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Assessment of the Impacts of Coastal Flooding using Remote Sensing and GIS: A Review

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Abstract: *Around the world, coastal regions are frequently densely populated, heavily farmed, unduly reliant on groundwater, and undergoing a rise in coastal development. The cumulative consequences of climate change make the vulnerability of coastal communities to floods an urgent concern. By using remote sensing and GIS techniques, it is possible to accurately anticipate future inundation scenarios, identify locations that are prone to floods, and measure the degree of flooding. This study aims to demonstrate the critical role that GIS and remote sensing play in expanding our knowledge of the effects of coastal flooding. Three case studies within Nigeria were selected and considered: Lagos Coastal Area, Niger Delta Coastal Region, and Calabar Coastal Zone. The case studies, which examined individual articles, assessed the effects of coastal flooding and demonstrated the versatility and intricacy of GIS and remote sensing in delivering useful information. Results from the reviewed studies indicate that the highly susceptible areas cover a larger percentage of the coastal regions in Nigeria, with approximately 41% highly susceptible area coverage in Lagos and 63% highly susceptible coverage in Delta. In the Calabar region, floods were recorded to have a significant negative influence on the socioeconomic and environmental well-being of the people living in the region. The study made future research directions promising by highlighting the combination of machine learning and cutting-edge technologies to improve the efficiency of GIS and remote sensing in coastal flooding assessments.*

Keywords: Assessment, impacts, coastal, flooding, remote sensing, GIS.

1. INTRODUCTION

The world is always evolving and changing (Jóhannsdóttir, 2019). The Earth's atmospheric structure has been greatly impacted by human activity ever since the Industrial Revolution began, which as result of changes in human activities or a wide range of events accelerated, many of which directly affect people (IPCC, 2015). Sea levels, which have been increasing since the early 20th century and predicted to keep rising, are one example of these man-made changes (Jóhannsdóttir, 2019). Flooding occurs in coastal regions as an effect of this rise in sea level. Flooding is the general temporal condition in which tidal or inland waters flood into places that are normally dry, or in which runoff accumulation is exceptionally large and rapid, leading to partial or total inundation (Birmah et al., 2021).

Coastal areas that are fewer than 10 meters above mean sea level are known as low-elevation coastal zones (Kirezci et al., 2023). Nearly 700 million people are supported by these locations, which also produce about US$13 trillion in income worldwide (Kirezci et al., 2023). According to the Coastal Hazard Wheel (2024) coastal flooding is defined as the rapid and intense flooding of a coastal region brought on by a temporary rise in water levels brought on by high tides and storm surges. It is known to happen when seawater floods low-lying areas of land. The start of a coastal flood occurs when waves break through or go inland overprotective structures like dikes and dunes (Hsu et al., 2017). Regular road closures decreased stormwater drainage capacity, infrastructure deterioration, and salt intrusion into drinking water are some of the repercussions of coastal flooding (Hadipour et al., 2020). For example, the deterioration of water infrastructure and seawater intrusion may raise the possibility that people would be exposed to harmful chemicals and illnesses. Human health may potentially be impacted by these consequences.

The United Nations Intergovernmental Panel on Climate Change (IPCC, 2015) recently predicted that global mean sea levels, which raise coastal flooding, will likely rise by 0.95 feet (0.29 meters) to 3.61 feet (1.1 meters) by the end of the twenty-first century. It is still very difficult to understand the complex effects of coastal flooding, which makes an integrated approach to evaluation and mitigation techniques necessary. Evaluating the effects of coastal flooding is essential because it helps create appropriate plans for the future and scientific catastrophe prevention and adaptation strategies (Klemas, 2009). Moreover, developing resilient policies and adaptation plans requires a thorough understanding of the effects of coastal flooding. The consequences of coastal flooding on infrastructure, ecosystems, and human populations may be better understood via the use of remote sensing and GIS research (Wang et al., 2022). These insights can then be used to enhance evidence-based decision-making processes related to disaster planning and response (Wang et al., 2022).

This paper aims to demonstrate the vital role that GIS and remote sensing play in expanding our knowledge of the repercussions of coastal flooding through an extensive assessment of techniques, case studies, and real-world applications. Considering different case studies from different coastal regions in Nigeria, the review emphasizes how important these technologies are to promoting sustainable and knowledgeable decision-making procedures for minimizing the effects of flooding incidents throughout coastal regions across the globe.

