GIS-BASED ANALYTICAL HIERARCHY PROCESS MODELLING AND MAPPING OF EROSION VULNERABILITY IN THE COASTAL AREAS OF RIVERS STATE, NIGERIA

Abstract- The problem of coastal erosion in r~~R~~ivers State Nigeria is a significant issue that has far-reaching consequences for the environment and local communities. Despite the efforts of previous research there remains a lack of comprehensive understanding of the factors contributing to erosion vulnerability and their relative importance, hindering effective decision-making and management practices aimed at mitigating the effects of coastal erosion in Rivers State. Therefore, this study aimed at a GIS-based analytical hierarchy process ~~modelling~~modeling and mapping of coastal erosion vulnerability in Rivers State, Nigeria. The objectives are to ~~;~~establish and classify the geophysical factors according to the levels of coastal erosion risk, calculate the reliability index of the classified geophysical factors, determine the coastal vulnerable areas across Rivers State using analytical hierarchical process and to produce a coastal vulnerability index map defining the extent of erosion vulnerability in Rivers State. The methodology comprises of the acquisition of primary and secondary data, image pre-processing, image classification, DEM~~em~~ processing, classification and standardization of factors, development of pairwise comparism, and weighted linear combination analysis. The study revealed three distinct coastal erosion vulnerability zones: high, moderate, and low vulnerability. The high vulnerability zone encompassed a total expanse of 545.29 square kilometers, constituting 6.38% of the study area. In contrast, the moderate and low vulnerability zones covered 1941.33 square kilometers and 6052.51 square kilometers, respectively, making up 22.73% and 70.89% of the total area. Bonny (139.28 sq km) was ranked as the most vulnerable due to its role as an oil and gas hub. Degema (111.28 sq km) ranked second and requires urgent erosion control. Okrika and Andoni (71.73 sq km and 62.20 sq km) were third and fourth respectively. It is recommended that an advocate for the systematic approach to coastal vulnerability zoning be introduced in the study. The categorization of areas into high, moderate, and low vulnerability zones provides a standardized framework for assessing coastal regions' susceptibility to erosion. This approach can be applied to other regions to facilitate consistent vulnerability assessments

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Keywords: Analytical Hierarchy Process (AHP); Coastal Areas; Erosion Vulnerability; Rivers State; Weighted Overlay

1. Introduction

Coastal erosion is a critical environmental issue that poses significant threats to coastal communities, habitats, and infrastructure (Kotta and Estevez, 2008). In Rivers State Nigeria, coastal erosion is particularly severe, and it is necessary to assess and map the vulnerability of the coastal areas to erosion in order to inform decision-making and support sustainable coastal management practices (Ndimele and Ofoezie, 2010). One approach to addressing this challenge is to use Geographic Information Systems (GIS) and the Analytical Hierarchy Process (AHP) ~~modelling~~modeling method to map the erosion vulnerability of the coastal areas of Rivers State, Nigeria.

GIS is a powerful tool for ~~analysing~~analyzing, visualizing, and modelling geospatial data, and it is widely used in environmental studies, including assessments of coastal erosion vulnerability (Zhang and Li, 2018). The AHP method is a multi-criteria decision-making tool that can be used to prioritize and weigh factors that contribute to erosion vulnerability, such as geology, hydrology, and human activities (Ranjbar *et al*., 2018). By combining these two approaches, it is possible to develop a comprehensive understanding of the factors contributing to erosion vulnerability and to produce a map of the erosion vulnerability of the coastal areas of Rivers State, Nigeria.

In a study conducted in the Niger Delta region, Ranjbar *et al*. (2018) used GIS and AHP modelling to assess and map the erosion vulnerability of the coastal areas of the region. The study used both primary and secondary data sources, including satellite imagery, field observations, and published literature, to gather information on the factors contributing to erosion vulnerability. The study found that the factors contributing to erosion vulnerability in the Niger Delta region included geology, hydrology, and human activities such as oil spills, overfishing, and urbanization. The results of the study showed that the AHP method provided a systematic and transparent approach to weighing the relative importance of these factors and that the resulting map of erosion vulnerability was a useful tool for decision-makers and stakeholders involved in coastal management and protection in the region.

The results of this study have important implications for coastal management and protection in Rivers State, Nigeria. By providing a comprehensive understanding of the factors contributing to erosion vulnerability and a map of the erosion vulnerability of the coastal areas, this study can inform decision-making and support the development of sustainable and effective management practices. Additionally, by demonstrating the potential of GIS and AHP modelling to assess and map erosion vulnerability, this study provides a valuable basis for further research on coastal erosion in Rivers State and other similar areas.

Moreover, it is important to note that coastal erosion is a dynamic process, and therefore the need for continuous assessment and monitoring is crucial (Li and Zhang, 2017; Shrestha and An, 2018; Zhang and Li, 2018). This study intends to build on previous works and also provide a foundation for future research on coastal erosion in Rivers State and other similar areas. The results of the study have the potential to inform the development of effective coastal management strategies and policies, ensuring the long-term protection and preservation of the coastal areas in Rivers State.

The problem of coastal erosion in Rivers State Nigeria is a significant issue that has far-reaching consequences for the environment and local communities. Despite the efforts of previous researchers (Ndimele and Ofoezie, 2010; Akinde *et al*., 2013; Akindele *et al*., 2017; Ranjbar *et al*., 2018; Egborge *et al*., 2019), there remains a lack of comprehensive understanding of the factors contributing to erosion vulnerability and their relative importance, hindering effective decision-making and management practices aimed at mitigating the effects of coastal erosion in Rivers State.

