Journal of Spatial Information Sciences

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ISSN: 2354-3361
DOI: https://doi.org/10.5281/zenodo.17175815

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GEOGRAPHIC INFORMATION SYSTEM-BASED MULTI-CRITERIA DECISION ANALYSIS OF FLOOD RISK ZONES IN MADAGALI, ADAMAWA STATE, NIGERIA

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DOI: https://doi.org/10.5281/zenodo.17175815

Abstract

The main purpose of this research was to apply geospatial methods to map flood risk zones within Madagali Local Government Area in Adamawa State of Nigeria towards developing enhanced measures for flood risk mitigation. Core variables assessed included topographic elevation, land use/land cover dynamics, rainfall variability, and characteristics of the drainage network. The study combined Landsat 8 satellite images, Digital Elevation Models (DEMs), and rainfall data using Multi-Criteria Decision Analysis (MCDA) with a weighted overlay method to assess flood susceptibility in the study area. The results indicate that approximately 35% of the study area is situated within high to very high flood risk categories, predominantly low-lying areas subject to intensive land-use patterns and variability in rainfall distributions. The vulnerability assessments undertaken in this study revealed distinct classifications such as: 18.53% of areas exhibit low vulnerability, 30.50% moderate vulnerability, 52.8% high vulnerability, and 60.7% very high vulnerability. In conclusion, the geospatial methods applied in this study provide evidence-based insights for policymakers thereby, supporting effective flood risk management and enhancing community resilience within Madagali Local Government Area. Key recommendations emerging from this study underscore the need for stakeholders to pursue afforestation interventions, river channel maintenance, development of contextually appropriate hydraulic infrastructure, and drainage infrastructure near Madara Mountain which can serve dual purposes of flood mitigation and dry-season agricultural water storage.

Keywords: Adamawa State, Digital Elevation Models, Geospatial Delineation, Landsat 8 OLI, Madagali, Flood Risk, Multi-Criteria Decision Analysis (MCDA).

1. Introduction

Flooding poses a significant threat to communities in Madagali Local Government Area of Adamawa State in Northeast, Nigeria. This scenario usually affect the socio-economic stability and environmental resilience [1]. The region's vulnerability is heightened by factors such as inadequate drainage systems and land-use practices ill-suited to its susceptibility to heavy rainfall [2]. The interplay of climatic, geomorphological, and anthropogenic factors underscores the complexity of addressing flood risks in this northeastern Nigerian locale [3].

Madagali is situated in northeastern Nigeria, an area prone to climatic variability and extreme weather events [4]. Its geographical characteristics, including proximity to Madara Mountain, contribute to hydrological dynamics that influence flood patterns. The local topography and rainfall distributions shape the nature of flood susceptibility, requiring context-specific understanding for effective management strategies. Local communities, particularly those dependent on agriculture, face severe disruptions from flooding, threatening food security and livelihoods. Recurrent flooding has led to displacement, infrastructure destruction, and significant agricultural losses in Madagali, underscoring the need for this present study. The economic toll of flooding further strains community resilience and regional development prospects in this vulnerable area. Inadequate drainage infrastructure and inappropriate land-use practices exacerbate flood risks in Madagali [5]. Rapid urbanisation and environmental changes further compound the challenges of managing flood-prone areas, necessitating context-specific interventions. Anthropogenic activities, including deforestation and poor watershed management, likely amplify hydrological extremes in the region [5].

Traditional flood management approaches in the region have been largely reactive, focusing on post-flood relief rather than proactive mitigation. Such strategies often prove insufficient in addressing the complexities of recurrent flooding, highlighting the need for innovative solutions [2]. Reliance on emergency response rather than prevention underscores gaps in current flood risk governance frameworks in Madagali. The integration of GIS technologies, including Geographic Information Systems (GIS) and remote sensing, offers promising capabilities for flood prediction, risk assessment, and enhanced preparedness [6]; [7].

ISSN: 2354-3361
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Madagali, Adamawa State, faces severe and recurring flooding, causing devastating impacts on communities and infrastructure. Despite this, there's a significant research gap in adopting geospatial intelligence tools for flood risk mapping in the area. Geospatial intelligence refers to the collection, analysis, and interpretation of geographic data using advanced technologies like Geographic Information Systems (GIS), remote sensing, and spatial analysis. These tools can significantly enhance flood management by providing detailed information on flood-prone areas, real-time monitoring, and the development of early warning systems. Geographic Information System (GIS) and remote sensing are proven geospatial intelligence tools for understanding and managing flood risks, globally. In Adamawa State, previous studies have applied GIS and Analytical Hierarchy Process (AHP) to assess flood vulnerability.