2. CONCEPTUAL FRAMEWORK

Birmah et al. (2021) defines flooding as an all-encompassing temporal condition when tidal or inland waters overflow into normally arid areas, or whether exceptionally rapid and heavy runoff accumulation results in partial or total swamping. In any segment of a stream that exceeds the natural or artificial banks, it can be defined as a rather vigorous water flow. Flooding frequently happens when a water body's volume surpasses the capacity of a drainage canal and exceeds its bounds (Cirella and Iyalomhe, 2018). The National Severe Storm Laboratory of the National Oceanic and Atmospheric Administration (NOAA, 2020) in the USA defines flooding as water spilling into normally dry terrain. It is recognized as the most common and widespread natural disaster caused by weather (NOAA, 2020). For a considerable amount of time, flooding has been the most common form of environmental danger, causing over 20,000 fatalities annually and affects approximately 75 million people globally (Ologunorisa and Abawua, 2005). The mechanisms of flooding often occur in combination with recent precipitation and soil moisture being the dominant drivers in many river catchments (Berghuijs et al., 2019; Jiang et al., 2022).

Flooding may take many different forms, including river (or fluvial) floods, flash flooding, coastal flooding, urban flooding, pluvial flooding, and groundwater flooding. River flooding, also referred to as fluvial flooding, is a complex phenomenon influenced by various factors, including rainfall intensity, catchment characteristics, and climate change (Kundzewicz and Pińskwar, 2022; Poljanšek et al., 2017). While precipitation extremes and pluvial floods are generally increasing globally, changes in river floods show regional variations (Kundzewicz and Pińskwar, 2022). Flash floods are rapid, localized flooding events that occur within minutes to hours of excessive rainfall or a sudden water release, often in small watersheds (Davis, 2001; Zanon, 2010). They pose significant hazards, causing loss of life and severe damage to infrastructure (Davis, 2001; Hapuarachchi et al., 2011). Flash floods result from intense thunderstorms, tropical systems, or dam failures, and may carry debris, destroy structures, and create new channels (Davis, 2001). A significant challenge in the developed areas is the urban flooding and it is characterized by rapid inundation due to increased impermeable surfaces and faster flow times (Ramachandra et al., 2012; Zameer et al., 2013). Pluvial flooding, caused by intense rainfall overwhelming drainage systems, is an increasing urban risk across Europe due to climate change and urbanization (Prokić et al., 2019; Rosenzweig et al., 2018). This type of flooding has been relatively understudied compared to river and coastal floods (Prokić et al., 2019). The occurrence of groundwater flooding is when the water table rises, causing surface inundation and significant disruption. Groundwater flooding manifests as prolonged surface flows and anomalous spring flows (Hughes et al., 2011). Coastal flooding poses significant challenges to communities worldwide, driven by factors such as storm surges, sea-level rise, and extreme weather events (Bertin, 2016; Gayathri et al., 2017). Storm surges, influenced by atmospheric pressure, wind, and waves, can cause extensive damage in shallow coastal areas (Bertin, 2016).

The Federal Emergency Management Agency (FEMA) states that coastal flooding happens when normally dry coastal regions are submerged or covered by high or rising tides or storm surges. It's a type of flood that happens when seawater floods normally dry (and frequently low-lying) land. Coastal flooding, a complex phenomenon with wide-ranging impacts on infrastructure, communities, and the environment, is caused by sea levels rising along the coast or in estuaries, surpassing nearby land levels, or waves overtaking the shore when coastal defenses are present (Xu et al., 2022). Coastal flooding poses serious problems for ecosystems, infrastructure, and human health (Nucera et al., 2018). Precise evaluations of the effects of coastal flooding are essential for mitigation and adaptation plans because of the expanding coastal development and rising sea levels brought on by climate change (Xu et al., 2022).

