 5)}$$

Where: X_1 to X_6 represent the normalized values of each aggregate stability index.

Data Analysis

Data obtained from the study were subjected to Analysis of Variance (ANOVA) to evaluate differences among treatments and locations. Mean separation was carried out using Fisher's Least Significant Difference (LSD) test at the 5% probability level

RESULTS AND DISCUSSION

Dry Stable Aggregates (DSA > 0.25 mm)

Results of aggregate stability are presented in Table 1. Dry stable aggregates (DSA) showed significant spatial variation ($P < 0.05$) among the study locations, with a mean value of 52.06%. The highest DSA value (63.30%) was recorded in Ogbia, while the lowest (33.08%) occurred in Tariladei. In Yenagoa LGA, soils of Ogbogoro (63.30%), Akaba (58.31%), Gbarama (53.95%), and Ikpetiama (52.21%) were rated high, while those in Kpansia (49.90%) were rated moderate, based on (United States Department of Agriculture [USDA] 2008; Nimmo, 2004) classifications. These values indicate high structural stability under dry conditions. The results indicate that the soils are well-aggregated, probably because of the high clay content and organic matter that improve structural stability (Bronick and Lal, 2005; Tisdall and Oades, 1982). High dry aggregate stability encourages favorable environments for water infiltration, aeration, microbial activity, and mechanical strength. Similarly, soils in Ogbia LGA had high dry aggregate stability values, ranging from 51.74% at Otuokpoti to 54.70% at Otuogori. These values were relatively similar and suggest a well-developed and stable soil structure under dry conditions (Igwe *et al.*, 2013). This stability may be associated with low tillage intensity and favorable interactions between soil minerals and organic matter (Six *et al.*, 2000). Conversely, the soil of Southern Ijaw LGA showed greater variability in dry aggregate stability. Although some areas like Igeibiri (55.61%), Aguobiri (54.58%), and Angiama (53.06%) had high stability, others like Amassoma (42.89%) and Tariladei (33.08%) had moderate stability. The moderate stability indicates a degree of soil structural degradation, which may be a result of low organic input, high sand content, and human activities, and thus requires conservation measures. In comparing the DSA data among the local governments, the trend: Yenagoa > Ogbia > Southern Ijaw was observed (Figure 4). The variation among the local governments emphasizes the need for location-specific

soil management, especially in areas with moderate stability such as Tariladei and Amassoma. The suggested measures include the use of organic residues, cover cropping, and reduced tillage to promote soil aggregate stability and reduce the risk of erosion.

The observed variability in the values of dry and wet stability indices at some sites indicates that cohesion is likely dominated by temporary cementing agents.

Table (1). Structural vulnerability Indices of the Studied Soil.

Location	DSA >0.25 mm (%)	Wsa >0.25 mm (%)	MWD (dry) (mm)	MWD (wet) (mm)	GMD (wet) (mm)	GMD (Dry) (mm)	PSDI (%)	WSI (%)	ASR	ASI (%)
Yenagoa										
KPA	49.90	31.61	0.50	0.32	0.29	0.42	36.00	79.80	0.61	63.36
OGB	63.30	33.85	0.63	0.34	0.31	0.55	46.70	81.97	0.69	53.49
GBA	53.95	35.84	0.54	0.36	0.32	0.46	33.40	71.52	0.72	66.61
IKP	52.21	33.05	0.52	0.33	0.30	0.45	37.70	86.50	0.89	64.24
AKB	58.31	38.23	0.58	0.38	0.33	0.50	35.00	76.78	0.79	65.49
LSD 0.05	0.53*	0.21*	NS	0.03*	0.16*	0.05*	0.18*	3.89 ^{NS}	0.02*	2.98*
Ogbia										
AGB	53.01	34.97	0.53	0.35	0.31	0.46	33.4	82.36	0.91	67.62
ONE	52.50	41.69	0.52	0.42	0.38	0.45	20.00	78.67	0.52	79.28
OUT	54.70	37.88	0.55	0.38	0.35	0.47	31.00	87.81	0.73	69.36
OTK	52.05	37.15	0.52	0.37	0.33	0.45	28.90	81.17	0.41	72.15
OTB	51.74	40.93	0.52	0.41	0.38	0.44	21.20	93.30	0.68	79.60
LSD 0.05	1.67*	2.21*	0.65*	0.06*	0.32*	0.15*	0.21*	2.92*	0.12*	3.29*
Southern Ijaw										
IGE	55.61	42.79	0.56	0.43	0.38	0.48	23.30	89.12	0.48	77.01
TAR	33.08	42.17	0.33	0.42	0.38	0.30	27.27	85.14	0.56	98.49
AGUOBIRI	54.58	32.95	0.55	0.33	0.30	0.47	40.00	71.71	0.60	60.49
AMA	42.89	34.26	0.43	0.34	0.31	0.37	21.00	68.98	0.52	82.43
ANG	53.06	43.09	0.53	0.43	0.38	0.45	18.90	71.68	0.31	82.34
LSD 0.0	1.89*	2.56 ^{NS}	0.11*	0.09*	0.01*	0.02*	0.07*	2.18*	1.00*	3.89*
Grand mean	52.06	37.36	0.52	0.38	0.34	0.45	30.25	81.36	0.63	73.88
LSD 0.05	5.79	5.79 NS	0.058 *	0.032 *	0.02*	0.04*	0.01*	5.8 ^{NS} NS	2.943 NS	13.274*

