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GIS-Based Flood Susceptibility Mapping Using the Analytical Hierarchy Process and Weighted Linear Combination in Warri North Local Government Area, Delta State, Nigeria

Anyadiegwu P C
Department of Surveying and Geoinformatics, Imo State University Owerri, Imo State, Nigeria

* Corresponding Author: **Anyadiegwu P C**

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Abstract
Flooding is one of the most recurrent environmental hazards affecting the Niger Delta, where low-lying terrain, dense river networks, tidal influence, and intense rainfall contribute to widespread inundation and increasing vulnerability of coastal communities. This study assessed flood susceptibility in Warri North Local Government Area, Delta State, Nigeria, using a Geographic Information System (GIS)-based Multi-Criteria Decision Analysis (MCDA) framework integrating the Analytical Hierarchy Process (AHP) and Weighted Linear Combination (WLC). Seven flood conditioning factors, namely elevation, slope, rainfall, soil, distance to river, distance to coastline, and land use/land cover (LULC), were selected based on their influence on flood occurrence. The factors were standardized to a common suitability scale, while their relative importance was determined using the Analytical Hierarchy Process. Pairwise comparisons produced a Consistency Ratio (CR) of 0.052, indicating acceptable consistency in the assigned criterion weights. The weighted factors were integrated using the WLC technique to generate the Flood Susceptibility Index (FSI), which was subsequently classified into five flood susceptibility categories: Very Low, Low, Moderate, High, and Very High. The results revealed that the Very High flood susceptibility class occupies 681.93 km² (37.29%) of the study area, while the High susceptibility class covers only 4.00 km² (0.22%). The Moderate, Low, and Very Low susceptibility classes account for 390.87 km² (21.38%), 389.55 km² (21.30%), and 362.18 km² (19.81%), respectively. Collectively, the High and Very High susceptibility classes occupy 685.93 km² (37.51%), indicating that more than one-third of the Local Government Area is highly susceptible to flooding. Settlement overlay analysis identified 41 settlements within the Very High susceptibility class, 61 settlements within the Moderate class, 42 settlements within the Very Low class, 9 settlements within the Low class, and no settlement within the High susceptibility class. The observed spatial pattern demonstrates that flood susceptibility in Warri North is primarily controlled by the interaction of low elevation, gentle slopes, proximity to river channels, coastal influence, high rainfall, poorly drained soils, and land use characteristics. The resulting flood susceptibility map provides a reliable spatial decision-support tool for flood risk reduction, sustainable land use planning, infrastructure development, disaster preparedness, and climate adaptation within Warri North Local Government Area and other coastal environments of the Niger Delta.

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1. Introduction

Flooding is one of the most destructive natural hazards globally, affecting millions of people annually through the loss of lives, destruction of infrastructure, disruption of economic activities, environmental degradation, and displacement of communities. Floods occur in different forms, including riverine, coastal, flash, urban, and groundwater flooding, depending on the dominant hydrological processes and environmental conditions (National Oceanic and Atmospheric Administration [NOAA], 2013) [4]. The increasing frequency and magnitude of flood events have been associated with climate variability, extreme rainfall, sealevel rise, rapid urbanization, and alterations to natural drainage systems, making flood risk management a priority for sustainable development worldwide (United Nations Office for Disaster Risk Reduction [UNDRR], 2015) [6]. Nigeria has experienced recurrent flood disasters over the past decades, with several events producing widespread socio-economic and environmental consequences across the country. Reports by the Nigeria Hydrological Services Agency (NIHSA, 2018) [9] identified many states along the Niger and Benue River systems as highly vulnerable to annual flooding. The devastating floods of recent years have resulted in extensive damage to residential buildings, transportation infrastructure, agricultural lands, and public utilities while disrupting livelihoods and increasing the vulnerability of affected populations (Ajumobi *et al*., 2023) [7]. Environmental impacts include soil erosion, deterioration of water quality, destruction of ecosystems, contamination of groundwater resources, and degradation of wetlands and biodiversity (Bariweni *et al*., 2012) [16]; (Edet, 1993) [13]; (Offidile, 1992) [14]. Flooding has therefore evolved from a seasonal hydrological phenomenon into a major environmental and developmental challenge requiring integrated planning and evidence-based mitigation strategies.

The Niger Delta represents one of the regions most susceptible to flooding in West Africa because of its extensive river networks, low elevations, tidal influence, coastal wetlands, and humid tropical climate. Seasonal flooding within the region results from the combined influence of intense rainfall, overflow of distributary river channels, tidal backwater effects, and coastal processes (Eteh *et al*., 2024) [17]. Dam operations upstream of the Niger River have also been shown to influence downstream flood behaviour by modifying river discharge during the rainy season, thereby increasing flood extent within several parts of the delta (Eteh *et al*., 2024) [17]. The environmental consequences of flooding are further compounded by degradation of mangrove ecosystems arising from oil exploration and pollution. Mangrove forests function as natural flood attenuation systems by reducing runoff velocity, stabilizing shorelines, and temporarily storing floodwaters; however, continued degradation has reduced their capacity to regulate flood processes across the Niger Delta (Jonathan *et al*., 2025) [18]. The rich mangrove ecosystems that characterize southern Nigeria therefore perform important hydrological and ecological functions whose degradation increases landscape vulnerability to flooding (Asuk *et al*., 2018) [15].

