Journal of Engineering Research and Reports

Volume 25, Issue 11, Page 123-134, 2023; Article no.JERR.109715
ISSN: 2582-2926

GIS-Based Analytical Hierarchy Process Modeling for Flood Vulnerability Assessment of Communities Along Otamiri River Basin Imo State, Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JERR/2023/v25i111027

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/109715

Original Research Article

Received: 22/09/2023
Accepted: 24/11/2023
Published: 27/11/2023

ABSTRACT

In recent times, communities along the Otamiri River Basin in Imo State have been grappling with flooding issues, especially during the rainy season. This occurs despite the presence of underground drainage systems. The primary concern is heavy rainfall causing the river to overflow and lead to flooding. Hence the study aimed at identifying the flood-prone areas in the Otamiri River Basin in Owerri, Imo State. The objectives are to establish factors for evaluating flood vulnerability within the study area; to classify and standardize the factors according to levels of vulnerability; to determine the reliability of the classified factors; and to produce a flood vulnerability map showing vulnerable areas in the study area. The methodology involved collecting Shuttle Radar Topography Mission and Sentinel 2A imagery of July 2022, and processing the data with ArcGIS and QGIS software to determine the topography and vulnerability areas through geo-referencing and

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classification. The Analytical Hierarchy Process (AHP) model was employed to identify high flood risk areas, considering factors like drainage density, slope, soil type, precipitation, population density, Euclidean distance, and land use. The study's results categorized vulnerability into five levels: Very Low (0.09% of Owerri, minimal risk), Low (12.93% with lower risk), Moderate (68.83% facing substantial risk), High (18.18% with significant risk), and Very High (0.03% posing extreme risk). These findings are recommended as foundational data for future flood studies in the region.

Keywords: AHP; Flood; GIS; Otamiri; Vulnerability.

1. INTRODUCTION

This study delves into the intricate complexities surrounding the critical issue of floods, a matter of paramount concern with profound implications across various sectors, including agriculture, civil engineering, and public health within the field of hydrology. The global impact of floods, often triggered by abnormal rainfall levels, is profound, resulting in widespread havoc characterized by significant damage to both life and property, disruptions in traffic flow, and the imposition of substantial health hazards [1-3].

Recognizing the gravity of this multifaceted challenge, the United Nations Environmental Program (UNEP) underscored the significant threat posed by uncontrolled stormwater to urban infrastructure in 1991, underscoring the urgent need for comprehensive management strategies [4]. Numerous nations, including Nigeria, have borne witness to devastating flood events, with specific regions such as Lokoja and Aguleri experiencing profound trauma, as documented by the Nigeria Television Authority.

The repercussions of floods extend beyond immediate visible damage, impacting a spectrum of human activities, cultivable lands, and dwellings, ultimately leading to substantial human and economic losses [5-7]. A detailed assessment by Duru and Chibo (2014) pinpointed specific Local Government Areas (LGAs) in Imo State that face the imminent threat of various flood types, each posing varying levels of risk, particularly during the peak rainy season [8]. The imperative for efficient flood hazard management has become increasingly evident for sustainable development, where accurate flood hazard and risk mapping play an indispensable role in achieving this goal [9-11].

This study aims to fill a critical void in flood risk mapping for Imo State by integrating pertinent factors into a Multi-Criteria Analysis (MCA) technique. Significantly, the proven effectiveness of Multi-Criteria Analysis (MCA) techniques in global flood management underscores their strategic role in this [12-14]. The Otamiri River Basin in Imo State, serving as a vital water source for nearby communities, grapples with persistent flooding challenges despite existing drainage networks. This research project undertakes a comprehensive assessment of flood risk and vulnerability within the Otamiri River Basin, employing a combination of GIS, Analytical Hierarchical Process (AHP), and the Weighted Linear Combination (WLC) component of MCA [15,16]. Building upon the groundwork laid by previous researchers, including Okorafor et al. (2021). The overarching goal of this research is to furnish decision support information crucial for planners and decision-makers, who grapple with the severe consequences of flooding in Otamiri town. Through the identification and mapping of potential flood risks, this study aims to contribute nuanced and valuable insights, thereby facilitating proper planning and mitigation efforts, and ultimately addressing critical gaps in the existing literature on flood risk mapping and vulnerability assessment [17,18].