Previous researchers have identified several factors contributing to coastal erosion in Rivers State, including sea-level rise (Akinde *et al*., 2013), human activities such as oil extraction and gas flaring (Egborge *et al*., 2019), and natural processes such as waves and tides (Akindele *et al*., 2017). However, these studies have primarily focused on individual factors, and there is a lack of studies that assess the relative importance of these factors in contributing to erosion vulnerability.

To address this problem, this study aims to use GIS and AHP modeling to comprehensively assess and map the erosion vulnerability of the coastal areas in Rivers State. This study provides a comprehensive understanding of the various factors contributing to erosion vulnerability and a map of the erosion vulnerability of the coastal areas, allowing for the development of effective and sustainable management practices aimed at mitigating the effects of coastal erosion in Rivers State.

The purpose of this research is to enhance our knowledge of the issue of coastal erosion in Rivers State area and furnish decision makers with valuable information for managing its impacts. Through the application of GIS and AHP modeling, the study will present a thorough evaluation of the factors contributing to the vulnerability of the coast to erosion and create a map showcasing the vulnerability of the coastal areas in Rivers State. This data is essential in creating effective and lasting management strategies to counteract the effects of coastal erosion in Rivers State.

2. Materials and Methods

2.1. Study Area

Rivers State is located in the southwestern region of Nigeria, covering approximately 11,077 square kilometers of land and waterand is situated between latitudes 4° 40` and 5° 20´ N and longitudes 6° 20` and 7° 40` E (Figure is needed)~~.~~

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Rivers State is a low-lying coastal plain located in the southwestern region of Nigeria. The region is characterized by its complex topography, which is shaped by a combination of natural and human-induced processes. The topography of the Rivers State is shaped by a combination of geomorphological and hydrological processes, including the deposition of sediment from rivers, tidal and storm-driven erosion, and subsidence due to over-extraction of oil and gas.

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The topography of the Rivers State is characterized by a series of deltaic lobes that have formed as a result of sediment deposition from multiple river channels. The deltaic lobes are separated by creeks and channels, which play an important role in controlling the flow of water and sediment in the region. The creeks and channels are also important habitats for a variety of plant and animal species, including mangroves and other coastal wetlands, which provide important ecosystem services to the region.

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One of the most important meteorological features of Rivers State is the harmattan, a dry and dusty trade wind that blows from the northeast during the dry season. The harmattan can reduce visibility and cause respiratory problems due to the dust and pollutants in the air.

2.2.Methodology

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2.2.1. Data Requirement and Acquisition

~~1.~~a. **Data Requirement:** The research utilized Sentinel-2, ALOS PALSAR, soil data, geology data, and rainfall data.

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~~2.~~b. **Data Acquisition:** Primary datasets, including 256 ground coastal erosion observations, were collected through field visits, while secondary datasets were sourced from various platforms: the administrative boundary map of Rivers State from the Department of Surveying and Geoinformatics, Nnamdi Azikiwe University, Awka; Sentinel-2 and ALOS PALSAR data from Open Access Hub (copernicus.eu); geology and soil data from www.fao.org; and rainfall data from CRU TS Version 4.07 (uea.ac.uk).

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~~1.~~a. **Image Pre-processing:** Prior to conducting any analysis on the acquired data, initial processing steps were implemented to ensure data accuracy. This involved rectifying any inaccuracies attributed to the imaging system and environmental conditions during image acquisition, despite standard correction measures applied by ground station operators. Additional correction steps were undertaken to ensure data accuracy. These procedures encompassed radiometric correction to standardize sensor responses across the image and geometric correction to mitigate distortion caused by Earth's rotation or other imaging conditions. Subsequently, the image was transformed to the UTM ZONE 32 NORTH map projection system using ground control points for precise geo-referencing. Further refinement of the image involved band combination to merge spectral bands and image subsetting to extract relevant study area portions, thereby optimizing data quality and analysis accuracy.

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~~1.~~b. **ALOS PALSAR Processing:** The ALOS PALSAR model, containing elevation records of specific-sized cells, was subject to potential data errors, particularly in capturing sunken areas or landforms with Karst Topography. To address these issues, a sink filling process was conducted using ArcGIS Pro software. Subsequently, elevation, aspect, flow accumulation, and slope of the area were calculated based on corrected Digital Elevation Model (DEM) data. These derived layers served as pivotal components in the suitability analysis, acting as constraints and factors for subsequent analysis.

~~1.~~c. **Development of Pairwise Comparison Matrix (PCM):** Pairwise comparisons were utilized to construct a ratio matrix, facilitating the derivation of relative weights from input comparisons. The process involved three stages: developing a pairwise comparison matrix, computing weights by normalizing the matrix, and ranking criteria options based on their relative importance. The Analytical Hierarchy Process (AHP) was employed to streamline complex decision-making by synthesizing pairwise comparisons, allowing for the incorporation of both subjective and objective aspects into decision-making processes.

~~1.~~d. **Pairwise Comparison Matrix Formation:** The AHP method utilized pairwise comparison matrices to determine criteria weights through comparisons of relative importance. These matrices were formed by inputting judgment values between factors, following established rules by Saaty. Matrix elements were filled based on preferences inferred from pairwise comparisons, subsequently allowing for computation of criteria weights.

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~~1.~~e. **Estimation of Consistency Ratio (CR):** To assess the reliability of judgment values, a consistency ratio (CR) was calculated, comparing it against a random index (RI). The CR was determined using the formula CR = CI/RI, where CI represents the Consistency Index. If the CR was less than 0.1, it indicated a reasonable level of consistency in pairwise comparisons and acceptable computed weights.

