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Geospatial Assessment of Flood-Prone Areas in Gombe Local Government Area, Gombe State, Nigeria

Abdulrashid Abdullahi, Abdulwahab Zakariya, Jimoh A. Ibrahim, Yusuf U. Ahmad.
Department of Geography, Gombe State University, PMB 127, Gombe State, Nigeria.
abdulrashidabdullahi@gsu.edu.ng

Abstract

This study assesses flood-prone areas in Gombe Local Government Area (LGA), Gombe State, Nigeria, using Geographic Information System (GIS) and Remote sensing techniques. The analysis focuses on key flood risk factors including elevation, soil composition, geology, stream density, and the Topographic Wetness Index (TWI). Findings indicate that low-lying areas (330-380 meters) covering 11.19% of the area are highly susceptible to flooding due to limited drainage capacity, while higher elevations (>590 meters) spanning 18.34% of the area act as natural buffers against inundation. Areas dominated by Arenosols (66.93% of the area) exhibit increased flood risk, contrasting with regions with Nitisols (0.41% of the area) that are less prone to flooding. Geological formations such as Gombe Sandstone (37.89% of the area) and Basement Complex (3.30% of the area) significantly influence flood dynamics. Higher stream density areas (56.17% of the area) experience intensified surface runoff and localized flooding, impacting flood susceptibility. The Topographic Wetness Index (TWI) analysis highlights moisture conditions, with higher TWI values indicating elevated flood risk. These insight are crucial for forming flood risk management strategies and disaster resilience effort in Gombe LGA and similar regions. Recommendations include enhanced land-use planning, improve drainage infrastructure, and community-based preparedness initiatives to mitigate flood impacts and build resilience.

Key words: Flood-prone areas, GIS, remote sensing, flood risk factors, spatiotemporal variation

Introduction

Flooding is one of the most pervasive and destructive natural hazards, leading to significant economic losses, infrastructure damage, and human suffering worldwide. The increasing frequency and intensity of floods are largely attributed to climate change, which disrupts the hydrological cycle, as well as to rapid urbanization and changes in land use that often place more people and assets in harm's way (Deepak et al., 2020). Floods occur when the capacity of a river or drainage system is overwhelmed by water discharge, causing water to overflow onto adjacent low-lying areas. These areas, often occupied by farmlands, residential, and commercial structures, become susceptible to extensive damage during flood events (Abashiya et al., 2019).

Floods are recognized as the most common and costly natural disasters, accounting for approximately one-third of all natural catastrophes globally. The financial and human toll of floods has escalated in recent decades due to the combined effects of extreme weather events, urban sprawl, and insufficient disaster preparedness and response mechanisms. For instance, the adoption of hydrologic model-based flood forecasting systems has been identified as one of the most effective approaches for early warning, monitoring, and mitigating flood hazards (Huane et al., 2012).

Flooding not only impacts human settlements but also interacts with various human activities, altering the environment and disrupting livelihoods. This phenomenon typically results from a combination of factors, including heavy rainfall, inadequate drainage infrastructure, and changes in land use that increase surface runoff and reduce natural infiltration rates. The application of Geographic Information Systems (GIS) in flood risk assessment has proven invaluable, as it allows for the integration of spatial data to assess and map flood-prone areas effectively. By utilizing GIS, planners and policymakers can develop more accurate flood risk assessments and implement targeted mitigation strategies (Jerome et al., 2022).

Globally, floods are responsible for significant casualties and economic losses. In Africa, floods are a common occurrence, particularly in countries like Rwanda, Kenya, Somalia, Nigeria, and Burundi. In 2020, devastating floods across these regions affected over 700,000 people, caused 430 deaths, and led to widespread displacement, particularly in Kenya and Rwanda. Africa's tropical climate contributes to the frequency of these events, with seasonal rainfall patterns often leading to excessive runoff and flooding (Jerome et al., 2022).