[8] mapped flood vulnerability in Adamawa Catchment, classifying areas as low (19.9%), moderate (31.4%), high (31.8%), and very high (16.9%) vulnerability by integrating factors like elevation and rainfall distribution. [9] used GIS to detect and map flood-prone areas in Jimeta, Adamawa State, identifying two extensive Benue floodplains. However, [10] study was on drought vulnerability assessment in Adamawa State using GIS and AHP, not Madagali's flood risk mapping specifically. Despite existing geospatial applications in Adamawa [11]; [12]; [8]; [9]; [13], Madagali's flood risk mapping via geospatial tools remains under-explored, highlighting a critical research gap. Research suggests integrating GIS, remote sensing, and hydrological models for comprehensive flood risk management in Adamawa State's flood-prone areas like Madagali, where factors like Lagdo Dam releases contribute to flooding risks [11]; [12]; [13]. Geospatial analysis can help improve how flood risks are managed in Madagali communities. The foregoing assertion justifies the need for this present paper, titled: "*Geographic information system-based multi-criteria decision analysis of flood risk zones in Madagali, Adamawa State, Nigeria*". According to [6], geospatial methods are divided into remote sensing and geographic information systems (GIS) while Multi-Criteria Decision Analysis (MCDA) is a systematic approach used to evaluate and compare different options or scenarios based on multiple criteria or factors [34]. MCDA) is a decision-making tool that helps in assessing complex problems where various factors need to be considered.

JOURNAL OF SPATIAL INFORMATION SCIENCES ISSN: 2354-3361
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www.journals.unizik.edu.ng/jsis

Multi-Criteria Decision Analysis (MCDA) is basically integrated with geospatial techniques, like Geographic Information Systems (GIS) and Remote Sensing (RS), to analyze and map spatial phenomena involving multiple factors. This integration enhances decision-making in spatial planning, environmental management, and natural resource management.

The main purpose of this research was to apply geospatial methods to map flood risk zones within Madagali Local Government Area in Adamawa State of Nigeria towards developing enhanced measures for flood risk mitigation.

1. Study Area

Madagali Local Government Area is situated in the northeastern part of Adamawa State, Nigeria, covering approximately 1,200 square kilometres. Geographically, Madagali is located at 10°53'27.3408"N, 13°37'39.3204"E (https://share.google/dwEaK4IhQkGUPmpcX), with an elevation of about 499.8 metres. The region experiences a tropical climate marked by distinct wet and dry seasons, rendering it susceptible to seasonal flooding, particularly between May and September. Major rivers, including the Gongola River, are prone to flooding during heavy rainfall, significantly impacting local communities and infrastructure [14]. Madagali's population is predominantly rural, with agriculture being a key livelihood source. However, recurrent floods cause crop damage, soil erosion, and transportation disruptions, leading to substantial economic losses and heightened vulnerability for residents [15]. Land use dynamics are basically characterised by unplanned settlements and population growth trends.

2. Methodology

2.1. Spatial Data Acquisition, Preprocessing and Masking of Area with Flood Risks

This data used in this study were extracted from four (4) spatial datasets: First, Landsat 8 Operational Land Imagery (OLI) Satellite Imagery (path 185; row 053/54) of October 10 of 2022, 2020 and 2018 were acquired from the United States Geological Survey (USGS) Archive, accessible at http://earthexplorer.usgs.gov. Flood-inundated areas delineated preceding and following significant flood events in October of 2022, 2020, 2018 and 2012. Unsupervised classification of the landcover types was also performed on the Landsat data. The second spatial

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dataset utilized in this study were rainfall data, obtained from the Nigerian Meteorological Agency - NiMet). Thirdly, both the elevation and slope data were derived from the SRTM (Shuttle Radar Topography Mission) digital elevation model (DEM) data as downloaded from the OpenTopography portal which is supported by the National Science Foundation and accessible at https://portal.opentopography.org/raster?opentopoID=OTSRTM.082015.4326.1. The SRTM data were utilized to mask out non-flood water located at elevations greater than 25 meters. Notably, the SRTM database offers global elevation data at a 3 arc-second (90 m) spatial resolution [16]. Fourthly, the research examined flood risk in Madagali, Adamawa State, using various spatial data - including past flooding records in maps and in literature.