Warri North Local Government Area, located within the western Niger Delta of Delta State, is among the coastal environments that experience recurrent flooding because of its low-lying terrain, dense network of distributary channels, tidal creeks, estuaries, wetlands, and proximity to the Atlantic coastline. The Local Government Area is characterized by poorly drained floodplains and extensive mangrove swamps that are periodically inundated during the rainy season. Flood events frequently disrupt transportation, damage residential and commercial infrastructure, affect fishing and agricultural activities, and constrain socio-economic development within riverine communities. Shoreline instability and continuous coastal morphological changes further modify drainage conditions and increase exposure to coastal flooding (Jonathan and Charles, 2025) [12]; (Oborie *et al*., 2023) [31]; (Osondu *et al*., 2025) [32]. These environmental characteristics necessitate comprehensive spatial assessment of flood susceptibility to support effective land use planning and disaster risk reduction.

Recent advances in Geographic Information Systems (GIS), Remote Sensing (RS), and earth observation technologies have significantly improved flood hazard assessment by enabling the integration of multiple environmental variables within a spatial modelling framework. Digital Elevation Models derived from the Shuttle Radar Topography Mission (SRTM) provide reliable information for terrain analysis and hydrological modelling (Farr *et al*., 2007) [20], while multispectral satellite imagery facilitates the extraction of land use and land cover information that influences runoff generation and infiltration. The Semi-Automatic Classification Plugin has further enhanced the efficient processing and classification of remotely sensed imagery within GIS environments (Congedo, 2021) [21]. Satellite observations acquired using Sentinel-1 Synthetic Aperture Radar (SAR) have also demonstrated considerable effectiveness for flood extent mapping, particularly within cloud-prone tropical environments where optical imagery is frequently limited (Thomas *et al*., 2020) [19].

Machine learning techniques have recently enhanced flood susceptibility modelling by improving predictive accuracy and enabling the integration of complex environmental datasets. Applications of machine learning have been reported for flood inundation mapping, flood depth estimation, runoff modelling, shoreline prediction, erosion assessment, and watershed prioritization (Prakash *et al*., 2021) [23]; (Saha *et al*., 2021) [26]; (Nhangumbe *et al*., 2023) [33]; (Ali *et al*., 2025) [27]. Similar techniques have also been applied to runoff dynamics within Bayelsa State (Jonathan *et al*., 2025) [11], shoreline change prediction in coastal Nigeria (Osondu *et al*., 2025) [32], and diverse geospatial applications involving environmental monitoring and hazard assessment (Corradino *et al*., 2019) [29]; (Chukwuemeka *et al*., 2025) [3]. Machine learning has further been integrated with geospatial datasets to support environmental planning and infrastructure suitability analysis, including dam site selection (Akajiaku *et al*., 2025) [36]. The broader adoption of artificial intelligence across engineering and environmental applications further demonstrates its increasing role in supporting spatial decision-making and sustainable infrastructure development (Oseji *et al*., 2025a) [34]; (Oseji *et al*., 2025b) [35].

Although machine learning provides powerful predictive capabilities, flood susceptibility assessment frequently relies on Multi-Criteria Decision Analysis (MCDA) techniques where historical flood inventories are limited. The Analytical Hierarchy Process (AHP) remains one of the most widely adopted MCDA techniques because it provides a structured procedure for assigning relative importance to environmental variables through pairwise comparisons while evaluating the logical consistency of expert judgements. When integrated with the Weighted Linear Combination (WLC) technique within a GIS environment, AHP enables the systematic combination of multiple flood conditioning factors to generate reliable flood susceptibility maps. Previous studies have successfully applied GIS-based AHP for flood risk evaluation and susceptibility mapping in different parts of Nigeria, including Bayelsa and Delta States (Eteh *et al*., 2019) [2]; (Oladimeji and Ohwo, 2022) [1]; (Chukwu *et al*., 2023) [8]. Similar GIS-based AHP frameworks have also been employed for environmental suitability analysis and spatial decision-making in other application domains (Joy *et al*., 2024) [24].

Flood vulnerability is influenced not only by natural environmental processes but also by patterns of human settlement and land use. Expansion of settlements into floodplains, increasing pressure on coastal resources, landscape modification, and informal urban development have significantly increased exposure to flood hazards in many developing countries (Amoako and Inkoom, 2017) [28]. Land use and land cover changes resulting from urban expansion and environmental degradation alter infiltration capacity, runoff generation, and the hydrological behaviour of floodplain ecosystems (Abaye *et al*., 2022) [30]; (Saha *et al*., 2024) [25]. Soil degradation and contamination associated with anthropogenic activities may also influence infiltration characteristics and surface hydrological responses within coastal environments (Amukali *et al*., 2018) [22]; (Nwankwoala *et al*., 2020) [10]. These interacting natural and human-induced processes highlight the importance of integrating multiple environmental variables during flood susceptibility assessment.