~~1.~~f. **Dataset Overlay:** Upon determining weights, the weighted criteria were overlaid and merged to generate a coastal erosion vulnerability index. This index categorized vulnerability into three levels: high, moderate, and low, based on values obtained from all points within the study area.

3. Results

3.1. Identification and Selection of Criteria

Selection of the criteria and factors for coastal erosion vulnerability was achieved based on their theoretical relevance as documented in by Naga *et al*, (2022). The following criteria (factors, table 1) were used in this research.

Table 1: Criteria and Requirements for coastal erosion vulnerability analysis

Criteria	Data Source	Requirement for suitability	Original Data Structure	Resolution / Feature Type
Slope	ALOS Palsar Dem (www.Earthexplorer.usgs.gov)	The steepness of coastal slopes is a critical factor in erosion. Steeper slopes generally experience more rapid erosion because gravity exerts a stronger pull-on loose material, causing them to move down slope more quickly.	Raster	12.5m
Elevation	ALOS Palsar Dem (www.Earthexplorer.usgs.gov)	Coastal elevation, or the height above sea level, impacts erosion vulnerability. Low-lying coastal areas are more susceptible to erosion	Raster	12.5m
Geology	certmapper.cr.usgs.gov/data/apps/world-maps/	Coastal regions with varying rock types and formations exhibit different susceptibility to erosion. Soft, unconsolidated sediments, such as sand and gravel, are more easily eroded compared to hard, resistant rocks like limestone or granite.	Vector	Polygon
Soil	www.fao.org	Soil type and quality significantly impact coastal erosion dynamics. Sandy soils, characterized by their loose, granular nature, are more easily eroded compared to clayey or loamy soils.	Vector	Polygon
Erosivity	CRU TS Version 4.07 (uea.ac.uk)	Coastal areas are subject to high erosivity factors, such as those in heavy rain-prone regions, may experience more severe erosion	Raster	30m

		events.		
Flow Accumulation	ALOS Palsar Dem (www.Earthexplorer.usgs.gov)	Regions with high flow accumulation, can result in increased water volume and velocity entering coastal zones.	Raster	12.5m
Aspect	ALOS Palsar Dem (www.Earthexplorer.usgs.gov)	Coastal areas with south or southwest-facing slopes in the Northern Hemisphere are often more exposed to prevailing winds and waves, potentially leading to higher erosion rates.	Raster	12.5m

Based on the criteria selected (table 1), the data used for achieving the aim of the research were assembled.

The data used in the study such as Flow Accumulation, Geology, Elevation, Aspect, Slope, Erosivity Factor and Soil data are important for determining erosion vulnerability in coastal areas of Rivers State Nigeria. Erosion in coastal areas is influenced by a combination of natural and anthropogenic factors

1. **Flow Accumulation**: Flow accumulation is a hydrological concept that relates to the gathering of water runoff from precipitation, snowmelt, or other sources. In the context of coastal erosion, it plays a pivotal role. In regions with high flow accumulation, excessive rainfall or rapid snowmelt can result in increased water volume and velocity entering coastal zones. This surplus of water can carry substantial amounts of sediment and debris, intensifying coastal erosion. Watersheds and river systems upstream of coastal areas significantly contribute to flow accumulation. Land use practices, such as deforestation or urban development, can alter flow accumulation patterns by increasing runoff and sediment transport.

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~~1.~~2. **Geology**: The geological composition of coastal areas has a profound influence on erosion dynamics. Coastal regions with varying rock types and formations exhibit different susceptibility to erosion. Soft, unconsolidated sediments, such as sand and gravel, are more easily eroded compared to hard, resistant rocks like limestone or granite. The erosive forces of waves, currents, and tides can wear away softer materials more rapidly. Geological faults and structures can create zones of weakness in coastal rocks, making them more prone to erosion. Over geological time scales, this can lead to the formation of sea cliffs or headlands.

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~~1.~~3. **Elevation**: Coastal elevation, or the height above sea level, impacts erosion vulnerability. Low-lying coastal areas are more susceptible to erosion because they are closer to sea level, making them prone to inundation during storms and high tides. Sea-level rise due to climate change further exacerbates erosion risks in low-lying coastal regions. Higher elevations, on the other hand, may provide some protection against erosion but can also influence local wind patterns and wave actions, which can either amplify or mitigate erosion processes.

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~~1.~~4. **Aspect**: ~~Aspect, which~~It refers to the direction a slope or coastal feature faces. It~~,~~ plays a significant role in erosion patterns. It influences sun exposure, wind patterns, and wave action.Coastal areas with south or southwest-facing slopes in the Northern Hemisphere are often more exposed to prevailing winds and waves, potentially leading to higher erosion rates. Conversely, areas facing away from dominant winds may experience comparatively less erosion.

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~~1.~~5. **Slope**: The steepness of coastal slopes is a critical factor in erosion. Steeper slopes generally experience more rapid erosion because gravity exerts a stronger pull on loose materials, causing them to move downslope more quickly. Coastal areas with gentle slopes may still be vulnerable to wave-driven erosion during storms and high

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tides. Slope stability can be affected by factors such as soil type, vegetation cover, and human activities.

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~~1.~~6.**Erosivity Factor**: The erosivity factor encompasses various climatic parameters that directly influence erosion. This includes factors like rainfall intensity, storm frequency, wind speed, and wave height.Coastal areas subject to high erosivity factors, such as those in hurricane-prone regions, may experience more severe erosion events. The combination of strong winds, heavy rainfall, and storm surges can lead to significant coastal erosion and land loss.