In Nigeria, flooding has become a critical concern, especially in urban areas where poor drainage systems exacerbate the problem. The country experienced one of its worst flooding disasters in 2012, with losses estimated at $16.9 billion. Between 1985 and 2014, floods affected more than 11 million Nigerians, resulting in 1,100 deaths and over $17 billion in property damage. The states most frequently affected include Niger, Adamawa, Oyo, Kano, and Jigawa, largely due to their proximity to major rivers such as the Niger, Benue, Ogun, and Hadeja. However, Lagos State, despite its extensive flood management efforts, remains one of the most flood-prone areas due to its dense population and coastal location (Ugonna, 2016).

Gombe State, located in northeastern Nigeria, is particularly vulnerable to urban flooding due to inadequate drainage systems. The topography and hydrological conditions of the region play a significant role in the occurrence and severity of floods. Poor urban planning, combined with the effects of climate change, has led to recurrent flood events that disrupt daily life, damage infrastructure, and threaten lives and livelihoods. The drainage patterns and the hydrological conditions of the area is crucial for assessing flood risks and implementing effective flood management strategies (Abashiya et al., 2019).

The challenge of flood management is complex, involving multiple criteria that must be evaluated and integrated to develop a comprehensive risk assessment. The use of GIS software for data integration and analysis is essential in this process, as it allows for the effective combination of various data sources to generate accurate flood risk maps. Management strategies need to be periodically revised, approximately every 30 to 50 years, to account for changes in climate, land use, and urban development (Tariq, 2020). In developing countries, where resources for flood management may be limited, innovative solutions such as Short Message Service (SMS) flood warning systems have been implemented in remote areas with high mobile phone penetration, providing timely warnings to at-risk populations (Goodwin, 2012).

In recent years, flooding has become an increasingly severe issue in Gombe Local Government Area (LGA), rendering many homes uninhabitable, destroying farmlands, and leading to the loss of human and animal life. Flooding is one of the most frequent environmental hazards globally, occurring in various forms and magnitudes across terrestrial regions. The impact of floods is profound, causing substantial annual losses in terms of economic livelihoods, business disruption, infrastructure damage, and public health crises (Dabara et al., 2012).

In Gombe LGA, the effects of flooding have led to deplorable living conditions, forcing residents to abandon their homes and negatively impacting agricultural productivity. Commuters face significant challenges due to the damage caused to transport routes, further exacerbating the region's socio-economic difficulties. Previous research in Gombe has primarily focused on soil fertility and land use, leaving a critical gap in the understanding of flood risks and management strategies in the area.

This study seeks to address this gap by examining the flood-prone areas in Gombe LGA and proposing sustainable solutions to mitigate future flood risks. By identifying the factors contributing to flooding and analyzing their spatial distribution, the research aims to provide actionable insights for improving flood management efforts in Gombe State. The outcomes of this study are intended to guide local authorities in implementing effective flood risk reduction measures, thereby enhancing the resilience of communities in Gombe LGA to future flood events.

Materials and Method

The research utilized ArcGIS for data analysis, where geographic coordinates were used to map the study area. Figure 1 shows the map of Gombe local government area. The challenge in multi-criteria evaluation (MCE) lies in integrating multiple criteria into a single assessment index, which was addressed using GIS software. The Analytical Hierarchy Process (AHP) was employed to prioritize flood risk factors, and a weighted overlay procedure was then applied to integrate these factors and create a flood vulnerability map. The study involved creating floodplain maps using gridded rainfall/precipitation data from the Climatic Research Unit (CRU) covering 1901 to 2022, and high-resolution Digital Elevation Models (DEMs) with 30m x 30m resolution, sourced from the United States Geological Survey (USGS).Data analysis involved using AHP to prioritize flood risk factors and then applying a weighted overlay in GIS to create a flood vulnerability map. Factors like elevation, slope, drainage density, and land use were weighted according to their impact on flood risk, and the resulting map visually identified areas most vulnerable to flooding.