1.1 Study Area

The study area in this investigation is Owerri, the capital city of Imo State in southeastern Nigeria, using Otamiri river basin as data collecting points. Otamiri drainage basin lies within longitudes 06^0 57'E and 07^0 07'E and latitudes $05^0$25'N and $05^0$32'N. The river with the length of 105 kilometers is the principal tributary of Imo River-a major river that washes through the landscape of Imo state. Imo State has a high population density; available statistics show that the study area has a population density of 814 persons per square kilometer.

The mean monthly temperature for dry season is 34^oC and 30^oC for rainy season. The river has average maximum flow of $10.7m^3/s$ in the rainy season (September – October) and a minimum average flow of about $3.4m^3/s$ in the dry season (November to February). The total annual discharge of the Otamiri is about $1.7\times10^8m^3$, and 22% of this ($3.4\ \times10^7m^3$) comes from direct runoff from rainwater and constitutes the safe yield of the river (Egboka and Uma, 1985). The area experiences two air masses – the Tropical Maritime Air mass which originates from the Southern high-pressure belts, crosses the equator, picks up moisture from over the Atlantic, enters Nigeria from the South, and then ushers in the rainy season. The Tropical Continental Air mass which enters the country from the Northeast and carries little or no moisture is responsible for the dry season. The area is low lying, being generally about 300m above sea level. The main stream draining the study area is the Otamiri River. The area presents a more or less dendritic pattern of drainage. [19,20].

2. MATERIALS AND METHODS

2.1 Methodology

The systematic methodology employed in this study commenced with the acquisition of Soil data, Precipitation data, River data, Road data, Sentinel-2 imagery and SRTM DEM, covering the entirety of the designated study area. This initial step aimed to secure a comprehensive and high-resolution dataset that would serve as the foundational source for subsequent analyses. Following the acquisition phase, a series of image pre-processing techniques were implemented. These pre-processing steps were crucial for enhancing the clarity and interpretability of the acquired imagery, ensuring that the subsequent analyses would be based on refined and accurate visual information.

Following image pre-processing, the study progressed to image classification using maximum likelihood for supervised classification. This entailed creating signature samples for each identified class feature in the imagery. These samples were then utilized to categorize and delineate distinct land cover and land use patterns within the acquired imagery. The resulting classification output generated a detailed dataset, capturing the spatial distribution of various land cover and land use categories across the study area. Subsequently, road and river data were converted to raster data, and Euclidean distances were computed from the converted raster dataset.

A crucial step in the methodology was the extraction of relevant environmental factors essential for flood modeling. Factors such as drainage density, slope, Topographic Wetness Index (TWI), and elevation were obtained from the SRTM DEM. Additionally, NDVI was systematically derived from Sentinel-2 imagery using band ratios. Precipitation and soil type data for the study area were extracted from soil and precipitation datasets.

To ensure compatibility and consistency in subsequent modeling efforts, a meticulous process of classification and standardization was applied to the extracted factors. This involved transforming the diverse data types and scales of the factors into a uniform Euclidean raster format, ranging from 1 to 5. This standardized format facilitated the seamless integration of these factors into the modeling framework, ensuring that each variable contributed proportionally and comparably to the overall flood hazard assessment (refer to Table 1).

The determination of modeling weights for each factor was a crucial step in the methodology. This was achieved through a rigorous pairwise comparison process see Tables 2 and 3, wherein the relative importance of each factor in influencing flood hazard was systematically evaluated by a consensus of multiple experts within the study area. This step added a layer of precision to the modeling process, accounting for the varying degrees of impact that each environmental factor exerted on the overall flood risk within the study area.