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~~1.~~7.**Soil**: Soil type and quality significantly impact coastal erosion dynamics. Sandy soils, characterized by their loose, granular nature, are more easily eroded compared to clayey or loamy soils.The presence of vegetation and root systems in the soil can play a protective role. Coastal vegetation, such as mangroves and salt marshes, stabilizes sediments, reduces erosion rates, and provides habitat for wildlife. Soil erosion can be exacerbated by human activities like construction, agriculture, and deforestation, which remove protective vegetation cover and disrupt natural erosion control mechanisms.

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3.2. Reclassification and Standardization of Criteria

The initial step in implementing the Analytical Hierarchical Process (AHP) and weighted linear combination model involves reclassifying and standardizing criteria. Each cell within the datasets possesses values for individual input criteria. However, combining these criteria directly is impractical due to disparities in measurement units. For example, attempting to combine a cell value indicating a 2° slope with an elevation layer value of 50m is challenging due to unit differences (ESRI, 2018). Therefore, reclassification of each dataset is necessary to standardize them into a common measurement system, enabling seamless analysis and demonstrating the suitability level for each criterion on a relative weighting scale.

To effectively combine datasets, it is essential to standardize or transform all individual datasets into a uniform measurement scale. In this research, all datasets were reclassified into three distinct classes: (1) highly vulnerable areas, (2) moderately vulnerable areas, and (3) low vulnerable areas. Initially, the values within the datasets ranged in a floating and continuous manner, necessitating reclassification to assign discrete integer values (such as 1, 2, and 3) to each value range based on the measurement scale. This reclassification is crucial as the inputs for weighted overlay must consist of discrete integer values. The reclassified and standardized criteria are presented in Table 2.

Table 2: Criteria and Requirements for coastal erosion vulnerability

Criteria	**Suitability Rank Value**	**Ranking**
Slope	0°- 10°	3
	10° - 30°	2
	30° - 43°	1
Elevation	74m - 50m	3
	50m - 30m	2
	30m - 1m	1
Geology	Granite, Basalt, And Quartzite	3
	Sandstone And Limestone	2
	Alluvial Deposits, Sand	1
Soil	Thionic Fluvisols	3
	Xanthis Ferrasols	2
	Dystric Regosols, Gleysols	1
Erosivity	8 – 10	3

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	10 – 13	2
	13 – 16	1
Flow Accumulation	0 – 182,000	3
	182,000 – 546,000	2
	546,000 – 1,300,000	1
Aspect	Flat	3
	North, Northeast, West	2
	South, Southwest	1

3.3. Analytical Hierarchy Process (AHP) and Determination of Criteria Weight

The Analytical Hierarchy Process (AHP) serves as a powerful tool for navigating complex decision-making scenarios, assisting decision-makers in establishing priorities and making optimal choices by breaking down intricate decisions into a series of pairwise comparisons and subsequently synthesizing the outcomes. AHP enables the incorporation of both subjective and objective aspects into decision-making processes. Moreover, it facilitates the assessment of both benefits and risks, assigning numerical values to each criterion (whether it be a benefit or a risk factor under consideration), with greater importance attributed to more significant benefits through higher numerical values on the scale. This aids in determining which projects possess the highest overall value or offer the most significant benefits while mitigating risks to the greatest extent possible.

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The AHP methodology utilizes a ratio matrix, often referred to as the Eigenvector method, to compare one criterion against another. Additionally, it employs a numerical scale ranging from 1 to 9, where a value of 1 signifies that the two factors under comparison hold equal importance, while a value of 9 indicates that one factor is significantly more important than the other, as illustrated in Table 3. Conversely, if one factor is deemed less important than another, this is denoted by the reciprocal of the 1 to 9 values (ranging from 1/1 to 1/9).

Table 3: Relative Importance in Pairwise Comparison ~~Source:~~ (Saaty, 1980).

Judgment value	Description
1	Equal importance
3	Moderately importance
5	Strongly Importance
7	Very strongly important
9	Extremely important

~~Source: (Saaty, 1980)~~

3.3.1. Pairwise Comparison Matrix Formation

The creation of the pairwise comparison (PCM) matrix involved inputting judgment values between factors as the matrix elements, following the fundamental rules established by (Saaty, 1980???). Utilizing Table 3 as a guide, Table 4 was generated through the construction of the pairwise comparison matrix.

Table 4. Pair-wise comparison matrix for coastal erosion vulnerability

Criterion	*Slope*	*Elevation*	*Geology*	*Soil*	*Erosivity*	*Flow Accumulation*	*Aspect*
Slope	1	2	3	4	5	5	9
Elevation	0.5	1	3	5	6	6	7
Geology	0.33	0.33	1	5	6	6	7
Soil	0.25	0.2	0.16	1	2	3	4
Erosivity	0.2	0.16	0.16	0.5	`1	2	3
Flow Accumulation	0.2	0.16	0.16	0.33	0.5	1	4
Aspect	0.11	0.14	0.14	0.25	0.33	0.25	1
Total	2.59	4.0	11.5	16	20.8	23.25	35

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3.3.2. Computation of the Criterion Weights

Upon the creation of the pairwise comparison matrix (PCM), the computation of criteria weights ensued, involving the following steps:

~~1.~~i. The summation of values within each column of the pairwise comparison matrix.

~~1.~~ii. Division of each element in the matrix by its respective column total, resulting in the formation of a normalized pairwise comparison matrix.