Despite numerous flood investigations undertaken within the Niger Delta, detailed flood susceptibility assessments focusing specifically on Warri North Local Government Area remain limited. Existing studies have primarily concentrated on flood hazard mapping, flood risk assessment, runoff modelling, shoreline dynamics, flood extent mapping, and environmental change at broader regional scales (Eteh *et al*., 2019) [2]; (Oladimeji and Ohwo, 2022) [1]; (Jonathan *et al*., 2025) [11]; (Osondu *et al*., 2025) [32]. Comprehensive integration of elevation, slope, rainfall, soil, distance to river, distance to coastline, and land use/land cover within an Analytical Hierarchy Process and Weighted Linear Combination framework has received comparatively little attention within Warri North. Consequently, spatial information required for local-scale flood mitigation, infrastructure planning, and sustainable land use management remains inadequate.

This study therefore employed a Geographic Information System-based Analytical Hierarchy Process (AHP) and Weighted Linear Combination (WLC) framework to assess flood susceptibility in Warri North Local Government Area, Delta State, Nigeria. Seven flood conditioning factors comprising elevation, slope, rainfall, soil, distance to river, distance to coastline, and land use/land cover were integrated to generate a Flood Susceptibility Index and identify settlements exposed to varying levels of flood hazard. The resulting flood susceptibility map provides a scientific basis for flood risk reduction, sustainable land use planning, infrastructure development, emergency preparedness, and climate adaptation within Warri North Local Government Area and similar coastal environments of the Niger Delta.

2. Materials and Methods

Warri North Local Government Area is located in the western part of Delta State, Nigeria, within the Niger Delta coastal region. The Local Government Area lies approximately between latitudes 5°40′N and 6°09′N and longitudes 5°02′E and 5°35′E, covering an area of approximately 1,828.53 km². The area is characterized by extensive floodplains, mangrove swamps, freshwater wetlands, tidal creeks, distributary channels, and estuarine environments. The terrain is predominantly low-lying with very gentle slopes, while the climate is humid tropical with high annual rainfall exceeding 2,500 mm. Fishing, farming, oil and gas exploration, and water transportation constitute the major economic activities. Owing to its location within the Niger Delta coastal plain, Warri North experiences frequent riverine and coastal flooding resulting from intense rainfall, river overflow, tidal influence, and poor drainage conditions.

2.1. Data Acquisition

Flood susceptibility modelling was carried out using remotely sensed and ancillary geospatial datasets. Seven flood conditioning factors were selected based on their influence on flood occurrence in coastal environments. These included elevation, slope, rainfall, soil, distance to river, distance to coastline, and land use/land cover (LULC).

The datasets employed in the study are presented in Table 1.

Table 1: Spatial Datasets Used for Flood Susceptibility Assessment

Dataset	Source	Spatial Resolution	Purpose
Digital Elevation Model (DEM)	Shuttle Radar Topography Mission (SRTM)	30 m	Elevation and slope derivation
Rainfall	CHIRPS Rainfall Dataset	0.05°	Rainfall distribution
Soil Map	FAO Digital Soil Database	250 m	Soil characteristics
River Network	HydroSHEDS/OpenStreetMap	Vector	Distance to river analysis
Coastline	OpenStreetMap	Vector	Distance to coastline analysis
Landsat 8 Operational Land Imager (OLI)	United States Geological Survey (USGS)	30 m	Land use/Land cover mapping
Administrative Boundary	Office of the Surveyor General	Vector	Extraction of study area

2.2. Data Preparation

The acquired datasets were preprocessed before spatial analysis. The Digital Elevation Model was clipped to the boundary of Warri North Local Government Area using the Extract by Mask tool in ArcGIS Pro. Elevation and slope raster layers were subsequently generated from the DEM using the Surface Analysis tools.

The river network and coastline vector layers were converted into Euclidean distance raster surfaces to determine the shortest distance from every raster cell to the nearest river and coastline. The rainfall dataset was resampled to the spatial resolution of the DEM. The soil dataset was converted to raster format, while Landsat 8 imagery was classified using the Maximum Likelihood Classification algorithm to produce the land use/land cover map.

2.3. Selection of Flood Conditioning Factors

Seven flood conditioning factors were selected based on their established influence on flood occurrence in coastal floodplain environments. Elevation determines the direction of surface runoff and identifies low-lying areas where floodwaters accumulate. Slope controls runoff velocity and influences the duration of water retention on the landscape. Rainfall supplies the primary hydrological input responsible for runoff generation. Soil influences infiltration capacity, permeability, and surface runoff production. Distance to river represents susceptibility associated with river overflow and floodplain inundation. Distance to coastline accounts for tidal influence, coastal flooding, and storm surge effects. Land use/land cover modifies infiltration, evapotranspiration, and runoff generation through differences in vegetation cover and impervious surfaces.

2.4. Standardization of Flood Conditioning Factors

The selected flood conditioning factors were measured using different units and scales; consequently, they were standardized before integration. Raster reclassification was performed to convert all factors into a common flood susceptibility scale ranging from 1 (Very Low) to 5 (Very High).