Table 1. Reclassification and standardization of factors according to levels of vulnerability

Flood Causative Criterion	Unit	Class	Susceptibility	Class Ratings
Topographic wetness index(TWI)	Level	≤ -3.3628	Very low	1
		≤ -1.1741	low	2
		≤ 1.0875	Moderate	3
		≤ 4.0057	High	4
		≤ 11.6661	Very high	5
Elevation	m	7 - 36	Very high	5
		36 - 57	High	4
		57 - 77	Moderate	3
		77 - 104	low	2
		104 -144	Very low	1
Slope	%	0 - 0.727	Very high	5

Flood Causative Criterion	Unit	Class	Susceptibility	Class Ratings
		0.728 -1.818	High	4
		1.819 - 3.345	Moderate	3
		3.345 - 5.962	low	2
		5.963 -18.54	Very low	1
Precipitation	mm/year	1.001 - 1.648	Very low	1
		1.649 - 2.174	low	2
		2.175 - 2.587	Moderate	3
		2.588 - 3.09	High	4
		3.091 - 3.851	Very high	5
Landuse/Landcover	Level	Water	Very high	5
		Developed	High	4
		Bare soil	Moderate	3
		Light vegetation	low	2
		Heavy vegetation	Very low	1
NDVI	Level	≤0.191	Very high	5
		0.192 - 0.319	High	4
		0.32 - 0.425	Moderate	3
		0.426 - 0.505	low	2
		0.506 - 0.709	Very low	1
Distance from river	m	0 - 0.019	Very high	5
		0.02 - 0.042	High	4
		0.043 - 0.068	Moderate	3
		0.069 - 0.094	low	2
		0.095 -0.129	Very low	1
Distance from road	m	0 - 0.014	Very high	5
		0.015 - 0.031	High	4
		0.032 - 0.051	Moderate	3
		0.051 - 0.074	low	2
		0.075 - 0.111	Very low	1
Soil type	Level	Sandy loam	Very high	5
		Clay loam	Moderate	3
		Silt loam	Very low	2
Drainage density	m/km	0.001 - 13.77	Very low	1
		13.77 - 38.182	low	2
		38.183 - 62.593	Moderate	3
		62.594 - 90.76	High	4
		90.761 -159.612	Very high	5

Following Tables 2 and 3, the value of Consistency index, CI was calculated from the pairwise matrix according to equation:

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

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 = (7.30*0.13) + (18.80*0.07) + (10.60*0.09) + (4.30*0.22) + (22.30*0.04) + (21*0.05) + (7.5*0.12) + (19*0.05) + (13.5*0.09) + (17*0.09)

λmax = 10.67

CI = (10.67 – 10)/ (10-1) = 0.074

In calculating the consistency ratio, the random index (RI) (Table 4) is the index of a randomly generated pair-wise comparison matrix of order 1 to 10 obtained by approximating random indices, (Saaty, 2001).

Table 2. Pair-Wise comparison matrix for flood vulnerability

Criterion	TWI	Elevation	Slope	Precipitation	LULC	NDVI	Dist. from Waterbody	Dist. From Road	Drainage Density	Soil
Topographic wetness index(TWI)	1	2	1	1	3	5	1	3	1	1
Elevation	0.5	1	1	0	2	3	1	3	0	0
Slope	1	1	1	0	3	1	1	1	1	3
Precipitation	1	5	3	1	3	2	2	3	5	5
LULC	0.3	0.5	0.3	0.3	1	1	0	3	0	0
NDVI	0.2	0.3	1	0.5	1	1	0	1	1	1
Distance from Waterbody	1	1	1	0.5	3	5	1	3	2	1
Distance from Road	0.3	0	1	0.3	0.3	1	0	1	2	2
Drainage Density	1	3	1	0.2	3	1	0.5	0.5	1	3
Soil	1	5	0.3	0.5	3	1	1	0.5	0.3	1
Total	7.3	18.8	10.6	4.3	22.3	21	7.5	19	13.3	17