Landsat 8 images have a spatial resolution of 30 metres for multispectral bands and 15 metres for panchromatic band [17]. A specific band combination of Landsat 8 OLI – incorporating Near Infrared (NIR), Short-Wave Infrared 1 (SWIR-1), and SWIR-2 (Bands 5, 6, 7) – was applied to enable flood water detection analysis. Adapting to the methods described in [18], digital datasets for these flood hazard factors were acquired, georeferenced, extracted, and resampled through a series of preprocessing steps. To ensure spatial accuracy, the Landsat satellite imagery was georeferenced using the *Minna* datum and projected in the Universal Transverse Mercator (UTM) coordinate system, specifically in Zone 33N [19]. Subsequent processing converted imagery to digital numbers (DNs), aligning with Landsat standard Level-1 products [20]. The selection of these image datasets was deliberate, given Adamawa State's recurrent flooding patterns since 2012. Notably, Landsat Level-1 products comprise quantized and calibrated scaled Digital Numbers (DN), amenable to rescaling into Top-of-Atmosphere (TOA) reflectance via application of radiometric rescaling coefficients, representing the standard output of Landsat sensors [20]. Validation spatial data through the use of very high satellite resolution imagery provided in the Google Earth Desktop tool [21].

2.2. Implementation of Multi-Criteria Decision Analysis (MCDA) with Geospatial Techniques for Flood Risk Assessment in Madagali

The evaluation of flood risk zones in Madagali, Adamawa State, was conducted using Multi-Criteria Decision Analysis (MCDA) integrated with geospatial methods, incorporating factors critical to flooding. The criteria selected for assessing flood risk in the study area included topographic elevation, land cover dynamics, rainfall variability, proximity to the drainage network, and slope characteristics, chosen based on their influence on flood susceptibility in the study area. To facilitate combination in MCDA, the criteria were standardised to comparable scales, typically ranging from 0 to 1 [22], reflecting their relative contribution to flood risk; for instance, lower elevations and higher rainfall intensities were associated with increased flood susceptibility. Weights reflecting the relative importance of each criterion were determined using the Analytic Hierarchy Process (AHP), involving pairwise comparisons informed by expert judgment pertinent to local conditions in Madagali. A decision tree methodology was implemented to detect flood-impacted zones, leveraging changes in spectral signatures. The Analytic Hierarchy Process (AHP) as illustrated in [22], [23] and [24] was applied to assign normalized weights to each flood hazard factor, incorporating expert judgment and empirical evidences from literature. For this study, the assigned weights were: elevation (0.35), rainfall (0.25), Landcover (0.20), drainage proximity/river distance (0.15), and slope (0.05).

2.3. Geo-statistical Accuracy Assessment from Landsat 8 OLI Remote Sensing for Land Cover Classification

The unsupervised classification was first performed on the images. The core objective of unsupervised image classification is to automatically categorise all pixels into land cover classes. The Landsat 8 OLI signatures for landcover classification as delineated in study resulted to five land cover classes within Madagali Local Government Area of Adamawa State, namely built-up area, water-bodies, farmland, bare land and grassland. The aforementioned land cover classes were determined based on the spectral characteristics evident from the Landsat 8 image analysis, as noted by [25].

Supervised classification was subsequently conducted through three distinct stages: training data sets, classification and output generation. Training samples were selected for each identified land cover type featured in the supervised classification output. The acquired Landsat data were analysed using the Maximum Likelihood Classifier and Confusion Matrix Spatial Analyst tools, as described by [26], within ArcGIS 10.7 software. Ground-truthing data from Google Earth were thereafter collected for validation purposes, as described by [21] and [27]. Google Earth enabled the identification of ground truth pixels that had been correctly classified. The ground-truthing

ISSN: 2354-3361
DOI: https://doi.org/10.5281/zenodo.17175815

process involved a comparative visual analysis of the Landsat imagery used based on the authors' existing knowledge of the area. Consequently, sixty (60) areas of interest (AOI) located near water bodies and drainage systems were purposefully sampled for each land cover class, delineated. The last step adopted was to check how accurate the classification results were. A confusion matrix was used to measure this accuracy, as described in [28]. A confusion matrix is a table that compares classified data with actual data [29]. The numbers in the diagonal cells show how many pixels were classified correctly. Accordingly, the methods described by [30] were followed to calculate user's accuracy, producer's accuracy, commission errors, omission errors, and the Kappa coefficient (K). These calculations helped check how well the land cover classification worked in this study.