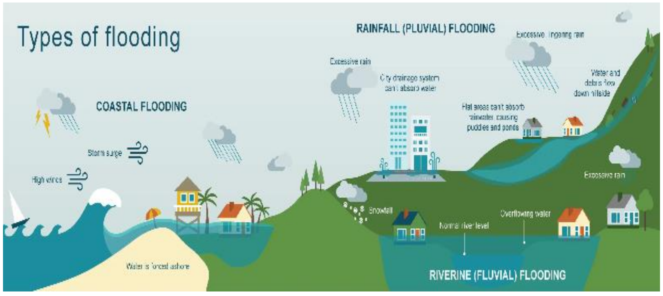

Figure 1: Illustration of flood concept and flood types
Source: Image from National Levee Database
https://levees.sec.usace.army.mil/flood-basics/about-flooding/

3. ROLE OF REMOTE SENSING AND GIS IN COASTAL FLOODING STUDIES

Coastal vulnerabilities are increasing due to storm surges, tsunamis, and sea level rise, therefore it's important to take preventative actions to identify high-risk regions before they flood (Koks et al., 2023). The detection and mapping of flooded regions is one of the main uses of remote sensing for coastal flooding assessment (Xu et al., 2022). Satellite imagery sensors such as Sentinel and Landsat missions provide high-resolution satellite photography that makes it possible to detect flood extents with remarkably high precision (Hermas et al., 2021). Differentiating between land and water surfaces is made possible by the use of multispectral and radar imaging, which makes it easier to define flooded zones both during and after inundation occurrences. To improve the recognition of flooded regions and ensure accurate quantification of flood extent, a variety of image processing methods are used on satellite imagery, which are initially corrected for atmospheric and radiometric factors to enhance data quality.

It is simpler to measure the extent of floods in a given region when using remote sensing for mapping or modelling flooding in river basins or coastal areas. Determining the areas at danger of flooding is aided by the size of the affected region. Coastal flooding occurrences' size and intensity can be determined with the use of remote sensing (Hadipour et al., 2020). Measuring the floodwater's magnitude is essential for risk reduction, disaster response, and understanding the intricate dynamics at work. Qualifying the flood's extent aids in monitoring the risk of coastal flooding (Jóhannsdóttir, 2019). The extent of flood over a long time period is quantified using the change detection techniques in GIS. The amount of flooding, changes to the shoreline, and changes in land cover are measured by comparing pre-and post-flooding imageries.

Prior research has demonstrated that the use of GIS and remote sensing technology has been crucial to managing coastal floods. It has undergone substantial advancements. A few of the previous studies relating to the topic are structurally reviewed in the Table 1.

Table 1: Previous studies and research gaps overview

S/N	RESEARCH AIM	METHODOLOGY	DISCUSSION	REFERENCES
1.	In the context of climate change, the study examines risk assessment and coastal flooding along Taiwan's mid-western coast.	The research utilized a combination of field surveys, data collection, and advanced modeling techniques. Relevant data were collected, and climate change projections were incorporated to simulate future scenarios. Further assessment was done on the possible flood hazards and effects on Taiwan's midwestern coast.	For the mid-western coast of Taiwan, the research projects sea level rise, wave conditions, and storm surge from 2020 to 2039. It also identifies certain townships at high risk that are sensitive, low-resistant, and low-resilient to guide the establishment of adaptation policies for the region.	(Hsu et al., 2017)
2.	The study's primary focus was on assessing coastal flooding risk, employing a spatial multi-criteria decision analysis (MCDA) method based on GIS.	Multi-Criteria Decision Analysis (MCDA) and Geographic Information System (GIS) technologies were integrated as part of the technique used.	Through the development of efficient and customized strategies, the spatial multi-criteria decision analysis (MCDA) approach, based on geographic information systems (GIS), may assist local organizations and decision-makers in Bandar Abbas City, Iran, in reducing flood risk and damage.	(Hadipour et al., 2020)
3.	The study explores a comprehensive method for coastal flooding risk assessment and simulation modeling.	The approach uses a combination of risk assessment and simulation modeling, taking into account a number of variables like terrain, storm surge, and sea level rise.	For flood simulation and risk assessment in the coastal areas of the Pearl River estuary, China, the authors demonstrate the effectiveness of their novel model, which includes a hydrodynamic and a risk assessment module, by comparing the simulation results with MIKE 21 and a social media-based dataset.	(Zheng and Sun, 2020)