Table 3. Normalized Pairwise Comparison Matrix for flood vulnerability

Criterion	TWI	Elevation	Slope	Precipitation	LULC	NDVI	Dist. from Waterbody	Dist. From Road	Drainage Density	Soil	Mean
Topographic wetness index(TWI)	0.14	0.11	0.09	0.23	0.13	0.24	0.13	0.16	0.08	0.06	0.14
Elevation	0.07	0.05	0.09	0.00	0.09	0.14	0.13	0.16	0.00	0.00	0.07
Slope	0.14	0.05	0.09	0.00	0.13	0.05	0.13	0.05	0.08	0.18	0.09
Precipitation	0.14	0.27	0.28	0.23	0.13	0.10	0.27	0.16	0.38	0.29	0.22
LULC	0.04	0.03	0.03	0.07	0.04	0.05	0.00	0.16	0.00	0.00	0.04
NDVI	0.03	0.02	0.09	0.12	0.04	0.05	0.00	0.05	0.08	0.06	0.05
Distance from Waterbody	0.14	0.05	0.09	0.12	0.13	0.24	0.13	0.16	0.15	0.06	0.13
Distance from Road	0.04	0.00	0.09	0.07	0.01	0.05	0.00	0.05	0.15	0.12	0.06
Drainage Density	0.14	0.16	0.09	0.05	0.13	0.05	0.07	0.03	0.08	0.18	0.10
Soil	0.14	0.27	0.03	0.12	0.13	0.05	0.13	0.03	0.02	0.06	0.10

Table 4. Random Index by Saaty

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

Therefore, using Table 4, the consistency ratio = 0.0.74/1.49 = 0.04

CR = 0.05 < 0.10 (Acceptable)

The consistency ratio (CR) is design in such a way that if CR<0.10, the ratio indicates a reasonable level of consistency in the pairwise comparisons; if, however, CR ≥ 0.10, the values of the ratio are indicative of inconsistent judgments. From the judgment a Consistency Ratio (CR) of 0.05 was achieved, which was less than the maximum allowable ratio of 0.10, hence the judgement is accepted.

With the modeling weights established by normalizing the pairwise matrix to obtain the weights and the consistency ratio, the study proceeded to the development of a comprehensive flood hazard index model. This model, informed by the weighted factors, provided a spatially explicit representation of flood risk across the study area. The integration of various environmental factors and the consideration of their relative importance through the modeling process contributed to a nuanced and accurate assessment of flood hazards.

3. RESULTS AND DISCUSSION

The results reveal different flood vulnerability zones in Owerri, each associated with a specific area in square kilometers. These zones are used to assess the susceptibility of the study area to flooding (Figs 1 and 2).

Referring to Figs 1 and 2, the vulnerability levels in Owerri can be segmented into five distinct categories, each with varying implications for flood risk and development:

Very Low Vulnerability: This zone, covering a mere 0.1 km², accounts for just 0.09% of the total area. It signifies that this area is at the lowest risk of flooding in Owerri. Consequently, it is a relatively safe region for diverse development and infrastructure projects. Residents and authorities can approach this zone with greater confidence, experiencing fewer concerns regarding flood-related issues.