3. Results and Discussion

The overall accuracy for the landcover classification results of this study is 78.54%. The integration of GIS-based spatial analysis and weighted overlay modelling enabled effective assessment of flood susceptibility in the Madagali – the study area. The Digital Elevation Model (DEM) provides the foundational topography, where low-lying regions indicate higher flood potential due to water accumulation [31]. Slope, derived from the DEM, inversely correlates with flood risk flatter terrains have reduced runoff velocity, increasing flood retention. Rainfall data, ideally acquired from remote sensing sources Nigerian Meteorological Agency (NIMET), directly influences runoff intensity and temporal water volume; higher precipitation zones are more prone to flooding. Flow length, or the hydrological distance water travels to reach a drainage outlet, identifies zones of flow accumulation; shorter lengths suggest immediate flood susceptibility, especially in conjunction with steep upstream slopes. River distance quantifies proximity to permanent or seasonal rivers; areas closer to riverbanks are at elevated flood risk due to overflow during peak rains. By standardizing and assigning weights to each factor (via the Analytic Hierarchy Process or expert scoring), a weighted overlay can classify zones into very high, in which some part of Visik, Sabon Gari, Chambula, Shugule, Kubu, Uda, Kaya, Wuro Allhamdu, Shuwa, Kirchinga, and Gulak falls in very low area. The final flood hazard map reveals that flood vulnerability is most acute in low-lying, high-rainfall, close-to-river areas with impervious land use, informing disaster mitigation and land-use planning in Madagali.

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PUBLISHED 22-09-2025
www.journals.unizik.edu.ng/jsis

3.1. Digital Elevation Model

The map (Figure 1) created from the Digital Elevation Models (DEMs) are integral to flood modeling as they furnish comprehensive representations of the Earth's topography, which are indispensable for forecasting flood dynamics and evaluating flood vulnerabilities. The radiometric integrity and spatial resolution of Digital Elevation Models (DEMs) substantially influence the precision of flood hazard delineation and the robustness of inundation prognostications, with implications for downstream hydrological modelling accuracy [32]. DEMs with high resolution, such as those exhibiting a one-meter resolution, provide enhanced terrain details, thereby diminishing the anticipated extent of flooding in comparison to models with lower resolution. This level of precision is essential for the formulation of effective flood management and mitigation approaches.

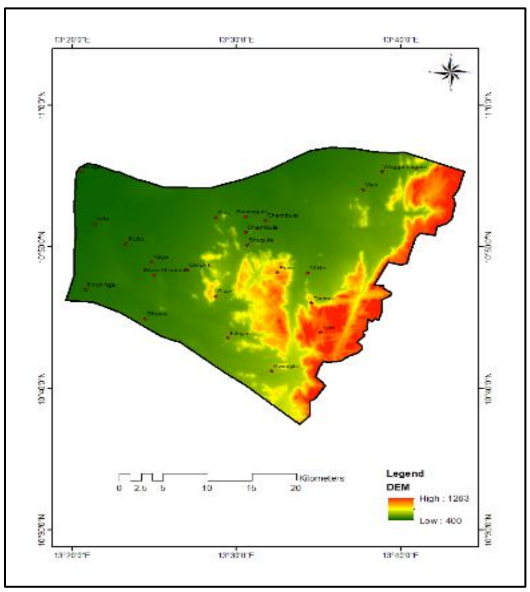

Figure 1: Digital Elevation Model (DTM) of Madagali LGA

3.2. Slope

Areas with low or gentle slopes in Madagali tend to accumulate water easily, slowing down surface runoff and increasing flood risk. Steep slopes, on the other hand, encourage rapid water flow, reducing local flooding but possibly increasing downstream flood hazards [2]. The slope length is as illustrated in Figure 2.