S/N	RESEARCH AIM	METHODOLOGY	DISCUSSION	REFERENCES
4.	The study examines the geographical evaluation of coastal flood risk in China's coastal zone, with a particular emphasis on the effects of sea level rise in the twenty-first century.	Coastal flood risk due to sea level rise was assessed by the study using sophisticated modeling techniques, including Geographic Information System (GIS) tools and data analysis. Topography, land use, and climate projections were taken into consideration in order to model and simulate possible flood scenarios.	To review, the high-resolution CFR maps show which regions and land uses are most at risk from coastal flooding, and they may help with decision-making for adaptation measures on a national and local scale.	(Xu et al., 2022)
5.	The study evaluates the danger of coastal flooding in Nigeria's vulnerable coastal areas using GIS techniques and suggests ways to reduce it.	Using satellite imagery and GIS-based hydrological modelling, the study identified areas that are vulnerable to flooding. determined flood vulnerability ratings by merging hydrological and topography information. evaluated flood-prone areas in the coastal states of Bayelsa and Delta, identifying high to very high and medium to high-risk areas. emphasized the value of GIS technology for disaster management and community resilience in flood risk assessment and mitigation.	The study highlights that in order to strengthen community resilience, rapid and deliberate mitigation actions are required to address the key high to very high flood risk regions in Bayelsa and the broad medium-to-high-risk flood zones in Delta. These flood hazards brought on by climate change should be evaluated and reduced using geospatial technologies.	(Bello et al., 2024)

4. CASE STUDIES ON COASTAL FLOODING IMPACT ASSESSMENT IN NIGERIA

The coastal areas in Nigeria face various challenges related to flooding, erosion, and climate change impacts. Three potential case studies having their locations in Nigeria were selected and considered. Through these case studies, the use of GIS and remote sensing in coastal flooding assessment was illustrated. The methods utilized in each case study were discussed. Important insights into the dynamics and ramifications of flooding occurrences in Nigeria's coastal regions may be gained from the case studies' conclusions.

4.1 Lagos Coastal Area

Lagos, one of Nigeria's largest coastal cities, is vulnerable to coastal flooding because of its low-lying terrain, increased urbanization, and close proximity to the Atlantic Ocean. Lagos's coastal districts are frequently flooded, especially during the rainy season and high tides. The area is distinguished by a blend of urban and rural environments, as well as vital infrastructure including ports, neighbourhoods, and industrial zones. This area is vulnerable due in part to its rapid urbanization and insufficient drainage infrastructure (Adegun, 2023). Comprehending how coastal flooding affects natural and urban elements is essential for resilience planning and sustainable development.

Isiaka et al. (2023) integrated and analyzed geospatial data related to the flood vulnerability assessment of Lagos State, Nigeria, using a frequency ratio model based on geographic information system (GIS). A thorough assessment of flood susceptibility across different regions of Lagos State in 2022 was done, providing useful information for planners and decision-makers. Ten contributing elements to flooding were examined in the study: land use/land cover (LULC), normalized difference vegetation index (NDVI), drainage density, elevation, slope, rainfall, soil type, curvature, drainage closeness, and topographic wetness index (TWI). Out of 100 inventory flood locations, 70 were utilized to train the model, and 30 were used to evaluate the flood inventory map. All vector data was converted to a raster with a resolution of 30 meters, and ArcGIS 10.7.1 and ArcGIS Pro 1.2 were used for all geoprocessing procedures of each factor. The geographical correlations between these characteristics and historical flood occurrences are analysed using the Frequency Ratio Model. The spatial analyses and maps of every element that show locations in Lagos State's coastline region that are more or less vulnerable to floods were displayed in the study. The results were interpreted in the discussion, which also looked at the connections between susceptibility and contributing variables. Five types of flood vulnerability were identified in the final map: very high, high, moderate, low, and very low. The final flood map indicates that the bulk of Lagos State's flood-prone areas were located very close to bodies of water and were often low-lying. Of Lagos State's total area, 12.54% (436,272.3 km^2) and 28.91% (1,006,050.6 km^2) were regions with extremely high and high flood vulnerability ratings, respectively. According to reports, a portion of the local government districts of Epe, Ibeju-Lekki, Amuwo-Odofin, Ojo, and Kosofe overlap with these extremely high and highly prone to flooding locations.