Table 5. Communities at risk of flooding

	Level of Vulnerability
Umuokpo	Moderate Vulnerability
Umuagwo	Moderate Vulnerability
Emeabiam	Moderate Vulnerability
Opete	Moderate Vulnerability
Obite	Moderate Vulnerability
Ibitte	Moderate Vulnerability
Umuikea-Emeabiam	Moderate Vulnerability
Obitti	Moderate Vulnerability
Umuikea	Moderate Vulnerability
Mberichi	Moderate Vulnerability
Umuuvo	Moderate Vulnerability
Umu-Okanne	Moderate Vulnerability
Okolochi	Moderate Vulnerability
Ezio0bodo	Moderate Vulnerability
Assa	Moderate Vulnerability
Obeke	Moderate Vulnerability
Amorie	Moderate Vulnerability
Umuokwo	Moderate Vulnerability
Umuaje	Moderate Vulnerability
Obinze	Moderate Vulnerability
Amaeze	Moderate Vulnerability
Ihiagwa	Moderate Vulnerability

	Level of Vulnerability
Emekeobibi	Moderate Vulnerability
Ohoba	Moderate Vulnerability
Ubube	Moderate Vulnerability
Oforola	Moderate Vulnerability
Umukida-Emeke	Moderate Vulnerability
Umugolog	Moderate Vulnerability
Umugologo	Moderate Vulnerability
Obesema	Moderate Vulnerability
Agbabia	Moderate Vulnerability
Umu-Oma	Moderate Vulnerability
Agbala	Moderate Vulnerability
Nekede	Moderate Vulnerability
Emohe	Moderate Vulnerability
Umejeren	Moderate Vulnerability
Avu	Moderate Vulnerability
Obosima	Moderate Vulnerability
Ekpe-Aga	Moderate Vulnerability
Naze	Moderate Vulnerability
Umudulu	Moderate Vulnerability
Ubah	Moderate Vulnerability
Oboku-Avu	Moderate Vulnerability
Emii	Moderate Vulnerability
Emii	Moderate Vulnerability
Umuolu	Moderate Vulnerability
Amafor	Moderate Vulnerability
Umuawuka	Moderate Vulnerability
Obigwe	Moderate Vulnerability
Etekwuru	Moderate Vulnerability
Awaka	Moderate Vulnerability
Obogwe	Moderate Vulnerability
Emekuku	Moderate Vulnerability
Amapun	Moderate Vulnerability
Ogbosisi	Moderate Vulnerability
Egbu	Moderate Vulnerability
Ekugba	Moderate Vulnerability
Owala	Moderate Vulnerability
Etekura	Moderate Vulnerability
Uborji	Moderate Vulnerability
Umuorji	Moderate Vulnerability
Obomo-Enyiogugu	Moderate Vulnerability
Owerri	Moderate Vulnerability
Ihitte	Moderate Vulnerability
Ekeugba	Moderate Vulnerability
Ekeigbo	Moderate Vulnerability
Mgbara	Moderate Vulnerability
Abacheke	Moderate Vulnerability
Obufie-Mmahu	Moderate Vulnerability
Ndegwu	Moderate Vulnerability
Amakohia	Moderate Vulnerability
Irete	Moderate Vulnerability
Owalla	Moderate Vulnerability
Amakohia	Moderate Vulnerability
Amakohia-Ubi	Moderate Vulnerability
Oseakishikpa	Moderate Vulnerability
Orji	Moderate Vulnerability