Table 2: Factor Standardization

Standardized Value	Flood Susceptibility
1	Very Low
2	Low
3	Moderate
4	High
5	Very High

Factors positively associated with flooding, including rainfall and poorly drained soils, received increasing susceptibility values as their magnitude increased. Conversely, factors negatively associated with flooding, including elevation, slope, distance to rivers, and distance to coastline, received higher susceptibility scores at lower values because low elevations and shorter distances increase flood occurrence.

2.5. Analytical Hierarchy Process (AHP)

The relative importance of the seven flood conditioning factors was determined using the Analytical Hierarchy Process (AHP) proposed by Saaty (1980). The method provides a structured framework for deriving criterion weights through pairwise comparisons based on expert judgement. The selected flood conditioning factors comprised elevation, slope, rainfall, soil, distance to river, distance to coastline, and land use/land cover (LULC). Considering the hydrological characteristics of Warri North Local Government Area, distance to river was regarded as the most influential factor because flooding is primarily controlled by overflow from distributary channels and tidal creeks. Elevation was assigned the next highest importance because the predominantly low-lying terrain promotes prolonged inundation. Distance to coastline and rainfall were considered highly influential because tidal processes and intense precipitation jointly influence flood occurrence. Slope, soil, and land use/land cover were assigned comparatively lower importance.
Each criterion was compared with every other criterion using Saaty's nine-point fundamental scale, where 1 represents equal importance and 9 indicates extreme importance. Reciprocal values were assigned whenever one criterion was considered less important than another.

Table 3: Pairwise Comparison Matrix

Criteria	Elevation	Slope	Rainfall	Soil	Distance to River	Distance to Coastline	LULC
Elevation	1	3	2	4	1/3	2	5
Slope	1/3	1	1/2	2	1/5	1/2	3
Rainfall	1/2	2	1	3	1/4	1	4
Soil	1/4	1/2	1/3	1	1/6	1/3	2
Distance to River	3	5	4	6	1	3	7
Distance to Coastline	1/2	2	1	3	1/3	1	4
LULC	1/5	1/3	1/4	1/2	1/7	1/4	1

The pairwise comparison matrix was normalized by dividing each matrix element by the sum of its corresponding column. The normalized pairwise comparison matrix is presented in Table 3.

Table 4: Normalized Pairwise Comparison Matrix

Criteria	Elevation	Slope	Rainfall	Soil	River	Coastline	LULC	Row Average
Elevation	0.173	0.217	0.221	0.205	0.137	0.247	0.192	0.199
Slope	0.058	0.072	0.055	0.103	0.082	0.062	0.115	0.078
Rainfall	0.087	0.145	0.111	0.154	0.103	0.123	0.154	0.125
Soil	0.043	0.036	0.037	0.051	0.068	0.041	0.077	0.050
Distance to River	0.520	0.362	0.442	0.308	0.411	0.370	0.269	0.383
Distance to Coastline	0.087	0.145	0.111	0.154	0.137	0.123	0.154	0.130
LULC	0.035	0.024	0.028	0.026	0.059	0.031	0.038	0.035

The normalized weight for each criterion was obtained by averaging the values across each row and the final weights were obtained as in table 5.

Table 5: Final AHP Weights

Criterion	Weight	Percentage (%)	Rank
Distance to River	0.383	38.3	1
Elevation	0.199	19.9	2
Distance to Coastline	0.130	13.0	3
Rainfall	0.125	12.5	4
Slope	0.078	7.8	5
Soil	0.050	5.0	6
Land Use/Land Cover	0.035	3.5	7
Total	1.000	100.0	

The consistency of the pairwise comparisons was evaluated using the Consistency Index (CI) and Consistency Ratio (CR). For the seven-factor model,

$$\lambda max = 7.41$$

$$CI = 0.068$$

$$RI = 1.32$$

$$CR = 0.052$$

Since the calculated Consistency Ratio (0.052) is less than the acceptable threshold of 0.10, the pairwise comparisons are considered logically consistent, and the derived criterion weights are suitable for flood susceptibility modelling.

2.6. Weighted Linear Combination (WLC)

The standardized flood conditioning factors were integrated using the Weighted Linear Combination (WLC) approach. Each standardized raster layer was multiplied by its corresponding AHP-derived weight before summation to generate the Flood Susceptibility Index (FSI). For this study,

$$FSI = (0.199E) + (0.078S) + (0.125R) + (0.050So) + (0.383DR) + (0.130DC) + (0.035L)$$

where
FSI = Flood Susceptibility Index,
E = Elevation,
S = Slope,
R = Rainfall,
So = Soil,
DR = Distance to River,
DC = Distance to Coastline,
L = Land Use/Land Cover.

The resulting Flood Susceptibility Index raster was classified into five susceptibility classes (Very Low, Low, Moderate, High, and Very High) using the Natural Breaks (Jenks) classification algorithm.

2.7. Settlement Exposure Analysis

Settlement locations were overlaid on the final flood susceptibility map using the Spatial Join tool in ArcGIS Pro. Each settlement inherited the flood susceptibility class corresponding to its geographic location. The resulting database was used to determine the number and distribution of settlements within each flood susceptibility class and to evaluate community exposure to flood hazards across Warri North Local Government Area.