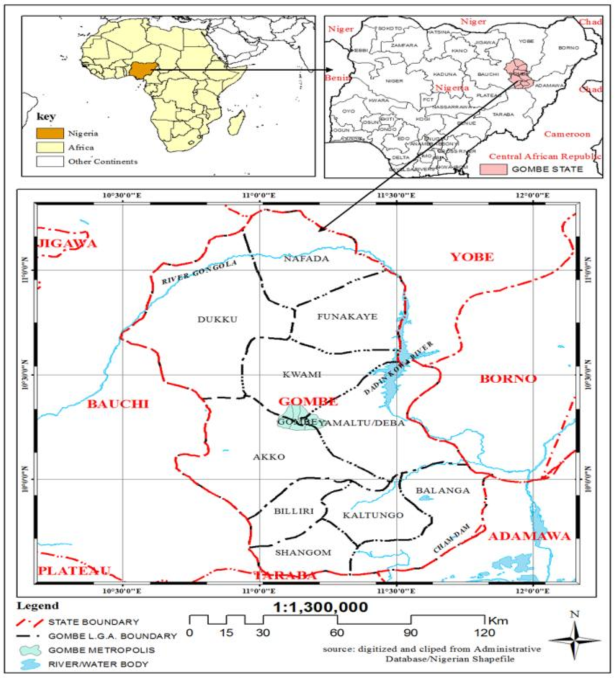

Figure 1: Map of Gombe State showing Gombe Local Government Area

Results and Discussion

Flood Risk Factors

Flood risk factors are critical components that contribute to the overall vulnerability of a region to flooding. These factors allow for the identification of high-risk areas and inform the development of mitigation strategies. In the study area, several key factors—elevation, soils, geology, stream density, topographic wetness index (TWI), slope, stream power index (SPI), landforms, land use/land cover (LULC), and valley depth—were analyzed to assess flood risk. Effective flood risk management utilizes advanced tools such as geographic information systems (GIS) to analyze spatial data, aiding in the identification of high-risk areas and improving planning efforts (M. Waseem et al., 2023). By implementing geospatial techniques, local authorities can better understand their vulnerabilities and craft tailored interventions.

Elevation

Elevation plays a pivotal role in flood risk assessment because it directly influences the potential for water accumulation and runoff. The study area's elevation ranges from 330 to 680 meters, with lower elevations (330-380 meters) being particularly vulnerable to flooding (Figure 2). These low-lying areas, covering 11.19% of the study area, are at a higher risk due to their proximity to water bodies and limited drainage capacity. On the other hand, higher elevations (590 meters and above), which cover about 18.34% of the area, act as natural barriers, reducing flood risk by facilitating runoff away from vulnerable areas.