	Level of Vulnerability
Umunamo	Moderate Vulnerability
Obofia	Moderate Vulnerability
Umunwaoha	Moderate Vulnerability
Umuoka	Moderate Vulnerability
Nworieubi	Moderate Vulnerability
Orogwe	Moderate Vulnerability
Ose-Acheke	Moderate Vulnerability
Obiokwu	Moderate Vulnerability
Umuopiri	Moderate Vulnerability
Obokofia	Moderate Vulnerability
Umuike	Moderate Vulnerability
Ukwu-Ugba	Moderate Vulnerability
Ohi	Moderate Vulnerability
Oseogwugwu	Moderate Vulnerability
Ukwagba	Moderate Vulnerability
Obiakpu	Moderate Vulnerability
Obeaka	Moderate Vulnerability
Nwari	Moderate Vulnerability
Nwan	Moderate Vulnerability
Mkpatuku	Moderate Vulnerability
Oburuoto	Moderate Vulnerability
Elue	Moderate Vulnerability
Ohobu	Low Vulnerability
Obuogwu	Low Vulnerability
Umukirie	Low Vulnerability
Okuku	Low Vulnerability
Ubotji	Low Vulnerability
Okwu	Low Vulnerability
Ubegbelu	Low Vulnerability
Umunahu	Low Vulnerability
Owaelu	Low Vulnerability
Ezi-Ossu-Camp	Low Vulnerability
Umuapu	High Vulnerability
Ngbisi	High Vulnerability
Oburugo	High Vulnerability
Etioha	High Vulnerability
Eteoha	High Vulnerability
Umuokoro	High Vulnerability
Umukunne-Graduate-Farm	High Vulnerability
Nkasi	High Vulnerability
Umukene	High Vulnerability
Umuagwo	High Vulnerability
Ihie	High Vulnerability
Mbyisii	High Vulnerability
Ogbeke	High Vulnerability
Awara	High Vulnerability
Ilile	High Vulnerability
Mgbirichi	High Vulnerability
Umuoku	High Vulnerability
Umuoguma	High Vulnerability

Low Vulnerability: Spanning 166.01 km², which corresponds to 12.93% of Owerri's total area, the low vulnerability zone is significantly larger. It indicates a lower risk of flooding compared to other parts of the city. This implies that urban development and infrastructure projects can proceed with a reasonable degree of confidence within this zone. However, it is essential to exercise caution and preparedness measures, given that no area is entirely immune to the threat of flooding.

Moderate Vulnerability: Encompassing a substantial 883.70 km², constituting 68.83% of Owerri,the moderate vulnerability zone is the most extensive flood vulnerability category. Its designation as "moderate vulnerability" suggests a notable flood risk. Urban planners, local authorities,and residents must prioritize flood management and preparedness within this area, recognizing the significance of its susceptibility to floods.

High Vulnerability: Covering 233.45 km², representing 18.18% of the city's area, the high vulnerability zone, although smaller than the moderate vulnerability zone, presents a considerable flood risk. Flood impact could be severe for both residents and infrastructure within this region. Therefore, stringent flood risk mitigation measures are imperative to protect lives and property.