KPA = Kpansia; OGB = Ogbogoro; GBA = Gbarama; IKP = Ikpetiama; AKB = Akaba; AGB = Agbura; ONE = Oneubum; OTU = Otuogori; OTK = Otuokpoti; OTB = Otuoba; TAR = Tariladei; AMA = Amassoma; ANG = Angiama, IGE = Igeibiri; GMD = geometric mean diameter; DSA = dry stable aggregates; WSA = water-stable aggregates; MWDd = mean weight diameter (dry aggregates); MWDw = mean weight diameter (wet aggregates); PSDI = potential structural deformation index (wet aggregates); WSI = water stability index; ASR = aggregate stability ratio; ASI = aggregate stability index. *Significant; NS = not significant; p = probability level at 5%; LSD (0.05) = least significant difference used for comparison among locations.

Water Stable Aggregates (WSA > 0.25 mm)

Moderate WSA contents were recorded in all three LGAs, but with different proportions within each LGA. In Yenagoa, values ranged from 31.61% in Kpansia to 38.23% in Akaba, with a mean of 34.51%. In Ogbia, soils showed slightly better water

stability, with WSA ranging from 34.97% in Agbura to 41.69% in Oneubum, averaging 38.53%. These values though of moderate stability, still require improvement through enhanced organic matter management and protective cover practices (Bronick and Lal, 2005). The results of Ogbia, though still within the moderate category, trend toward the upper threshold, indicating relatively well-developed soil structure potentially due to higher biological activity, finer soil textures, and stable organic-mineral linkages (Six *et al.*, 2000). Soils from Southern Ijaw showed the widest range in WSA, from 32.95% at Aguobiri to 43.09% at Angiama, with a mean of 37.36 %. The observed WSA > 0.25 mm trend across the local governments: Southern Ijaw > Ogbia > Yenagoa (Figure 4), suggests differences in land use intensity, soil texture, and organic amendments inputs (Six *et al.*, 2000). It is worthy of note that, frequent and intense rainfall events place substantial stress on soil aggregates in humid tropics that soils with moderate WSA can undergo structural breakdown, leading to surface crusting, reduced water infiltration, and increased erosion. As such, soil conservation practices like the addition of organic matter, development of cover crops, and reduced tillage are advocated as ways of improving aggregate stability under water stress conditions (Bronick and Lal, 2005).