There are places with a very low and low level of flood susceptibility of 11.62% (404,465.4 km^2) and 21.94% (763,539.3 km^2), and areas with a moderate level of susceptibility of 24.99% (869435.1 km^2). The degree of satisfaction with the area's flood susceptibility map and the mapping methodology was evaluated and verified using the area under the curve (AUC) metric. With a 64% success rate and a 61% prediction rate, the final flood susceptibility was verified using the AUC approach (Figure 1). The study emphasizes how important it is to reduce the risk of floods and support local and governmental planners in making decisions.

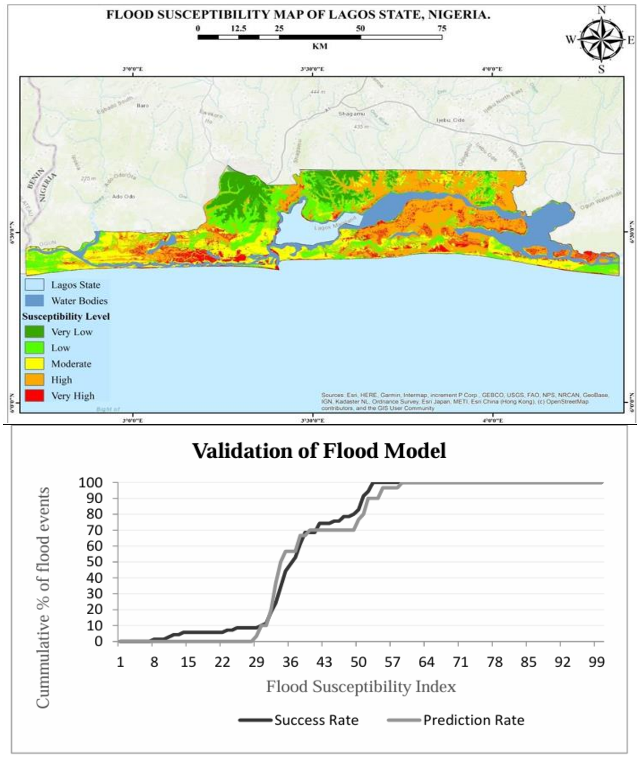

Figure 1: Lagos state flood susceptibility map. Validation of the flood susceptibility model. Source: Data extracted from (Isiaka et al., 2023)

4.2 Niger Delta Region

The Niger Delta, with its intricate network of rivers, estuaries, and mangrove ecosystems, is a region of immense ecological importance and economic significance (Nwanosike et al., 2021). Sea level rise, storm surges, and river flow are some of the causes of coastal flooding in the Niger Delta (Ugwu et al., 2022). The area is home to diverse ecosystems, including mangrove forests and wetlands, as well as oil and gas infrastructure. Coastal erosion, oil spillage, and rising sea levels pose significant threats to both the environment and local communities (Nwanosike et al., 2021).

Ahuchaogu et al. (2021) also used remote sensing and GIS to assess flood hazards along the Delta State River Niger Basin. Because of its location along the Atlantic Ocean coast, Delta State, Nigeria, experiences annual floods. The study identified spatial differences in flood hazard potentials in Delta State by mapping regions vulnerable to flooding using remote sensing and GIS techniques. This allowed for the promotion of the most efficient flood control approach. Using a multi-criteria evaluation, flood hazard zones were defined in a GIS context by combining flood-influencing parameters such as elevation, river proximity, population density, drainage density, and land use. Landsat images and SRTM DEM data of 30m resolutions were used to construct these variables, which were then classed using a ranking approach into four levels of hazard categories: very high, high, low, and very low. Using an addition operator, these reclassified factors were overlaid. According to the study's findings, the State's coastline areas and the River Niger are the most susceptible to flood threats, with the hazard's severity reducing as one move northward in the state. Some areas were exposed to very high hazard of the study area, accounting for 4,143.455 km^2 (24%) of the study area; high, low, and free hazard zones covered 11,000.874 km^2 (63%), 1,323.75 km^2 (7%), and 1,061.927 km^2 (6%) of the study area, respectively (Figure 2).

The 2012 flood extent map inside the research region was utilized to validate the final flood risk map. According to the study's conclusion, some parts of the study area are highly hazardous because of their low relief, pattern of land use, and proximity to rivers. Nevertheless, it is advised that communities in coastal areas undergo regular enlightenment programs, and that settlement in floodplains be strongly discouraged.