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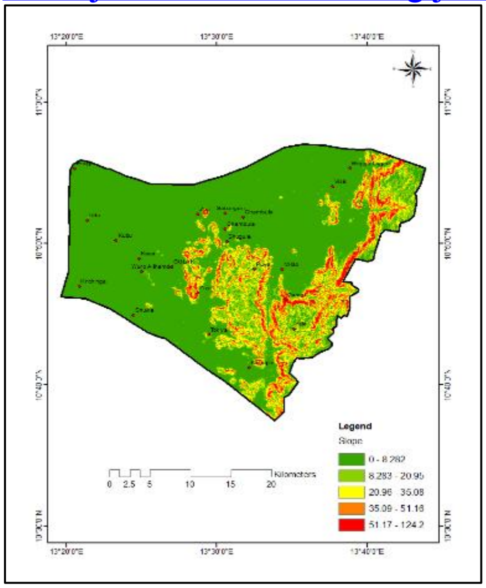
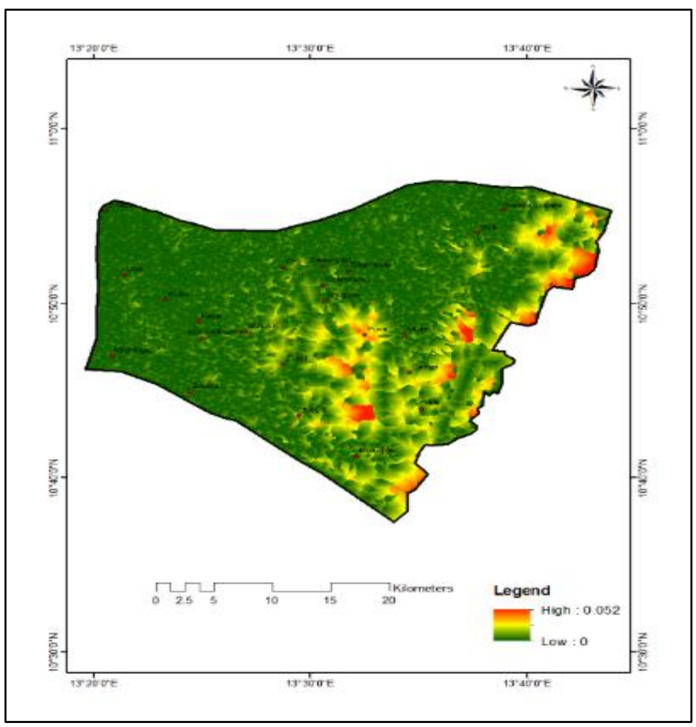


Figure 2: Slope length (SL) image of Madagali LGA

3.3. Flow Length

Flow length (Figure 3) affects how long it takes water to travel across the landscape. Shorter flow lengths in flatter terrains can lead to water stagnation and ponding, enhancing flood susceptibility, especially during intense rainfall events [33].



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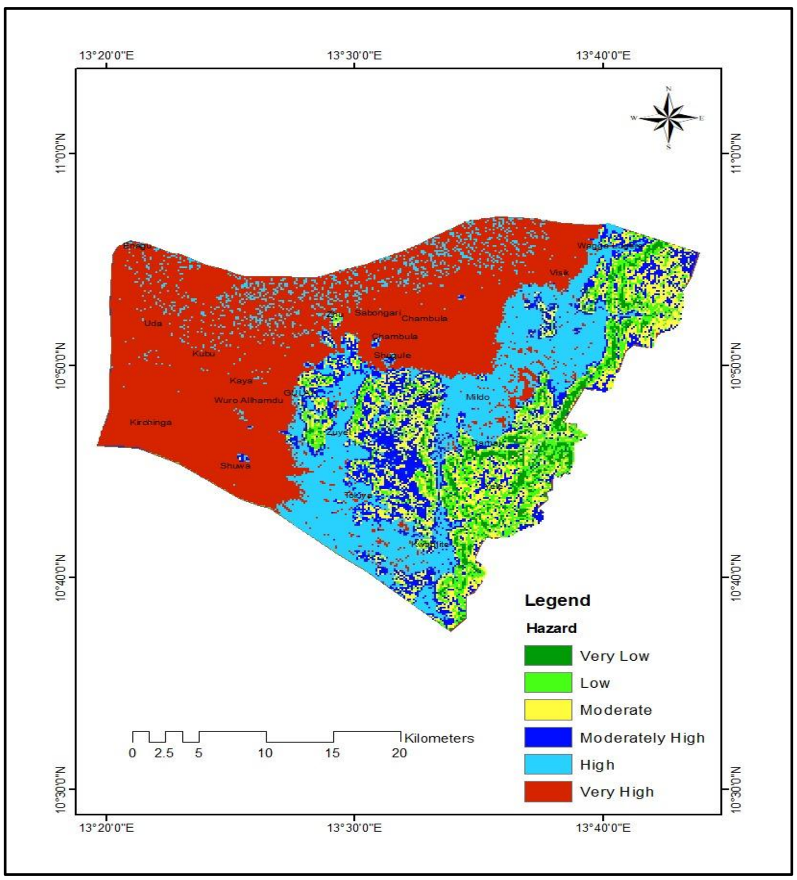
PUBLISHED 22-09-2025
www.journals.unizik.edu.ng/jsis