Mean Weight Diameter (MWD)

The dry MWD (MWDd) values in Yenagoa, varied from 0.50 mm to 0.63 mm, while the average value was above 0.55 mm, which is an indication of highly stable aggregates (Agbede, 2009; Reike *et al.*, 2022). However, the wet MWD (MWDw) values were between 0.32 mm and 0.38 mm, which is a reflection of moderate aggregate stability, possibly showing the susceptibility of the soil to slaking during heavy rainfall. In Ogbia, the dry MWD values were between 0.52 mm and 0.55 mm, while the wet MWD values were between 0.35 mm and 0.42 mm. The slightly higher wet MWD values compared to Yenagoa indicate higher bonding between the aggregates and their resistance to both mechanical and hydrological forces, possibly as a result of enhanced organic matter and clay interactions. Southern Ijaw had the highest variability. The dry mean weight diameter (MWDd) ranged from 0.33 mm in Tariladei to 0.56 mm in Igeibiri, while wet mean weight diameter (MWDw) varied between 0.33 mm and 0.43 mm across the study sites. Sites such as Igeibiri and Angiama approached the upper limit of aggregate stability. Across the LGAs, MWDd followed the order Southern Ijaw > Yenagoa > Ogbia, whereas MWDw followed the sequence Ogbia > Southern Ijaw > Yenagoa (Figure 5). These spatial differences likely reflect variations in soil texture, organic matter content, and levels of anthropogenic disturbance (Agbede, 2009). The relatively low MWD observed in Tariladei suggests greater susceptibility to surface crusting and reduced water infiltration under environmental stress. In tropical soils, Six *et al.* (2000) reported that macro-aggregate stability is strongly influenced by micro-aggregate formation processes driven by fungal activity and stable organic carbon fractions. The low wet mean weight diameter (MWDw) values in Table 1 indicate a low level of protection and possible depletion in micro aggregates and stable carbon.

Potential structural deformation index

The potential structural deformation index (PSDI) values in Yenagoa ranged from 33.4 to 46.7% in Gbarama and Ogbogoro (Table 1) respectively, placing most soils in the moderate to high-risk category. This structural weakness emphasizes the immediate need for conservation practices such as incorporating organic matter, retaining residues, and reducing tillage. In Ogbia, PSDI values ranged from 20.00 % (Oneubum) to 33.4% (Agbura), placing the soil in the moderate deformation category. These values indicate more cohesive aggregates and a higher degree of structural resistance, possibly as a result of effective land use, greater organic matter, or favorable textural conditions (Nimmo and Perkins 2002). A broader range of values, from 18.9% (Angiama) to 40.0% (Aguobiri) were recorded in Southern Ijaw. Although Aguobiri was in the high deformation group, the majority of the soils were of low to moderate susceptibility. In the comparison of the PSDI values across the LGAs, the following order was observed: Southern Ijaw < Ogbia < Yenagoa (Figure 6). This indicates that the soils of southern Ijaw soil exhibited the lowest deformation among other LGAs. Areas such as Ogbogoro and Aguobiri, which experienced higher values of PSDI, could be witnessing progressive structural degradation as a result of hydrological and land use changes. The lower values of PSDI in Southern Ijaw could be indicative of higher resistance to structural collapse as a result of better vegetative cover and sediment composition.

Water Stability Index (WSI)

Results presented in Table 1 showed that the water stability index (WSI) values were between 71.52 % at Gbarama and 86.50% at Ikpetiama, showing that most of the soil types in the area are of moderate to high stability as indicated by (Igwe *et al.*, 2013). The high WSI at Ikpetiama indicates high resistance to disintegration by water, possibly due to favorable organic matter, texture, or type of clay minerals. On the other hand, the low WSI at Gbarama implied high susceptibility to disintegration during heavy rainfall. In Ogbia, the WSI values ranged from 78.67% at Oneubum to 93.30% at Otuoba, indicating high to very high levels of water-stable aggregates. Areas such as Otuoba and Agbura, which have values above the 85% threshold, are most likely benefiting from practices such as minimal tillage and increased organic carbon input, which are factors that improve aggregate cohesion and decrease erosion potential. In Southern Ijaw, the values of WSI ranged from 68.98% at Amassoma to 89.12% at Igeibiri. Areas such as Amassoma and Angiama, which have WSI \leq 70%, are less stable and are likely to have structural failure and surface runoff. In comparing the three Local government Areas (LGAs), in terms WSI, the order of Ogbia > Yenagoa > Southern Ijaw was observed (Figure 7). This is most likely due to differences in organic matter input, land use, and microclimate. Regardless of the result obtained, areas with low WSI need soil improvement practices such as compost, biochar, and vegetation to improve water stability and decrease erosive loss (Barthes and Roose, 2002).