~~1.~~iii. The calculation of the average of elements within each row of the normalized matrix. This process entails dividing the sum of normalized scores for each row by the total number of criteria.

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These averages serve as an approximation of the relative weights of the criteria under comparison. Importantly, to mitigate bias in criteria weighting, the consistency ratio (CR) was employed.

3.3.3. Normalized Pairwise Comparison Matrix

Table 5 displays the normalized pairwise comparison matrices that were generated. As an illustration, to derive the element of the normalized matrix for the comparison between slope (row) and slope (column) – indicated by the matrix element at position 1, 1 – the value 2.59 represents the sum of elements in the second column, while 1 denotes the judgment value of slope (row) against slope (column). Consequently, the normalized value for F1, F1 = (1/2.59) = 0.39, as presented in Table 5.

Table 5: Normalized Pairwise Comparison Matrix for coastal erosion vulnerability

Criterion	*Slope*	*Elevation*	*Geology*	*Soil*	*Erosivity*	*Flow Accumulation*	*Aspect*	*Mean*
Slope	0.39	0.50	0.39	0.25	0.25	0.22	0.26	0.32
Elevation	0.19	0.25	0.39	0.31	0.30	0.26	0.20	0.27
Geology	0.13	0.08	0.13	0.31	0.30	0.26	0.20	0.20

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Soil	0.10	0.05	0.02	0.06	0.10	0.13	0.11	0.08
Erosivity	0.08	0.04	0.02	0.03	0.05	0.09	0.09	0.06
Flow Accumulation	0.08	0.04	0.02	0.02	0.03	0.04	0.11	0.05
Aspect	0.04	0.04	0.02	0.02	0.02	0.01	0.03	0.02

3.3.4. Prioritization weight matrix

In computing the element of this matrix, the normalized sum of each row is divided by the total number of its criteria. The obtained averages provide an estimate of the relative weights of the criteria being compared. For instance, the criteria weight of slope as a factor can be obtained thus;

Slope = 0.39 + 0.50+ 0.39+ 0.25+ 0.25+ 0.22+ 0.26 (sum of the elements in row 1)

Total number of criteria in row 1 = 7

Therefore, A {weight of factor 1 (F1)} = 2.26/7 = 0.3228 = 0.32

A% (criteria in percentage) = A x 100 = 0.32 * 100 = 32%, see table 6 for more details.

Table 6: Prioritization weight matrix for coastal erosion vulnerability

Criterion	*Slope*	*Elevation*	*Geology*	*Soil*	*Erosivity*	*Flow Accumulation*	*Aspect*	*Mean*	*W%*	*row total of normalized matrix*
Slope	0.39	0.50	0.39	0.25	0.25	0.22	0.26	0.32	32.20	2.25
Elevation	0.19	0.25	0.39	0.31	0.30	0.26	0.20	0.27	27.27	1.91
Geology	0.13	0.08	0.13	0.31	0.30	0.26	0.20	0.20	20.18	1.41
Soil	0.10	0.05	0.02	0.06	0.10	0.13	0.11	0.08	8.20	0.57
Erosivity	0.08	0.04	0.02	0.03	0.05	0.09	0.09	0.06	5.59	0.39
Flow Accumulation	0.08	0.04	0.02	0.02	0.03	0.04	0.11	0.05	4.88	0.34

Aspect	0.04	0.04	0.02	0.02	0.02	0.01	0.03	0.02	2.39	0.17
Total	1.00	1.00	1.00	1.00	1.05	1.00	1.00	1.01	100.72	7.05

3.3.5. Estimation of the Consistency Ratio (CR).

This stage involved calculating a consistency ratio (CR) to check reliability of the judgments values which are relative to large samples of purely random judgments. The AHP deals with consistency explicitly because in making paired comparisons, just as in thinking, people do not have the intrinsic logical ability to always be consistent.

To determine consistency ratio, the analytical hierarchy process compares it by random index (R.I.). Mathematically, Consistency Ratio (C.R.), can be defined using equation:

$$CR = CI/RI \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Random index (RI) is the consistency index of a randomly generated pair-wise comparison matrix of order 1 to 10 obtained by approximating random indices.

Table 7: Random Index by (Saaty, 2008)

Size of matrix (n)	1	2	3	4	5	6	7	8	9	10
Random index (RI)	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.46	1.49

Note: If the value of the obtained Consistency Ratio is less than 0.1, it means that there is a reasonable level of consistency in the pairwise comparisons, and that the computed weights are within the acceptable limit. If the reverse is the case (CR > 0.1) it means that the weights obtained are inconsistent and needs to be checked.

1. The value of Consistency index, CI for coastal erosion vulnerability was calculated from the preference matrix according to equation below

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$CI = \frac{\lambda\text{max} - n}{n-1}$ .... (2)

λmax is the Principal Eigen Value; n is the number of factors

λmax = Σ of the products between each element of the priority vector and relative weights

λmax = (2.59*0.32) + (3.99*0.27) + (7.62*0.20) + (16.08*0.08) + (20.83*0.06) + (23.25*0.05) + (35*0.02)

= 0.82 + 1.07 + 1.52 + 1.28 + 1.24 + 1.16 + 0.7

λmax = 7.79

CI = (7.79 – 7)/ (7-1) = 0.131

CR = 0.131/1.32 = 0.09

CR = 0.09< 0.10 (Acceptable)