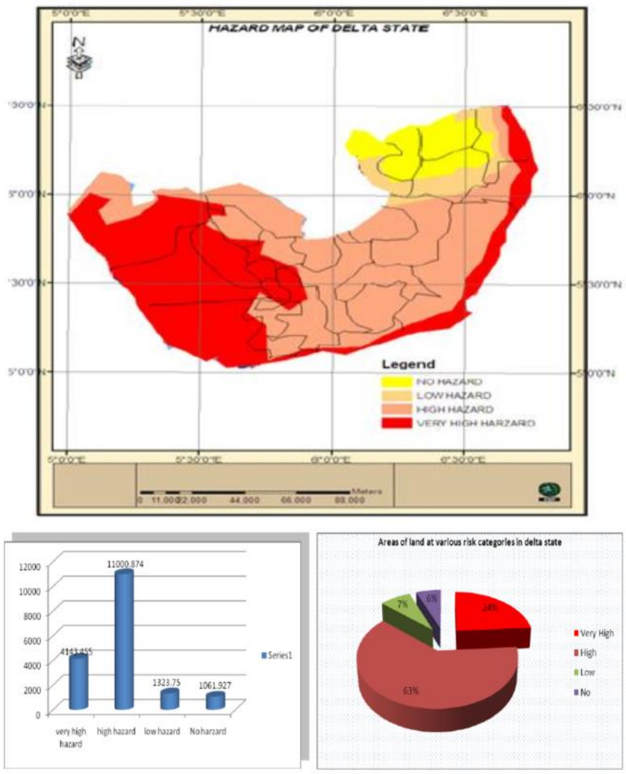

Figure 2: Delta state flood hazard map. Area extent in square km and percentage illustrated in histogram and pie chart. Source: Data extracted from (Ahuchaogu et al., 2021).

4.3 Calabar Coastal Zone

Nigeria's southeast zone, Calabar, boasts a varied coastal environment with beaches, estuaries, and mangrove habitats. The coastal zone of Calabar is confronted with issues including erosion, intrusion of seawater, and floods (Opaminola et al., 2022). The region is well-known for its biodiversity, essential to the local populations' way of life. Knowing the effects of coastal flooding in the context of the coastal zone around Calabar illuminates the susceptibility of various communities and ecosystems (Opaminola et al., 2022)

Okey et al. (2022) considered floods to be an ecological barrier to housing development in the city of Calabar. The study also evaluated how the study area's residential property owners responded to floods. The study incorporated rainfall, digital elevation models, satellite images, and other data to create a flood risk map. Multi-research design to determine the flood risk zones was utilized. By overlaying the street map of Calabar city and the flood risk map, certain common roads were exposed to the high-risk area (Figure 3). Although residents of flood-risk locations are aware of the dangers of flooding and their vulnerability, the study found that many were compelled to remain because they could not afford a better house in a low-risk area. The study found that floods have a significant negative influence on the socioeconomic and environmental well-being of the people living in the study region, necessitating immediate government action. The report did, however, suggest that the government make an effort to inform those living in high-risk flood zones of the serious consequences of doing so. In addition, buffer zones are used to discourage developers from building in areas that are vulnerable to flooding.

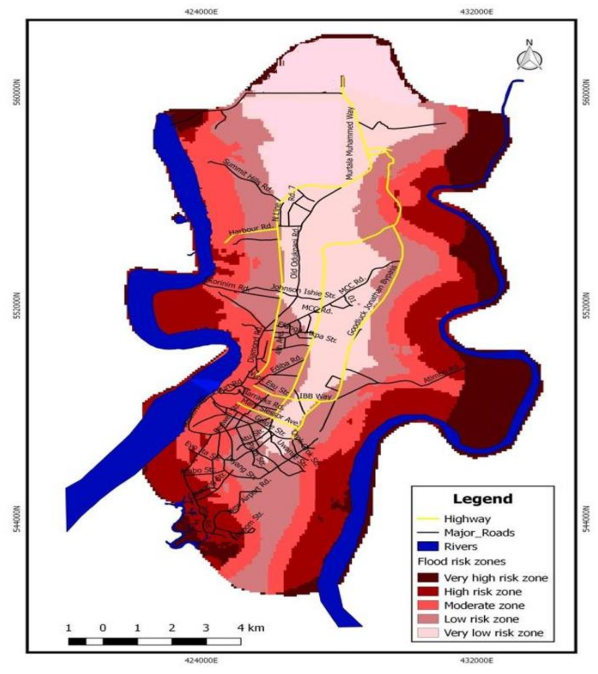

Figure 3: Calabar flood risk zone map. Source: Map extracted from (Okey et al., 2022)