Aggregate Stability Ratio (ASR)

Based on the classification by Okeke *et al.*, (2019), soil is said to be highly stable if ASR is above 0.7, moderately stable if between 0.5 and 0.7, and poorly stable if below 0.5. Extending this to the results, soils in Yenagoa:Ikpetiama (0.89) and Akaba (0.79). Table 1, show high structural strength against mechanical disruption,

which is most likely attributed to the availability of organic matter and favorable soil texture (Locatelli *et al.*, 2023). Areas with high ASR values, especially, may particularly require less natural binding agents and low biological activity. In Ogbia, the values of ASR showed a large range, from 0.41 to 0.91 in Otuokpoti and Agbura respectively. Soil under Otuokpoti (0.41) was below the 0.5 mark, indicating low aggregate strength, low aggregate resistance and high susceptibility to mechanical disruption by high rainfall, land use pattern, and tillage (Xiao *et al.*, 2025). Organic mulching or composting may be site-specific approaches that could be used to improve soil structure in this area. Southern Ijaw had the lowest mean ASR, with site values between 0.31 and 0.60 in Angiama and Aguobiri respectively. Areas such as Angiama and Amassoma had values well below 0.5, which made them prone to degradation by wetting or tillage than others. Such conditions may lead to crusting, runoff, and poor infiltration, especially during the high rainfall events characteristic of the Niger Delta. The ASR followed the ascending order: Angiama < Otuokpoti < Igeibiri < Oneubum = Amassoma < Tariladei < Aguobiri < Kpansia < Otuoba < Ogbogoro < Gbarama < Otuogori < Akaba < Ikpetiama < Agbura. Result obtained (Figure 8), revealed that soil in Yenagoa was generally more stable in physical properties, while that in Southern Ijaw was very unstable and required better management approaches to improve its structure and reduce erosion potential (Loaiza- Usuga *et al.*, 2025).

Aggregate Stability Index (ASI)

In Yenagoa, the ASI was generally moderate, with values ranging from 53.49% at Ogbogoro to 66.61% at Gbarama. This indicates that while the soil structure is relatively stable, it could be made even better, particularly in areas such as Ogbogoro, which is relatively closer to the lower limit. Addition of organic matter would be beneficial in improving aggregate stability during intense rainfall (Bashir *et al.*, 2025). In Ogbia, the ASI was generally higher, ranging from 67.62% to 79.60%, with an average of 73.06%. This indicates that the area has high structural stability. This is likely due to the good interaction between clay and organic matter, as well as to possibly good land-use practices that help maintain or improve soil cohesion (Guiwan *et al.*, 2026). This makes the soil less prone to erosion and ensures better water flow, hence more sustainable land use. Southern Ijaw LGA had a broader range of ASI values, from 60.49% at Aguobiri to an exceptionally high 98.49% at Tariladei, with an average of 73.88%. This indicates that, despite the high average, there is variation: although some soils are stable, others, such as Aguobiri, are close to moderate stability. The very high value recorded at Tariladei could be attributed to a variety of favorable factors, such as high vegetation, undisturbed soil, or the addition of organic matter (Udoh *et al.*, 2016). The ASI of the soil follows the ascending order; Ogbogoro < Kpansia < Aguobiri < Ikpetiama < Akaba < Gbarama < Agbura < Otuogori < Otuokpoti < Igeibiri < Oneubum < Otuoba < Angiama < Amassoma < Tariladei. In the comparison of the LGAs, the trend: Ogbia > Southern Ijaw > Yenagoa (Figure 9) where observed, showing the actual differences in the soil aggregate stability. This further supports the importance of localized approaches to soil management, especially in areas of moderate stability, such as parts of Yenagoa, where approaches such as organic matter addition, residue retention, (Igwe *et al.*, 2013) and reduced tillage is beneficial in increasing stability (Guiwan *et al.*, 2026).