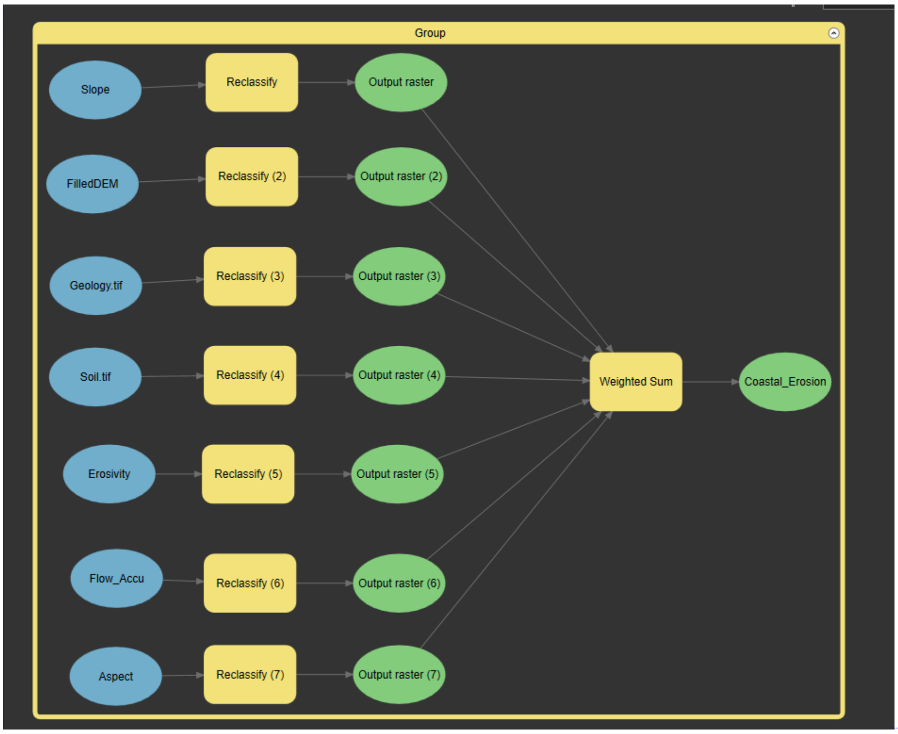
3.4. Suitability Calculation

Coastal erosion vulnerability was assessed using a weighted sum technique within ArcGIS Pro. To ensure flexibility in site selection, the criteria were standardized to a continuous scale of suitability, ranging from the least to the most suitable.

The suitability index method, allowing for the assignment of weights, was implemented in ArcGIS Pro. To enhance the map's interpretability, a reclassification process was conducted to delineate three suitability index levels or categories—namely, low, moderate, and high. The natural breaks reclassification method was utilized for this purpose. This algorithm, known as the natural breaks (Jenks) classification, identifies breakpoints in the data based on natural clustering patterns, setting class breakpoints where significant jumps in data values occur.

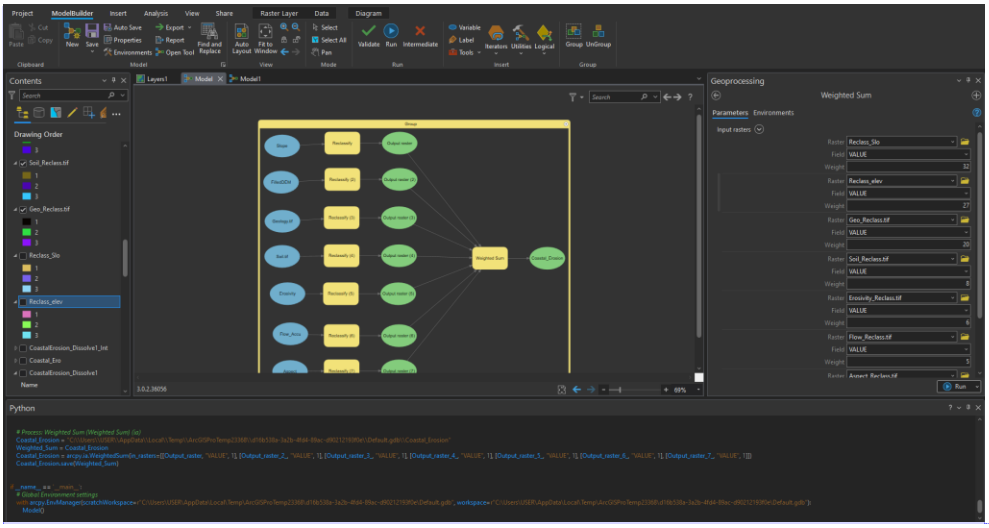
Subsequently, the coastal erosion vulnerability was computed using the formula: CI = (C1 * 32) + (C2 * 27) + (C3 * 20) + (C4 * 8) + (C5 * 6) + (C6 * 5) + (C7 * 2)), as depicted in Figures 2 and 3.

Comment [الطالب19]: Where is Figure 1????