5. IMPLICATIONS FOR FUTURE RESEARCH AND APPLICATIONS

GIS and remote sensing technology have become essential resources for evaluating the effects of coastal flooding and assisting with coastal management choices (Masria, 2024; Yin et al., 2010). The monitoring of shoreline dynamics, land use changes, coastal ecosystems, and disaster response is made possible by these technologies (Masria, 2024). Additionally, they make it easier to assess the vulnerability of storm surge flooding and sea level rise, giving stakeholders and policymakers important information (Yin et al., 2010).

Future research and practical applications of GIS and remote sensing in evaluating coastal flooding will be significantly influenced by the findings presented in this paper. Exploring cutting-edge earth observation technologies, such as UAVs, hyperspectral imaging, and high-resolution SAR, for future study would lead to a productive direction (Klemas, 2009). By incorporating advanced technologies such as these into evaluations of coastal flooding in the communal world, data resolution—both temporally and spatially—would be improved, yielding information that is more precise and detailed. Expanding and improving the use of these cutting-edge instruments to record complex coastal dynamics should be the main goals of future research.

The exploration of artificial intelligence and machine learning for automated feature extraction and flood detection points to a revolutionary possibility (Syifa et al., 2019). Recent research shows that integrating Geographic Information Systems (GIS) with artificial intelligence (AI) and machine learning (ML) can enhance flood risk mapping and assessment. AI-powered GIS aids in analyzing historical flood events, population impacts, and ecological solutions like mangrove protection (Atmaja and Fukushi, 2022). For flood mapping and damage assessment, remote sensing imagery has been effectively processed using machine learning techniques including support vector machines and artificial neural networks (Syifa et al., 2019). These methods offer advantages in accuracy, speed, and cost-effectiveness compared to traditional approaches (Wagenaar et al., 2019). Further development of early warning systems and more accurate flood assessments may result from the incorporation of machine learning into current models (Syifa et al., 2019). The focus on early warning systems and real-time monitoring emphasizes how critical it is to find quick and precise ways to identify and react to coastal flooding incidents. Upgrading these systems and incorporating remote sensing data for quick decision-making and community resilience should be the main focus of future research. Additionally, facilitating information exchange and fostering connections between researchers, and governmental and non-governmental groups can quicken the rate of innovation and increase the accuracy of evaluations. Hence, data exchange and cooperative research projects need to be given top priority in future applications.

The implications for future studies and applications highlight the necessity of a comprehensive and technologically sophisticated method for evaluating the effects of coastal flooding. Future research projects can help provide more precise, timely, and useful findings by adopting evolving technology and incorporating socio-economic factors (Khan et al., 2023). This would therefore encourage the creation of robust coastal management plans, which are crucial in the growing problems posed by climate change.

6. CONCLUSION

This study explored the comprehensive evaluation of the effects of coastal flooding as well as the capabilities and prospects for future research in this sensitive area. The study utilized case studies from the Lagos Coastal Area, Niger Delta Coastal Area, and Calabar Coastal Area, each providing distinct perspectives by highlighting the adaptability of these technologies in capturing intricate coastal dynamics and their consequential socio-economic effects. The study finally provided an outline of future directions for research, focusing on the incorporation of socio-economic factors, community-based techniques, real-time monitoring, machine learning, and advanced technology. The review of the impacts of coastal flooding assessment utilizing remote sensing and GIS consolidates existing fragmented studies across various coastal regions in Nigeria, such as Lagos, Niger Delta, and Calabar, into a coherent synthesis that highlights key trends, spatial patterns, and technological approaches in flood impact assessments. Importantly, this study identifies data gaps, regional vulnerabilities, and methodological strengths or weaknesses in previous studies, thereby guiding future research and policy. It also illustrates how remote sensing and GIS technologies can serve as cost-effective, scalable tools for real-time monitoring, risk mapping, and predictive modeling, even in data-scarce environments.

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