3. Results

3.1. Spatial Pattern of Flood Susceptibility in Warri North Local Government Area

The integration of elevation, slope, rainfall, soil, distance to river, distance to coastline, and land use/land cover (LULC) using the Analytical Hierarchy Process (AHP) and Weighted Linear Combination (WLC) produced the flood susceptibility map of Warri North Local Government Area (Figure 3.1). The resulting Flood Susceptibility Index (FSI) was classified into five categories representing increasing levels of flood susceptibility: Very Low, Low, Moderate, High, and Very High.

Rather than exhibiting a gradual transition from low to high susceptibility, the flood susceptibility pattern reveals a distinct dominance of the extreme susceptibility class. The spatial statistics of the classified map are presented in Table 6, while the spatial arrangement of the susceptibility classes is illustrated in Figure 1.

Table 6: Extent of Flood Susceptibility Classes in Warri North Local Government Area

Flood Susceptibility Class	Area (km²)	Percentage (%)
Very Low	362.18	19.81
Low	389.55	21.30
Moderate	390.87	21.38
High	4.00	0.22
Very High	681.93	37.29
Total	1,828.53	100.00

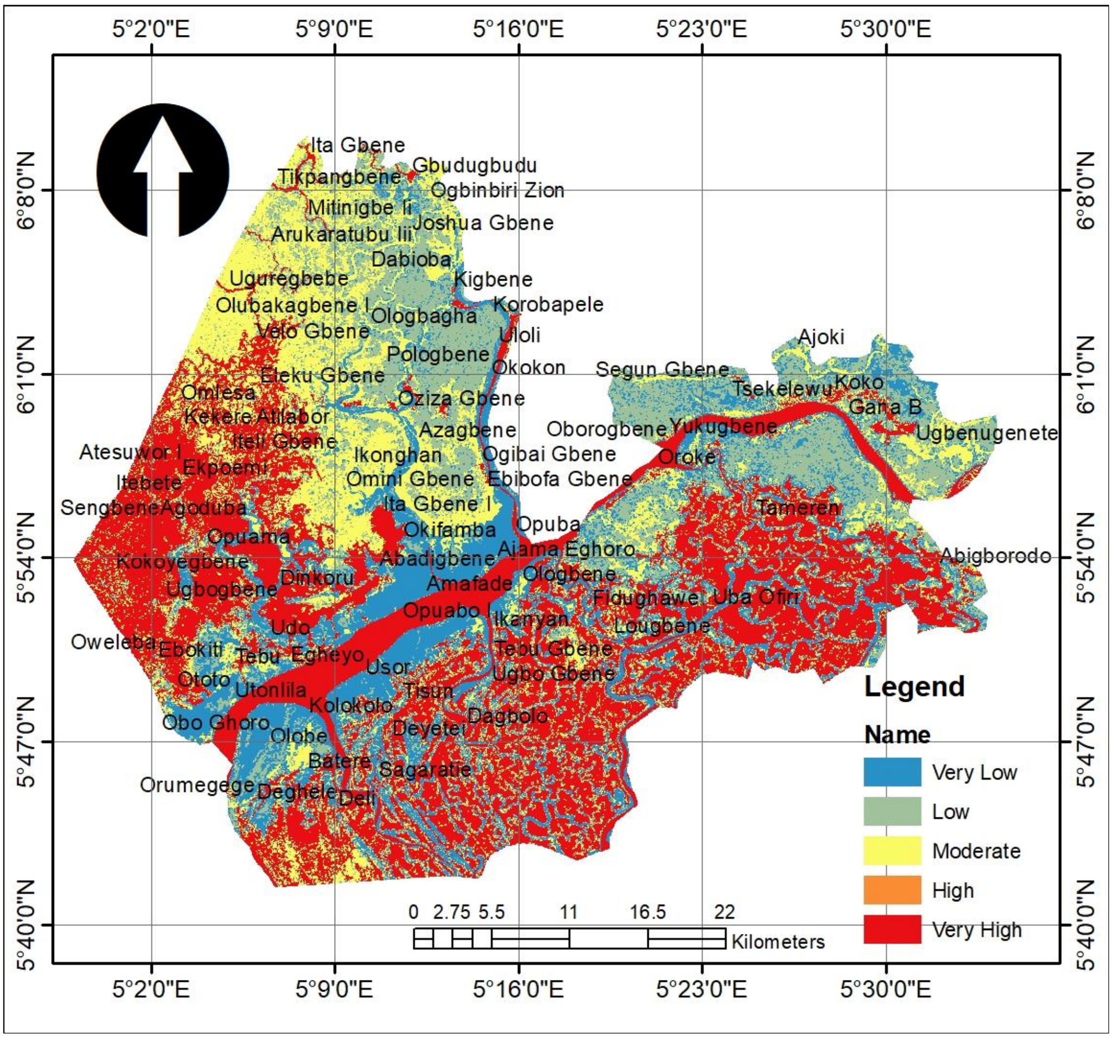

Fig 1: Flood Susceptibility in Warri North LGA

As presented in Table 6, the Very High susceptibility class constitutes the largest land cover category, occupying 681.93 km² (37.29%) of the Local Government Area. The Moderate and Low susceptibility classes occupy comparable proportions of the landscape, covering 390.87 km² (21.38%) and 389.55 km² (21.30%), respectively, while the Very Low class accounts for 362.18 km² (19.81%). The High susceptibility class occupies only 4.00 km² (0.22%), representing the smallest proportion of the study area.