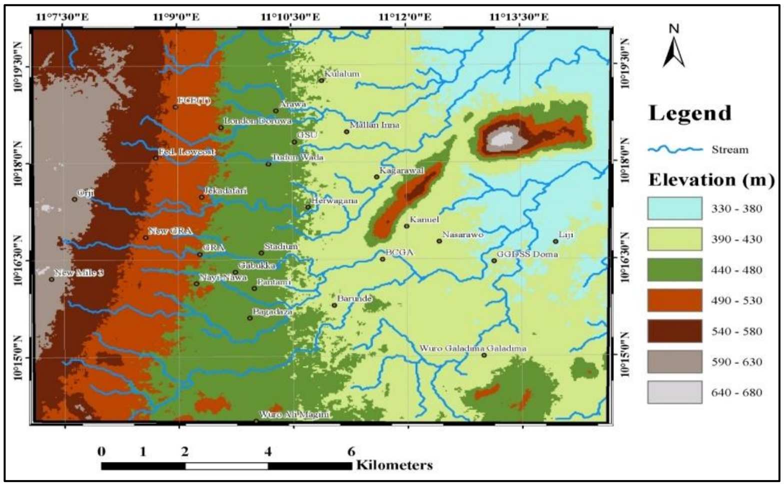

Figure 2: Elevation Map of Study Area

The varying elevations create a natural gradient, where water flows from higher to lower areas, increasing the risk of flooding in the low-lying regions. These distribution of elevations within the study area helps in identifying the zones that require more focused flood prevention and mitigation efforts. The natural gradient of an area significantly influences water flow dynamics, which can lead to various environmental consequences. Topography shapes how water moves across landscapes, impacting groundwater levels and surface water runoff. For example, uneven terrain can result in increased flooding risk in certain regions, especially in urban environments where natural drainage is altered by human activities (Ol'gaHryanina et al., 2019). The management of these water dynamics is crucial, particularly in areas with aging infrastructure, where failures can exacerbate flooding and disrupt local economies (Tayyab Ahmad et al., 2023).

Soils

Soil composition is another crucial factor that influences flood risk. The study area is dominated by Arenosols, which cover 66.93% of the area (Figure 3). Arenosols are sandy soils with low water retention capacity, leading to rapid surface runoff and increased flood risk during heavy rainfall. This characteristic makes areas with Arenosols particularly vulnerable to flash floods.

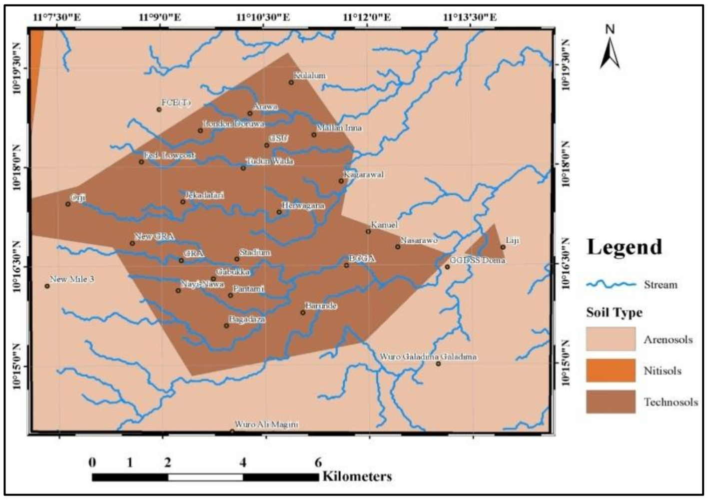

Figure 3: Soil Map of the Study Area

In contrast, Nitisols, though covering only 0.41% of the area, have better water retention properties, which can reduce flood risk by slowing down runoff and allowing more water to infiltrate the soil. Technosols, covering 32.66% of the area, exhibit varied permeability, which can either mitigate or exacerbate flood risk depending on the specific characteristics of these soils in different locations. Soils rich in organic matter, such as Histosols, enhance water infiltration and improve overall water availability, thereby reducing flood risks (Muhammad YusrilIhzaKurzah et al., 2024). Effective land use planning should incorporate comprehensive soil type mapping, allowing for targeted conservation efforts that bolster ecosystem resilience while simultaneously addressing the challenges posed by varying soil characteristics in relation to flood vulnerability.

Geology

The geological formations within the study area play a crucial role in determining the flood risk. The area is characterized by three distinct formations: Gombe Sandstone, Keri-Keri, and the Basement Complex (Figure 4). Gombe Sandstone, which covers a significant portion of the area at 37.89%, is highly permeable, facilitating groundwater recharge and potentially reducing surface runoff. This permeability of the Gombe Sandstone can be attributed to its sedimentary nature, which typically exhibits primary porosity and permeability characteristics.

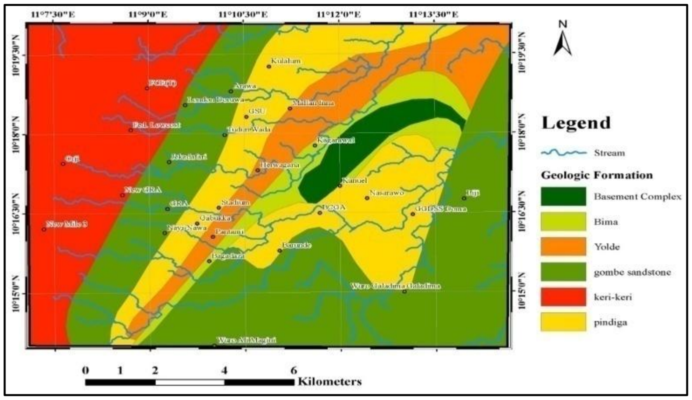

Figure 4: Geological Map of the Study Area (Source: remote sensing imaging)