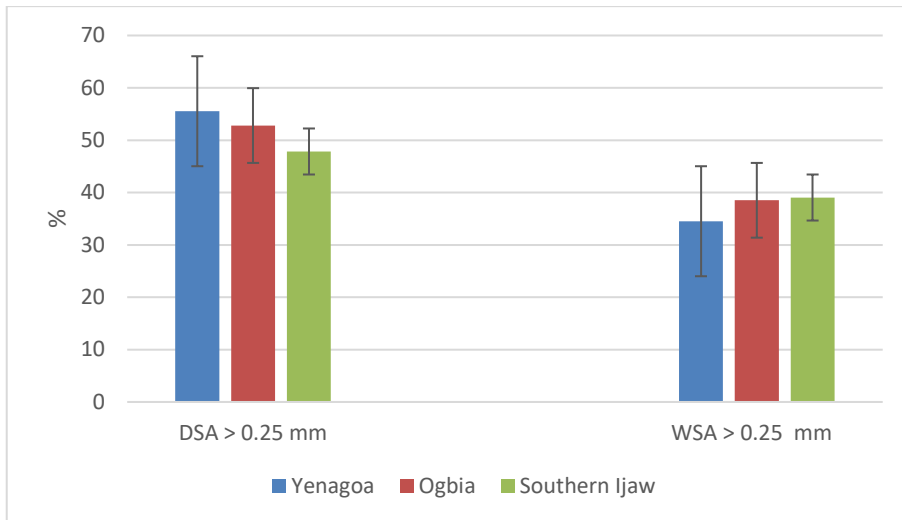


Figure (4). Dry stable aggregates and water stable aggregates according to the Local Government Areas

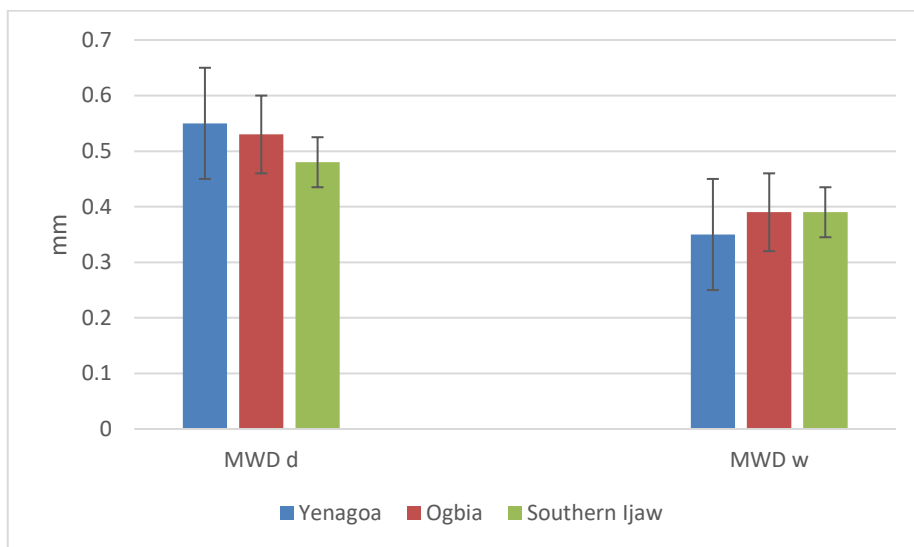


Figure (5). Mean weight diameter (dry and wet) according to local government areas