The distribution shown in Figure 1 reveals that the Very High susceptibility zones form extensive and relatively continuous belts across the southern, southeastern, southwestern, and western portions of the Local Government Area. Moderate and Low susceptibility zones occur mainly within the northern and central parts of the study area, where they form transitional landscapes between highly susceptible floodplains and relatively stable terrain. The Very Low class appears as fragmented patches distributed primarily around elevated or relatively well-drained sections of the Local Government Area.

An important characteristic of the susceptibility map is the almost complete absence of isolated High susceptibility zones. Instead, the model transitions directly from Moderate to Very High susceptibility over much of the landscape. This pattern indicates that environmental conditions within Warri North either strongly favour flood occurrence or provide relatively stable conditions with few intermediate areas. Such behaviour is typical of coastal floodplain environments where extensive low-lying terrain and interconnected river systems produce widespread inundation once hydrological thresholds are exceeded.

The spatial distribution reflects the combined influence of the seven conditioning factors incorporated within the AHP-WLC model. Low elevations, gentle terrain, short distances to major river channels, proximity to the Atlantic coastline, abundant rainfall, poorly drained alluvial soils, and land cover characteristics collectively promote prolonged water accumulation across large sections of the Local Government Area. The resulting flood susceptibility map therefore identifies extensive landscapes where environmental conditions are favourable for recurrent flooding and provides a comprehensive representation of flood-prone areas within Warri North.

3.2. Distribution of Settlements within Flood Susceptibility Classes

To evaluate community exposure to flooding, settlement locations were superimposed on the flood susceptibility map using spatial overlay analysis. This procedure enabled each settlement to inherit the susceptibility class of the raster cell in which it is located. The resulting distribution is summarized in Table 7.

Table 7: Settlement Distribution by Flood Susceptibility Class

Flood Susceptibility Class	Number of Settlements	Percentage (%)
Very Low	42	27.50
Low	9	5.88
Moderate	61	39.87
High	0	0.00
Very High	41	26.80
Total	153	100.00

The settlement distribution presented in Table 7 indicates that 61 settlements (39.87%) occur within the Moderate flood susceptibility class, representing the largest concentration of communities. A further 42 settlements (27.50%) are situated within the Very Low susceptibility class, while 41 settlements (26.80%) occur within the Very High susceptibility class. Only 9 settlements (5.88%) are located within the Low susceptibility class, and no settlement falls within the High susceptibility category.

The settlement exposure pattern differs from the areal distribution of flood susceptibility. Although the Very High class occupies over one-third of the Local Government Area, the largest proportion of settlements occurs within the Moderate susceptibility class. This indicates that historical settlement development has tended to concentrate within relatively accessible environments that are not entirely free from flood hazards but are less hazardous than the most flood-prone coastal floodplains.

Communities located within the Very High susceptibility zones remain particularly vulnerable because they are exposed to the combined influence of river overflow, tidal inundation, and prolonged surface water accumulation. These settlements are likely to experience more frequent disruption of transportation, residential infrastructure, agricultural activities, and economic livelihoods during periods of severe flooding. Conversely, settlements located within the Very Low and Low susceptibility classes occupy relatively more stable terrain and are expected to experience comparatively lower flood frequency and reduced inundation severity.

The complete absence of settlements within the High susceptibility class is consistent with the spatial characteristics of the susceptibility map, where the High category occupies only 4.00 km² (0.22%) of the Local Government Area. The limited spatial extent of this class provides little opportunity for settlement development and further confirms that the flood susceptibility landscape of Warri North is characterized by a direct transition between Moderate and Very High susceptibility across much of the area.

Overall, the settlement analysis demonstrates that while a considerable proportion of communities are located within areas of Moderate susceptibility, more than one-quarter of all settlements remain directly exposed to Very High flood susceptibility. The spatial correspondence between settlement locations and flood-prone environments highlights the need for targeted flood mitigation measures, land use regulation, and community-based disaster preparedness programmes within the Local Government Area.

4. Discussion of Results

The flood susceptibility assessment demonstrates that flooding in Warri North Local Government Area is principally controlled by the interaction of topographic, hydrological, climatic, and coastal environmental conditions. The integration of elevation, slope, rainfall, soil, distance to river, distance to coastline, and land use/land cover using the Analytical Hierarchy Process (AHP) and Weighted Linear Combination (WLC) revealed that the Very High flood susceptibility class occupies the largest proportion of the Local Government Area. This finding indicates that flood-prone environments dominate much of the landscape and reflects the cumulative influence of multiple flood conditioning factors acting simultaneously rather than the effect of any single environmental variable.