Figure 3: Flow length (FL) image of Madagali LGA

3.4. Flood Risk Assessment

The GIS and remote sensing analysis revealed that certain areas in Madagali Local Government Area as shown in Table 1, are more prone to flooding due to their low elevation, proximity to major rivers, and poor drainage systems. The flood hazard map (Figure 4) indicated that the towns of Madagali, Michika, and Gulak are particularly vulnerable to flooding, with large portions of these areas located within flood-prone zones. Communities like Uda, Kubu, Kaya, Gulak, Wuro Alhamdu, Kirchinga, Shuwa, Zuyel, Zhu, Sabon gari, Chambula, Shugule, Mildo, Damai, Visik and Wagga Lugere were heavily eroded due to their spatial location on the low land. The results indicate that approximately 35% of the study area is situated within high to very high flood risk categories, predominantly low-lying areas subject to intensive land-use patterns and variability in rainfall distributions. The study area's proximity to Madara Mountain exacerbates its flood susceptibility, driven by underlying geomorphological and hydrological factors.



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PUBLISHED 22-09-2025
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Figure 4: Flood risk/hazard map of Madagali LGA of Adamawa State

Table 1. Showing various flood affected area and their coverage

SN	*Grades*	*Area (Km^2)*	*% Vulnerability*	*Colour*
1	Very Low	428.04	15.55%	Green
2	Low	663.93	18.53%	Light Green
3	Moderate	301.41	30.50%	Yellow
4	Moderately High	743.04	49.20%	Blue
5	High	633.96	52.8%	Cyan
6	Very High	1215.27	60.7%	Red

Source: This study

The vulnerability assessments undertaken in this study revealed distinct classifications such as: 18.53% of areas exhibit low vulnerability, 30.50% moderate vulnerability, 52.8% high vulnerability, and 60.7% very high vulnerability.

4. Conclusion and recommendations

4.1. Conclusion

The paper demonstrates that leveraging on geospatial information can substantially enhance flood management capabilities in Madagali Local Government Area. Local officials can bolster their flood planning and response strategies by integrating data from GIS, satellite imagery, and rainfall records. The overall accuracy for the landcover classification results of this study is 78.54%. Also, the results indicate that approximately 35% of the study area is situated within high to very high flood risk categories, predominantly low-lying areas subject to intensive land-use patterns and variability in rainfall distributions. The vulnerability assessments undertaken in this study revealed distinct classifications such as: 18.53% of areas exhibit low vulnerability, 30.50% moderate vulnerability, 52.8% high vulnerability, and 60.7% very high vulnerability. Literally, prominent urban centres including Madagali, Michika, and Gulak are situated within high-risk flood zones. Communities such as Uda, Kubu, Kaya, Wuro Alhamdu, Kirchinga, Shuwa, Zuyel, and Sabon Gari face considerable erosion challenges attributable to their low-lying topographic positioning. The Gongola River and its tributaries are key hydrological features exerting significant influence on flood dynamics, highlighting their critical role in catchment-scale flooding events. The study

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area's proximity to Madara Mountain exacerbates its flood susceptibility, driven by underlying geomorphological and hydrological factors. In conclusion, the geospatial methods applied in this study provide evidence-based insights for policymakers thereby, supporting effective flood risk management and enhancing community resilience within Madagali Local Government Area.

4.2. Recommendations

This study highlights several key suggestions for stakeholders. They should consider initiatives like planting more trees, keeping river channels clear, building suitable water management structures, and creating drainage systems near Madara Mountain. Such actions could help reduce floods and also provide water for farming during dry periods. Future research could investigate the relationship between land use patterns and flood vulnerability in Madagali Local Government Area to elucidate how land use dynamics shape flood risk profiles.

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ISSN: 2354-3361
DOI: https://doi.org/10.5281/zenodo.17175815
www.journals.unizik.edu.ng/jsis

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ISSN: 2354-3361
VOL. 2, ISSUE 3, PP 119–137, 2025
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