Comment [الطالب20]: Maximize the text within the flowchart

Figure 2: Coastal Erosion Vulnerability Graphic Model



Weighted Sum

Input rasters

Raster Reclass_Slo
Field VALUE
Weight 32

Raster Reclass_elev
Field VALUE
Weight 27

Raster Geo_Reclass.tif
Field VALUE
Weight 20

Raster Soil_Reclass.tif
Field VALUE
Weight 8

Raster Erosivity_Reclass.tif
Field VALUE
Weight 6

Raster Flow_Reclass.tif
Field VALUE
Weight 5

Raster Aspect_Reclass.tif

```
    # Process: Weighted Sum (Weighted Sum) (ia)
    Coastal_Erosion = "C:\\Users\\USER\\AppData\\Local\\Temp\\ArcGISProTemp23368\\d16b538a-3a2b-4fd4-89ac-d90212193f0e\\Default.gdb\\Coastal_Erosion"
    Weighted_Sum = Coastal_Erosion
    Coastal_Erosion = arcpy.ia.WeightedSum(in_rasters=[[Output_raster, "VALUE", 1], [Output_raster_2_, "VALUE", 1], [Output_raster_3_, "VALUE", 1], [Output_raster_4_, "VALUE", 1], [Output_raster_5_, "VALUE", 1], [Output_raster_6_, "VALUE", 1], [Output_raster_7_, "VALUE", 1]])
    Coastal_Erosion.save(Weighted_Sum)


if __name__ == '__main__':
    # Global Environment settings
    with arcpy.EnvManager(scratchWorkspace=r"C:\Users\USER\AppData\Local\Temp\ArcGISProTemp23368\d16b538a-3a2b-4fd4-89ac-d90212193f0e\Default.gdb", workspace=r"C:\Users\USER\AppData\Local\Temp\ArcGISProTemp23368\d16b538a-3a2b-4fd4-89ac-d90212193f0e\Default.gdb"):
        Model()
```

Comment [ب طال ال21]: Not clear, You have to improve the interface such that the text will be clarified

Figure 3: Coastal erosion vulnerability weighted sum calculation in the Graphic Model

Please note: C1..., denote thematic layers representing the factors contributing to Coastal Erosion Vulnerability; refer to Table 8. The output illustrates the areas of coastal erosion vulnerability in Rivers State, Nigeria. The findings are depicted in Figure 4.

Table 8: Coding of Factors

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Code	Factors
C1	Slope
C2	Elevation
C3	Geology
C4	Soil
C5	Erosivity
C6	Flow Accumulation
C7	Aspect

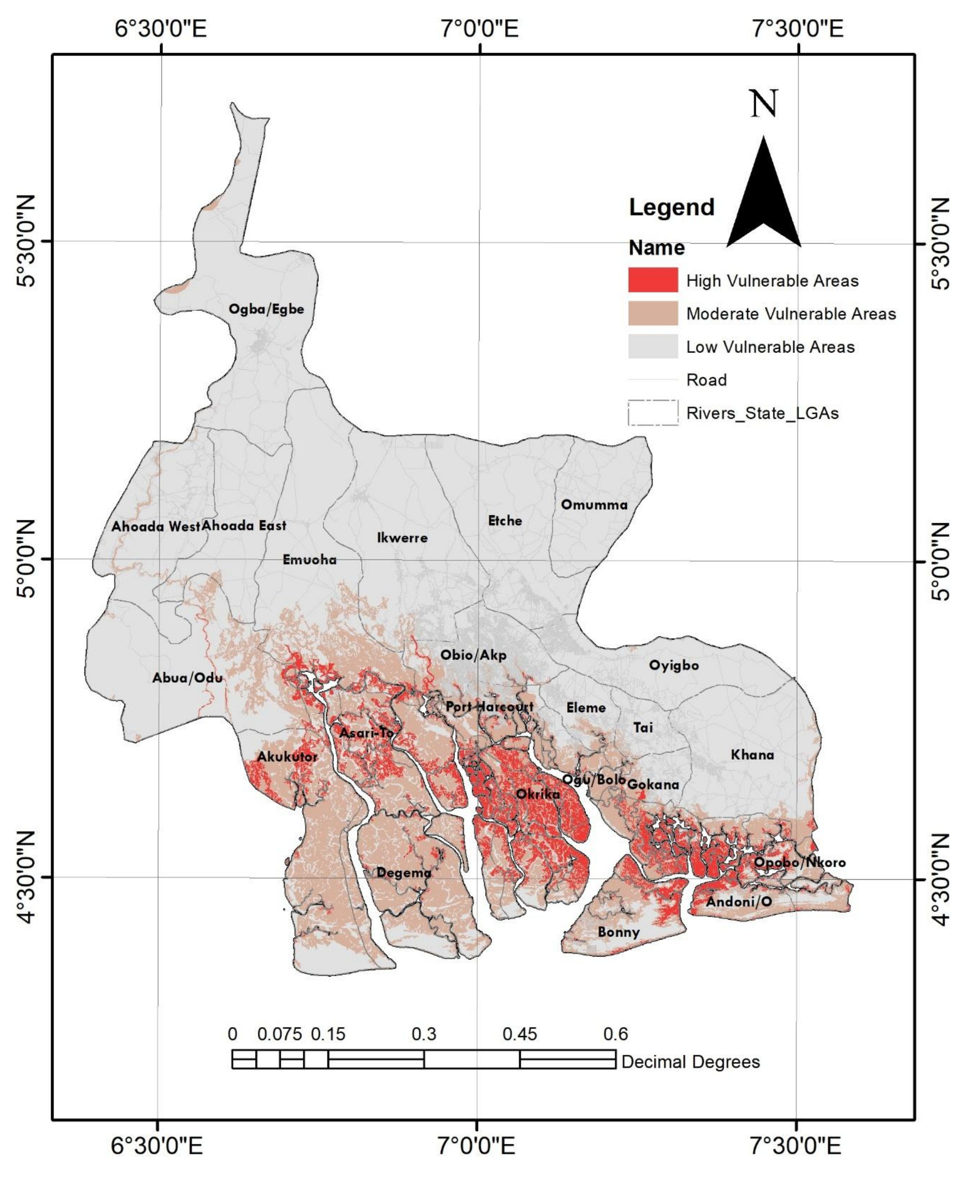
6°30'0"E
7°0'0"E
7°30'0"E
5°30'0"N
5°0'0"N
4°30'0"N
N
Legend
Name
High Vulnerable Areas
Moderate Vulnerable Areas
Low Vulnerable Areas
Road
Rivers_State_LGAs
Ogba/Egbe
Ahoada West
Ahoada East
Emuoha
Ikwerre
Etche
Omumma
Obio/Akp
Oyigbo
Abua/Odu
Port Harcourt
Eleme
Tai
Asari-To
Akukutor
Khana
Ogu/Bolo
Gokana
Okrika
Opobo/Nkoro
Andoni/O
Degema
Bonny
0
0.075
0.15
0.3
0.45
0.6
Decimal Degrees