The predominance of the Very High flood susceptibility class is closely associated with the physiographic characteristics of Warri North. The Local Government Area lies within the Niger Delta coastal plain, where extensive low-lying terrain provides favourable conditions for the accumulation of surface water. Low elevations function as natural receiving zones for runoff originating from surrounding areas, while limited relief reduces the capacity of floodwaters to drain rapidly. Consequently, floodwaters remain on the landscape for extended periods following heavy rainfall or river overflow, thereby increasing both flood depth and flood duration. The widespread occurrence of low-lying terrain therefore provides a physical explanation for the extensive distribution of highly susceptible areas across the southern, western, and southeastern parts of the Local Government Area.

Slope further reinforces the observed susceptibility pattern. Much of Warri North is characterized by very gentle gradients, which reduce runoff velocity and restrict the efficient movement of surface water towards river channels and coastal outlets. Under such conditions, rainfall-generated runoff accumulates over broad areas instead of being rapidly conveyed downstream. Areas exhibiting relatively higher elevations and slightly steeper terrain, particularly within portions of the northern section of the Local Government Area, demonstrate comparatively lower flood susceptibility because runoff is discharged more efficiently, thereby reducing opportunities for prolonged inundation.

The hydrological characteristics of Warri North constitute another major determinant of flood occurrence. The Local Government Area is intersected by numerous distributary channels, tidal creeks, estuaries, and interconnected waterways that form part of the lower Niger Delta drainage system. The close proximity of large portions of the landscape to these waterways increases exposure to riverine flooding during periods of high river discharge. Overflow from distributary channels frequently inundates adjacent floodplains, particularly during the peak rainy season when river discharge coincides with elevated tidal conditions. The concentration of Very High susceptibility zones along major river corridors therefore demonstrates the strong influence of river proximity on flood occurrence.

Distance to the coastline also contributes significantly to the observed susceptibility pattern. Coastal sections of Warri North experience the combined effects of river flooding, tidal inundation, and storm surge processes. During periods of high tide, river discharge into the Atlantic Ocean is partially restricted, creating backwater effects that delay the recession of floodwaters within distributary channels and adjoining floodplains. The interaction between river overflow and tidal influence therefore produces compound flooding, which is characteristic of many coastal environments within the western Niger Delta. This explains the continuous belts of Very High susceptibility observed across large portions of the southern coastal landscape.

Rainfall provides the principal hydrological input responsible for flood generation throughout the study area. Warri North experiences high annual rainfall associated with the humid tropical climate of southern Nigeria. Although rainfall is relatively widespread across the Local Government Area, its contribution to flooding depends largely on local terrain, drainage characteristics, soil properties, and proximity to river systems. Prolonged rainfall rapidly saturates the predominantly low-lying landscape, producing substantial runoff that subsequently accumulates within poorly drained depressions and floodplains.

Soil characteristics further increase flood susceptibility by influencing infiltration capacity. Large portions of the Local Government Area consist of poorly drained alluvial and hydromorphic soils that become saturated after prolonged rainfall. Once saturation occurs, infiltration declines substantially and additional rainfall is converted into surface runoff. This process contributes to the persistence of floodwaters and reinforces the influence of elevation and slope on flood development. Consequently, soil properties interact with hydrological and topographic conditions to increase the extent of flood-prone areas across Warri North.

Land use and land cover also modify the hydrological behaviour of the landscape. Wetlands and mangrove forests naturally function as temporary flood storage systems that attenuate flood peaks through water retention. However, settlement expansion, infrastructure development, and modification of natural vegetation alter runoff generation and reduce infiltration. Areas where human activities coincide with naturally flood-prone environments therefore exhibit increased flood susceptibility because the hydrological buffering capacity of the landscape has been partially reduced.

An interesting outcome of the analysis is the extremely limited spatial extent of the High susceptibility class compared with the Very High class. Rather than indicating gradual transitions between susceptibility levels, the flood susceptibility map demonstrates that environmental conditions within Warri North tend to shift directly from Moderate to Very High susceptibility. This pattern reflects the relatively uniform physiographic characteristics of coastal floodplains, where slight reductions in elevation or proximity to major waterways rapidly increase flood potential. Such behaviour suggests that once critical hydrological thresholds are exceeded, extensive portions of the landscape become susceptible to widespread inundation.

The settlement exposure analysis provides additional insight into flood risk within the Local Government Area. Although the Very High susceptibility class occupies the largest proportion of the landscape, the greatest number of settlements occurs within the Moderate susceptibility class. This distribution suggests that historical settlement development has generally favoured relatively stable environments that balance accessibility to waterways with reduced exposure to severe flooding. Nevertheless, the presence of 41 settlements within the Very High susceptibility class indicates that a considerable proportion of communities remain directly exposed to recurrent flood hazards.

Communities located within these highly susceptible zones are likely to experience repeated disruption of transportation, residential infrastructure, fishing activities, agricultural production, and public services during major flood events. The dependence of local populations on rivers for transportation and livelihoods further increases vulnerability because flood events frequently interrupt economic activities and isolate communities from essential services. Flood risk within Warri North is therefore determined not only by environmental susceptibility but also by the spatial concentration of settlements within flood-prone landscapes.