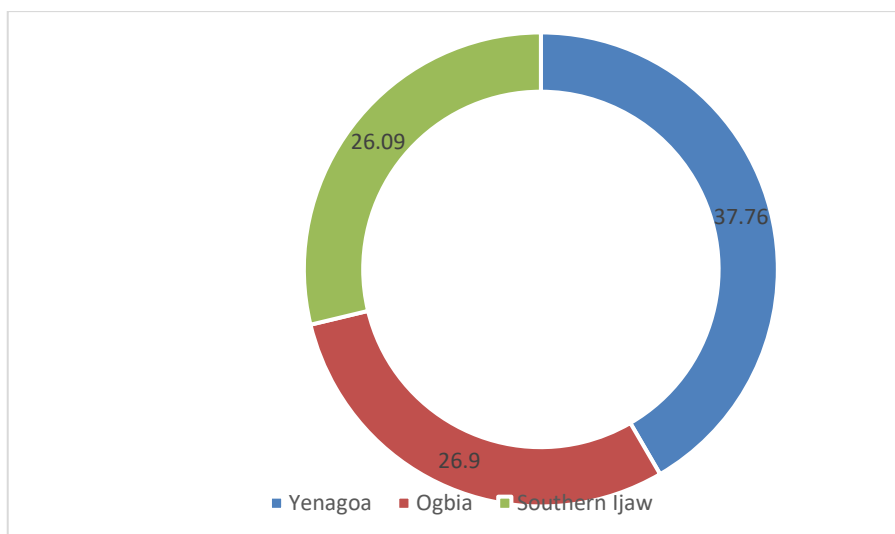


Figure (6). Potential structural deformation Index (PSDI) according to the Local Government Areas

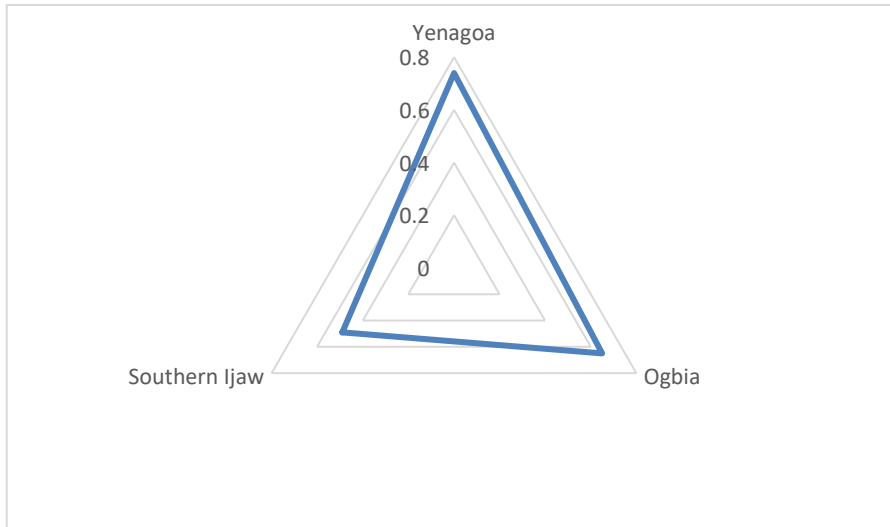


Figure (7). Aggregate stability ratio (ASR) of the studied local government Areas

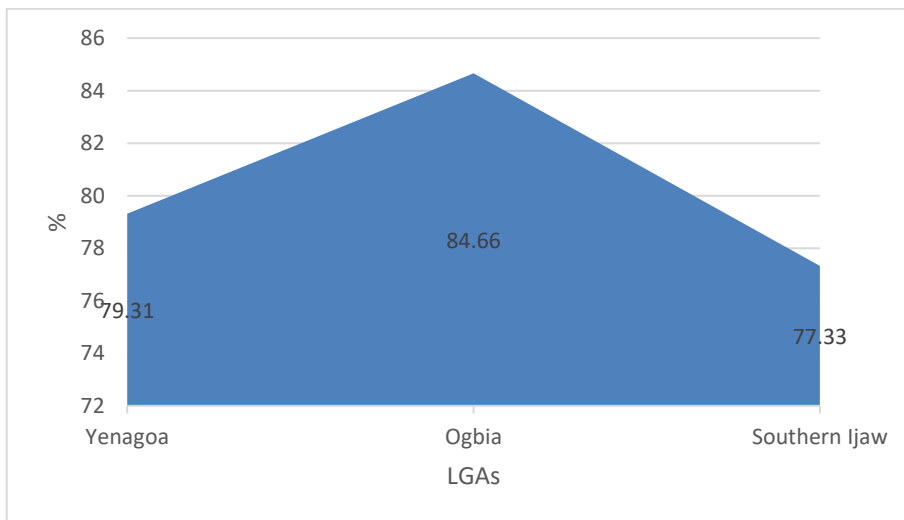


Figure (8). Water stability index (WSI) Index according to the Local Governments Areas