Figure 4: Coastal Erosion Vulnerability in Rivers State, Nigeria

The findings, depicted in Figure 4, unveiled the existence of three distinct coastal erosion vulnerability zones: high, moderate, and low vulnerability. The high vulnerability zone encompassed a total expanse of 545.29 square kilometers, constituting 6.38% of the study area. In contrast, the moderate and low vulnerability zones covered 1941.33 square kilometers and 6052.51 square kilometers, respectively, making up 22.73% and 70.89% of the total area.

Among these zones, Bonny emerged as the most vulnerable, spanning approximately 139.28 square kilometers. Addressing erosion in this area is of utmost significance due to its role as a crucial oil and gas hub, where severe erosion could trigger far-reaching environmental and economic repercussions.

Degema, covering about 111.28 square kilometers, ranked as the second highest in coastal erosion vulnerability. Effective planning and intervention strategies are imperative to combat coastal erosion here, given its substantial size and economic importance.

Okrika and Andoni, with extensive coverage areas of 71.73 square kilometers and 62.20 square kilometers, respectively, occupied the third and fourth positions in terms of coastal erosion vulnerability. Protecting this region is vital not only for its rich biodiversity and cultural heritage but also for the well-being of local ecosystems and communities. Implementing coastal protection measures is essential to safeguard this culturally significant area that supports local livelihoods.

Akuku-toru featured a substantial high vulnerability zone, spanning about 32.97 square kilometers. The emphasis on comprehensive erosion control measures is crucial, particularly considering the region's renowned for its cultural and natural heritage.

Emuoha's vulnerability zone, covering approximately 24.78 square kilometers, ranked seventh in vulnerability. Protective measures are necessary to combat coastal erosion, especially considering its potential impact on agriculture and infrastructure.

Port Harcourt, encompassing approximately 23.56 square kilometers, ranked sixth in vulnerability. Erosion in this area could have severe economic and infrastructural consequences, given its status as a major commercial and industrial center.

Asari-Toru, with an area coverage of approximately 22.41 square kilometers, stood as the ninth highest in vulnerability. Focused erosion management strategies are essential to safeguard its coastal assets, including riverine communities and areas of cultural significance.

Opobo/Nkoro featured a high vulnerability zone spanning approximately 20.59 square kilometers, ranking eighth in vulnerability. Effective erosion control and mitigation strategies are required to protect this area and its associated ecosystems.

Understanding these vulnerability zones holds paramount importance in the realm of environmental conservation. It enables the precise targeting of initiatives aimed at safeguarding ecologically delicate regions, including those distinguished by their abundant biodiversity and distinctive ecosystems.

The delineation of high vulnerability zones, notably within economically pivotal areas like Bonny and Degema, underscores the potential economic repercussions stemming from coastal erosion. The risk of losing critical infrastructure, industrial assets, and the disruption of economic activities looms large, casting a broad shadow over both local communities and the broader region.

The heightened vulnerability of Bonny assumes particular significance due to its pivotal role as an oil and gas hub. Erosion in this area poses a tangible threat to oil and gas infrastructure, potentially culminating in oil spills and environmental calamities. These implications extend beyond regional boundaries, resonating in global energy markets and the sphere of energy security.

Coastal erosion poses a threat to essential infrastructure elements such as roads, bridges, and ports. Tackling erosion in areas like Port Harcourt is indispensable to the preservation of transportation networks and the bolstering of regional development.

The safeguarding of culturally significant locales, exemplified by Okrika, Andoni, and Asari-Toru, emerges as a matter of utmost importance in the preservation of the cultural heritage cherished by local communities. Coastal erosion looms as a menace capable of erasing or obliterating historical sites and invaluable artifacts of cultural significance.

4. Conclusion

The results of this study have provided crucial insights into coastal erosion vulnerability in Rivers State. These findings have significant implications for environmental conservation, economic sustainability, cultural heritage preservation, and infrastructure protection.

The identification of high, moderate, and low vulnerability zones using a systematic approach has not only enhanced our understanding of the spatial distribution of coastal erosion risk but also introduced a transparent and adaptable model for future assessments in Nigeria and potentially in other regions. This model can serve as a valuable tool for researchers, planners, and policymakers to develop and implement effective coastal erosion mitigation and adaptation strategies.

The prominence of high vulnerability zones in economically important areas like Bonny and Degema underscores the potential economic consequences of coastal erosion, emphasizing the need for proactive planning and intervention. Moreover, the heightened vulnerability of

Bonny due to its status as an oil and gas hub highlights the global energy security implications of coastal erosion in key energy-producing regions.

The study also emphasizes the significance of protecting culturally significant areas, such as Okrika, Andoni, and Asari-Toru, in preserving the rich cultural heritage of local communities. Furthermore, the potential damage to critical infrastructure, including roads, bridges, and ports, underscores the importance of infrastructure protection and resilience building.

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Comment [طالب ال22]: A very few reference used. You should support the paper by many more up to date references