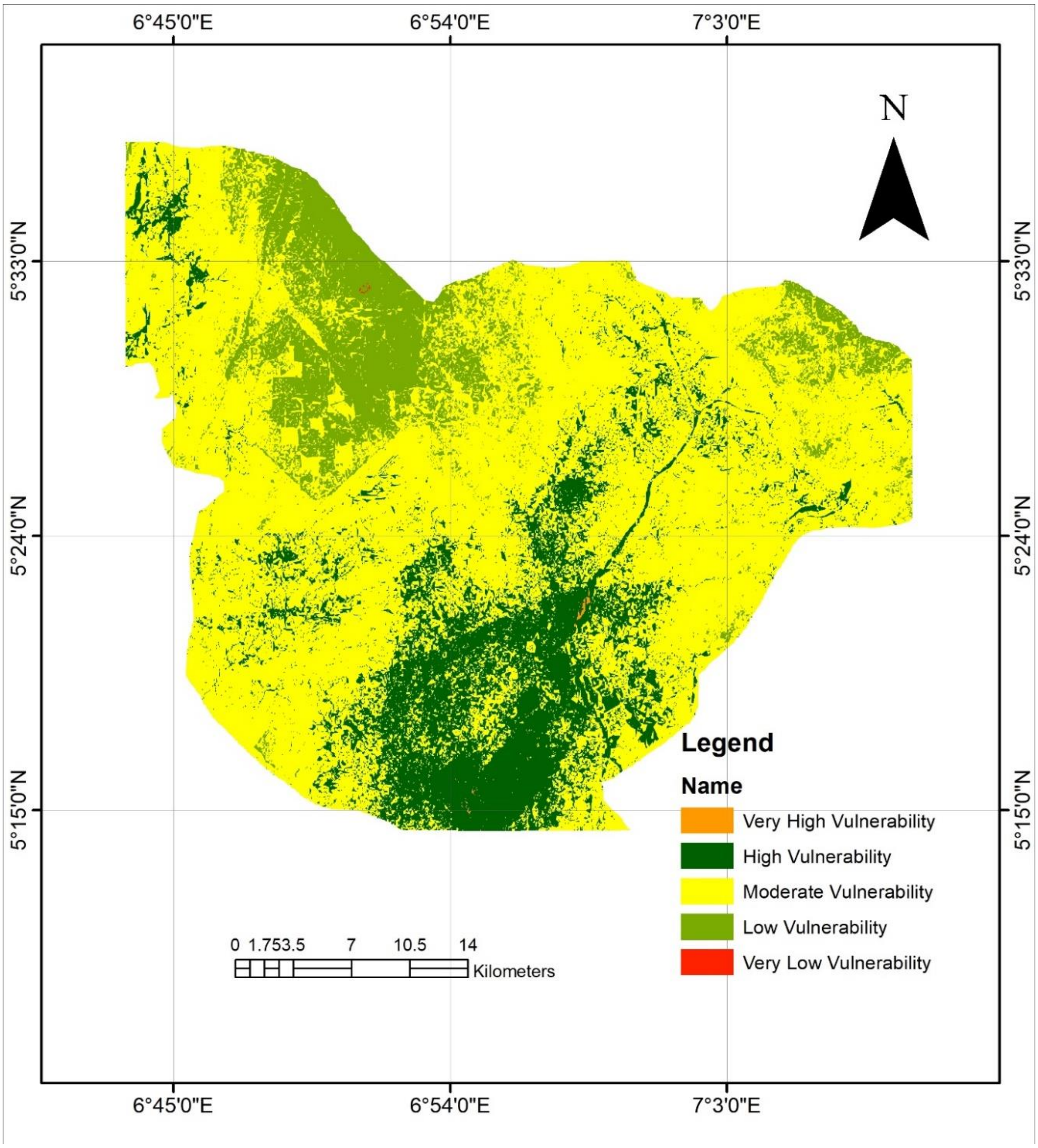

Fig. 1. Flood vulnerability map

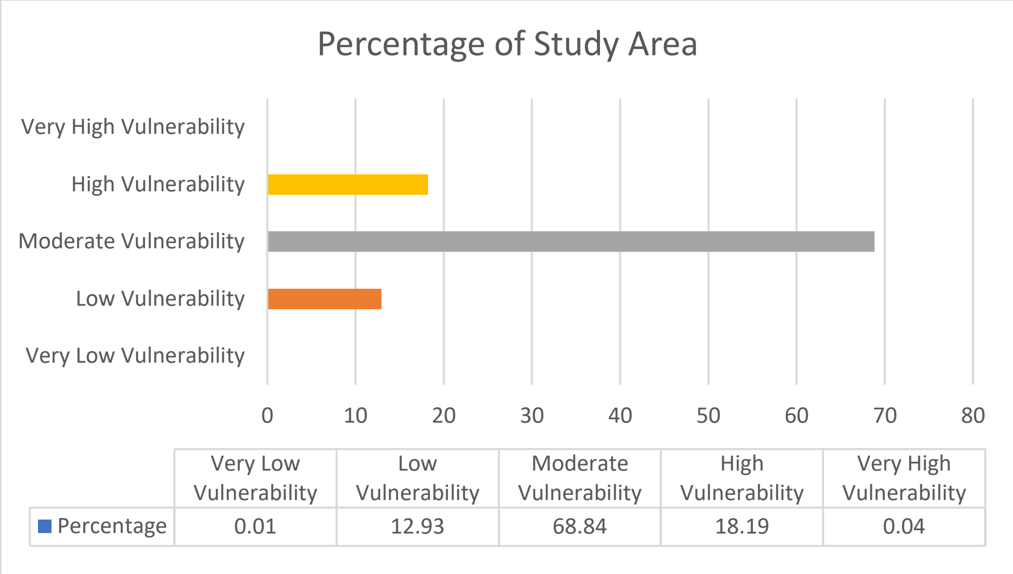

Fig. 2. Flood vulnerability zones within the study area

Very High Vulnerability: Despite its limited area of 0.51 km², making up just 0.03% of Owerri, the very high vulnerability zone is categorized as extremely high risk in terms of flooding. Its small size does not diminish the critical nature of the flood risk it presents. Consequently, special attention should be devoted to this area to minimize potential flood-related damage and risks, recognizing the gravity of its vulnerability.

In summary, the five vulnerability categories in Owerri provide valuable insights into flood risk, ranging from very low to very high. The size and risk level of each zone carry significant implications for urban development, infrastructure planning, and flood risk management. Each category demands a specific approach to ensure the safety and resilience of both residents and the built environment in the face of potential flooding.

Table 5 presents the vulnerability levels of various settlements to flooding. This holds a wealth of information that has significant implications for disaster preparedness and management in the affected regions.

4. CONCLUSION AND RECOMMENDATIONS

The comprehensive flood vulnerability assessment conducted in this research has provided valuable insights into the flood risk landscape of the study area, Owerri. The reclassification of various datasets into five distinct vulnerability categories, ranging from very low to very high, has allowed for a nuanced understanding of flood vulnerability, with each category carrying specific implications for development and flood risk management.

The findings reveal that Owerri's vulnerability levels are diverse, reflecting a range of flood risk scenarios. The very low vulnerability zone, albeit small, offers a safe environment for development, while the low vulnerability zone provides a larger area with a lower risk, although some caution and preparedness are still necessary. The moderate vulnerability zone, covering the majority of the city, underscores the importance of proactive flood management measures due to its significant susceptibility to floods. The high vulnerability zone, although smaller, poses a considerable flood risk, necessitating stringent risk mitigation strategies. The very high vulnerability zone, despite its limited area, demands special attention to minimize potential flood-related damage and risks.