The Basement Complex, on the other hand, is composed of weathered and fractured crystalline rocks. While crystalline rocks may have lower primary porosity and permeability, the presence of secondary porosity and permeability created by fracturing can enhance their ability to serve as aquifers. This fracturing and weathering of the Basement Complex can influence the area's hydrology and potentially contribute to groundwater recharge, affecting the overall flood risk (Kabite & Gessesse, 2018).

Stream Density

Stream density is a measure of the number of streams per unit area, which directly correlates with the potential for flooding. Areas with high stream density, such as those in the 0-1.1 km² class (covering 56.17% of the area), are more prone to flooding due to the increased convergence of surface runoff (Figure 5). High stream density areas are likely to experience frequent channel overflow, leading to localized flooding, especially during heavy rainfall events.

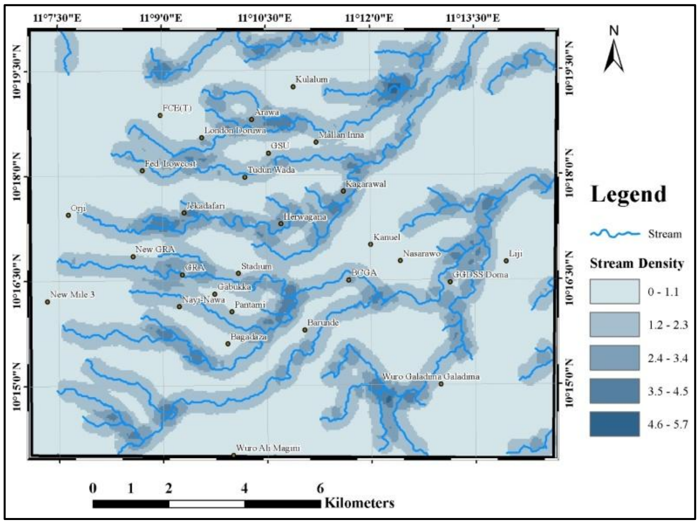

Figure 5: Stream Density map of the study area

Lower stream density areas, such as those in the 4.6-5.7 km² class (covering only 0.07% of the area), have better drainage capacity, reducing the risk of flooding. These areas are less likely to experience significant flooding unless subjected to extreme weather conditions. Stream density is an important factor in flood risk assessment because it highlights areas where water is likely to accumulate, leading to potential flood events. It also helps in planning drainage systems and flood mitigation infrastructure (Zhang et al., 2013).

Topographic Wetness Index (TWI)

The Topographic Wetness Index (TWI) is a measure of the wetness potential of the terrain, taking into accounts both slope and upstream contributing area. High TWI values indicate areas with higher moisture retention and, consequently, higher flood risk. In the study area (Figure 6), regions with TWI values in the -16 to -15 and -20 to -17 classes are particularly prone to waterlogging and prolonged surface runoff, increasing the likelihood of flooding.