The findings demonstrate that flood susceptibility in Warri North results from the combined influence of terrain characteristics, river systems, coastal processes, rainfall, soil conditions, and land use dynamics. The AHP-WLC framework successfully integrated these variables to produce a spatial representation of flood susceptibility that reflects the environmental complexity of the Niger Delta coastal plain. The resulting flood susceptibility map provides an effective decision-support tool for flood mitigation planning, infrastructure development, emergency preparedness, and sustainable land use management within Warri North Local Government Area. Particular attention should be directed towards the extensive Very High susceptibility zones because these areas represent the greatest potential for future flood impacts on both natural systems and human settlements.

5. Conclusion and Recommendations

This study assessed flood susceptibility in Warri North Local Government Area, Delta State, using a Geographic Information System (GIS)-based Multi-Criteria Decision Analysis framework integrating the Analytical Hierarchy Process (AHP) and Weighted Linear Combination (WLC). Seven flood conditioning factors comprising elevation, slope, rainfall, soil, distance to river, distance to coastline, and land use/land cover were analysed to generate a Flood Susceptibility Index and delineate areas with varying levels of flood susceptibility. The resulting flood susceptibility map classified the Local Government Area into Very Low, Low, Moderate, High, and Very High susceptibility zones. The analysis revealed that the Very High susceptibility class occupies 681.93 km² (37.29%) of the study area, while the combined High and Very High susceptibility classes account for 685.93 km² (37.51%). The spatial distribution of these classes demonstrates that flooding represents a major environmental challenge throughout Warri North because extensive portions of the landscape possess physical characteristics that favour recurrent inundation.

The observed flood susceptibility pattern is primarily controlled by the interaction of low elevation, gentle slopes, extensive distributary river systems, proximity to the Atlantic coastline, high annual rainfall, poorly drained alluvial soils, and land use characteristics. These environmental factors collectively promote runoff accumulation, slow drainage, prolonged water retention, and frequent river overflow across large sections of the Local Government Area. The dominance of the Very High susceptibility class further indicates that flood hazards are widespread rather than localized, reflecting the physiographic characteristics of the Niger Delta coastal plain.

Settlement exposure analysis revealed that 41 settlements are located within the Very High flood susceptibility zone, while 61 settlements occur within the Moderate susceptibility class. Although the largest proportion of settlements occupies areas of Moderate susceptibility, a considerable number of communities remain directly exposed to severe flood hazards. These settlements are particularly vulnerable to disruption of transportation, residential infrastructure, fishing activities, agriculture, public services, and other socio-economic activities during major flood events. The findings therefore demonstrate that flood risk in Warri North is governed by both the environmental susceptibility of the landscape and the spatial distribution of settlements within flood-prone environments.

The AHP-WLC framework proved effective for integrating multiple flood conditioning factors into a single Flood Susceptibility Index, thereby providing a scientifically reliable representation of flood-prone areas. The resulting flood susceptibility map constitutes an important spatial decision-support tool for flood risk reduction, land use planning, infrastructure development, environmental management, emergency preparedness, and climate adaptation within Warri North Local Government Area.

Based on these findings, future residential, commercial, and public infrastructure development should be preferentially located within areas classified as Very Low and Low flood susceptibility. Development proposed within Moderate, High, and Very High susceptibility zones should be supported by detailed flood risk assessments and appropriate flood-resilient engineering designs before implementation.

Settlements located within the Very High susceptibility class should receive priority attention through the construction and rehabilitation of drainage infrastructure, regular desilting of natural and artificial drainage channels, and the implementation of structural flood control measures capable of reducing flood depth and duration.

Government agencies responsible for disaster management should strengthen flood forecasting, early warning systems, emergency response planning, and community-based preparedness programmes, particularly for settlements situated within the Very High susceptibility zones. Public awareness campaigns should also be intensified to improve community preparedness, evacuation planning, and understanding of flood hazards.

Wetlands, mangrove forests, and natural flood retention areas should be protected and restored because they play an important role in attenuating floodwaters, reducing runoff velocity, and maintaining the hydrological balance of the coastal ecosystem. Encroachment into floodplains, indiscriminate land reclamation, and uncontrolled alteration of natural drainage pathways should be effectively regulated through appropriate environmental and physical planning policies.

The flood susceptibility map generated in this study should be incorporated into local and state development plans to guide land use zoning, infrastructure investment, environmental conservation, and disaster risk reduction strategies. Integrating flood susceptibility information into planning decisions will reduce future exposure of settlements and critical infrastructure while supporting sustainable development within Warri North Local Government Area.

Future investigations should incorporate additional hydrological variables such as drainage density, flow accumulation, groundwater level, tidal dynamics, storm surge modelling, and projected climate change scenarios to further improve flood susceptibility assessment in coastal environments. Validation using historical flood inventories, hydraulic modelling, and higher-resolution remotely sensed datasets would further enhance the predictive accuracy and operational application of flood susceptibility models across the Niger Delta.

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