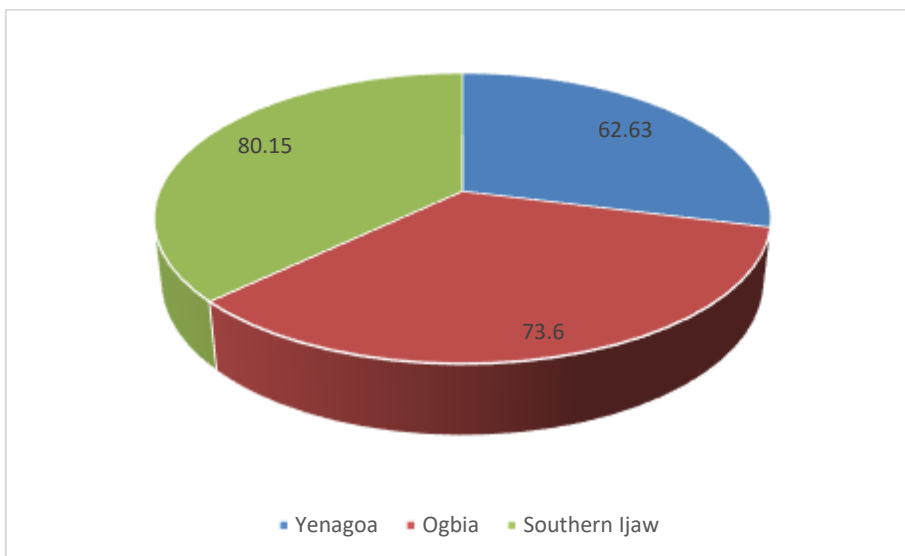


Figure 9. Aggregate stability Index according to the studied local government Areas

Environmental Quality Index (EQI) rating of the studied soils

The outcome of the Environmental Quality Index (EQI) rating of the studied soils is shown in Table 2. The results ranked the studied soil as Top tier, Mid tier, and Low tier soils respectively.

Table (2). Environmental Quality Index (EQI) Ranking and Scores of the studied soils.

	Location	LGA	EQI Score	Interpretation	Rank
1	Tariladei	Southern Ijaw	0.609	Best structural integrity; high WSA (85.14%), WSI, and low PSDI (0.33)	Top-Tier Soils
2	Ikpetiama	Yenagoa	0.542	High dry/wet MWD and GMD, moderate DSA, low ASR	Top-Tier Soils
3	Agbura	Ogbia	0.537	Excellent GMD (wet and dry), good WSA (82.36%), moderate ASI	Top-Tier Soils
4	Ogbogoro	Yenagoa	0.492	High DSA (46.7%), strong ASI (53.49), balanced structural parameters	Mid-Tier Soils
5	Otuoba	Ogbia	0.491	Best WSI (93.3%), stable GMD, strong ASR (0.68)	Mid-Tier Soils
6	Otuogori	Ogbia	0.486	High WSA, moderate PSDI, good MWD and ASI	Mid-Tier Soils
7	Kpansia	Yenagoa	0.465	Good MWD (dry/wet), average PSDI, moderate WSI	Mid-Tier Soils
8	Akaba	Yenagoa	0.453	Balanced structure, stable WSA and ASI, midrange stability metrics	Mid-Tier Soils
9	Otuokpoti	Ogbia	0.440	Moderate DSA and WSA, stable PSDI, average ASI	Low-Tier Soils
10	Oneubum	Ogbia	0.413	Highest MWD (dry), low DSA, average GMDs, lower ASI	Low-Tier Soils
11	Gbarama	Yenagoa	0.406	Moderate structure, but lower WSA and ASI values	Low-Tier Soils
12	Igeibiri	Southern Ijaw	0.354	moderate GMD, high ASR, low ASI (33.08)	Low-Tier Soils
13	Aguobiri	Southern Ijaw	0.384	High DSA (40%), lower ASI (42.89), average MWD	Low-Tier Soils
14	Amassoma	Southern Ijaw	0.265	Weakest structure overall low DSA (21%), lowest GMD (wet), poor ASI but good PSDI	Low-Tier Soils
15	Angiama	Southern Ijaw	0.367	High ASR (poor), low DSA and ASI, structurally weak	Low-Tier Soils