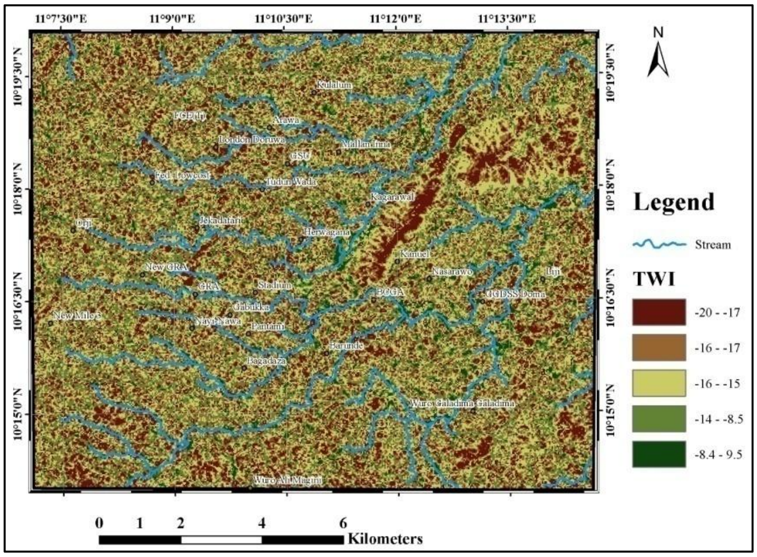

Figure 6: Topographic Wetness Index of the Study Area

Lower TWI values correspond to drier areas with better drainage, reducing flood risk (Buchanan et al., 2014). The distribution of TWI within the study area provides valuable insights into potential flood hotspots and helps in the design of effective water management and flood prevention strategies.

Slope

Slope is a critical determinant of flood risk because it influences the velocity of surface runoff. Gentle slopes (0-5.00 km² class), covering 66.58% of the area, generally allow for greater water infiltration and slower runoff, reducing flood risk. However, steep slopes (greater than 20), covering 3.45% of the area, can lead to rapid runoff, erosion, and increased flood risk downstream (Zhao et al., 2022).

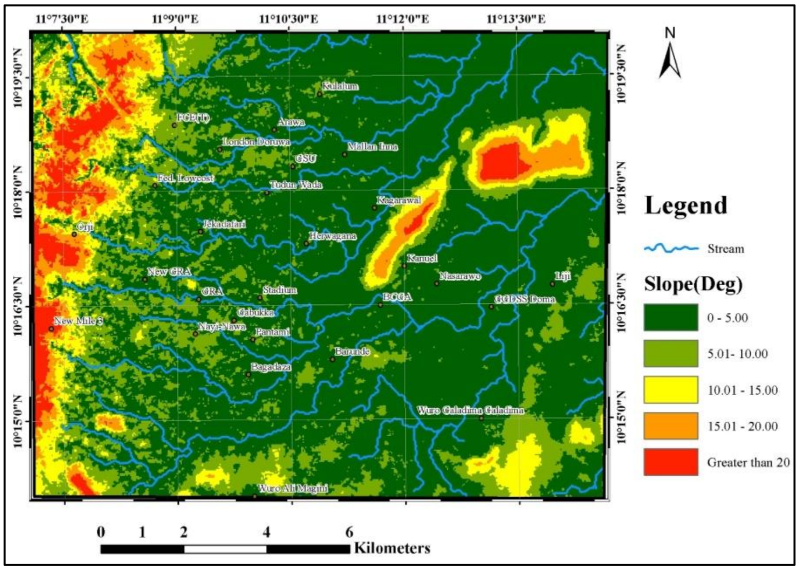

Figure 7: Slope Map of the Study Area

The distribution of slope classes within the study area is essential for identifying areas that are prone to rapid runoff and potential erosion, which can exacerbate flooding (Figure 7).

Stream Power Index (SPI)

The Stream Power Index (SPI) quantifies the erosive power of streams, which directly impacts flood risk. High SPI values indicate areas where streams have significant energy to cause erosion and transport sediments, contributing to the formation of floodplains and increasing flood risk. In the study area, regions with high SPI values (3,100,000 - 6,800,000 class, covering 39.02% of the area) are particularly vulnerable to erosion and flooding (Figure 8). Conversely, lower SPI values correspond to areas with more stable channels, reducing the risk of erosion and subsequent flooding (Tarolli et al., 2021). The SPI is a crucial in understanding the dynamics of river systems and their potential to contribute to flooding.