Moreover, the categorization of surveyed communities into three distinct vulnerability groups - Low Vulnerability, Moderate Vulnerability, and High Vulnerability (Table 1) - highlights the varying degrees of flood risk within the region. This classification provides a basis for targeted resource allocation and disaster preparedness, ensuring that communities with different vulnerability levels receive appropriate attention and support.

In essence, these findings emphasize the need for tailored flood management strategies that recognize the specific vulnerabilities of different areas within Owerri. Effective resource allocation, proactive preparedness measures, and collaboration among local authorities, disaster management agencies, and the affected communities are essential to mitigate the impact of potential flood events and enhance the resilience of both residents and the built environment.

This research serves as a valuable foundation for informed decision-making and proactive flood risk mitigation in Owerri. By understanding the diverse vulnerability levels and their implications, stakeholders can work together to create a safer and more resilient city in the face of potential flooding.

Based on the findings from this study the following recommendation are made:

1. Thorough scrutiny of developmental projects in flood-prone regions is imperative, with a focus on identifying and addressing the specific factors contributing to flooding to effectively mitigate the associated hazards.
2. Rigorous monitoring is advised for all impending structures in the southern section of the research area due to the heightened vulnerability to flooding. The potential consequences include severe damage and elevated risks, making pre-emptive measures crucial.
3. The findings of this study are proposed to serve as foundational data for future flood-related investigations within the study area, establishing a valuable baseline for ongoing and forthcoming research endeavours.
4. Ongoing attention and oversight are recommended for the implementation of an adequate drainage and channelization system. Additionally, strict adherence to regulated planning schemes in Owerri urban should be closely monitored by researchers to ensure effective flood management.
5. Constructing drainage systems that follow the natural flow or free movement of floodwaters is advisable. This approach facilitates unobstructed water flow and passage, contributing to a more efficient and natural flood management system.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/109715