Top-Tier Soils (High EQI Scores)

Tariladei (0.609), Ikpetiama (0.542), and Agbura (0.537) (Table 2) were ranked as the top-tier soils with high EQI. These soils have the following favorable characteristics: High values of WAS (up to 85.14%) that show their ability to withstand water-related disintegration. Low PSDI (e.g., 0.33), which shows low structural vulnerability to physical forces. High MWD in both dry and saturated conditions, which reflects a high level of cohesion and aggregate strength.

Mid-Tier Soils (Moderate EQI Scores).

Soil locations such as Ogbogoro (0.492), Otuoba (0.491), Otuoguori (0.486), Kpansia (0.465), and Akaba (0.453) had moderate structural strength. The soil properties of these locations were characterized by: Moderate MWD and GMD, but with slightly high PSDI or moderate ASR and DSA. These soils may not be highly susceptible to erosion but may require improvement measures such as: Addition of organic matter (compost, green manure). Conservation tillage or cover crops to improve soil aggregation and minimize compaction. These soils are amenable to sustainable use, but periodic monitoring and maintenance may be necessary to avoid structural degradation under heavy use.

Low-Tier Soils (Low EQI Scores)

Areas such as Otuokpoti (0.440), Oneubum (0.413), Gbarama (0.406), and more so Aguobiri (0.384), Angiama (0.367), Igeibiri (0.354), and Amassoma (0.265) exhibited evidence of poor soil structure. The low GMD, DSA, and ASI values revealed a susceptibility to both mechanical and water forces. The high ASR and low WSA values also revealed a lack of water stability, making the soil highly susceptible to erosion, sealing, and crusting. Amassoma, with the lowest EQI of 0.265, had the poorest soil structure, low wet GMD, and high dispersion. These locations require urgent soil conservation interventions, such as: liming to improve pH and flocculation, especially in sodic or dispersive soils. Deep tillage with organic matter incorporation to improve porosity and structure. Erosion barriers (e.g., mulching, grass strips) and re-vegetation for long-term protection.

CONCLUSIONS

This study provides a comprehensive assessment of soil structural vulnerability and environmental quality in erosion-prone coastal soils of Bayelsa State, Nigeria, using a multi-index approach integrated into an Environmental Quality Index (EQI). The results demonstrate pronounced spatial variability in soil structural properties across the three Local Government Areas, reflecting differences in land use intensity, organic matter status, and hydrological stress conditions. Overall, most soils exhibited moderate structural stability under dry conditions, while water-stable indices indicated greater susceptibility to degradation under wet conditions typical of the humid tropical environment. The integrated indices (DSA, WSA, MWD, PSDI, WSI, ASR, and ASI) consistently revealed that soil structural integrity is strongly influenced by moisture-driven disintegration processes and anthropogenic disturbances. The EQI effectively synthesized these multiple indicators into a single comparative framework, enabling clear site ranking. Based on the EQI results, Tariladei, Ikpetiama, and Agbura were identified as the most structurally stable soils,

characterized by higher aggregate stability and lower vulnerability to deformation. In contrast, Amassoma, Angiama, Igeibiri, and other low-ranking sites exhibited weak structural integrity and higher susceptibility to erosion and surface sealing. Importantly, Southern Ijaw Local Government Area showed the widest variability, ranging from highly stable soils at Tariladei to highly degraded conditions at Amassoma and Angiama, while Ogbia generally exhibited moderate to high structural stability and Yenagoa displayed intermediate conditions.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest (financial, personal, or scientific) related to the submitted work titled Integrated Multi-Index Evaluation of Structural Vulnerability and Environmental Quality in Eroding Coastal Soils of Bayelsa State, Nigeria.

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