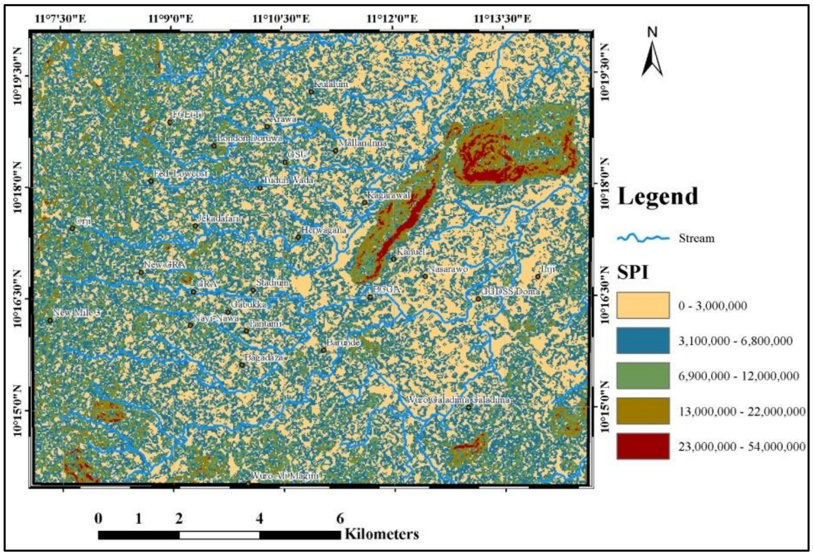

Figure 8: Stream Power Index Map of the Study Area

Landforms

Landforms describe the physical features of the landscape, which influence flood dynamics. In the study area, dominant landforms such as flats and slopes play a significant role in surface runoff patterns and flood propagation (Figure 9). Flats, covering 73.53% of the area, are particularly prone to water accumulation and flooding, while slopes may facilitate runoff and reduce the risk of flooding (Smith & Brown, 2023).

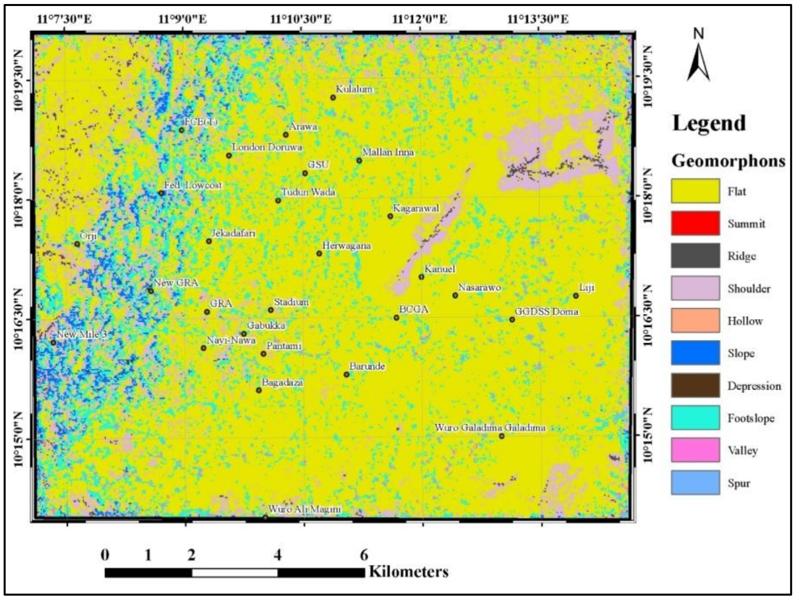

Figure 9: Landform Distribution Map of Study Area

The distribution of landforms within the study area helps in predicting flood behavior and identifying areas that require targeted flood mitigation efforts.

Land Use/Land Cover (LULC)

Land use and land cover (LULC) significantly influence flood risk by affecting surface runoff and infiltration. In the study area, built-up areas and barren land contribute to increased flood risk due to reduced infiltration and higher surface runoff (Figure 10). Vegetation cover, which accounts for 39.41% of the area, helps to mitigate flood risk by intercepting rainfall, enhancing soil permeability, and stabilizing slopes (Zhang, Li, & Wang, 2024).

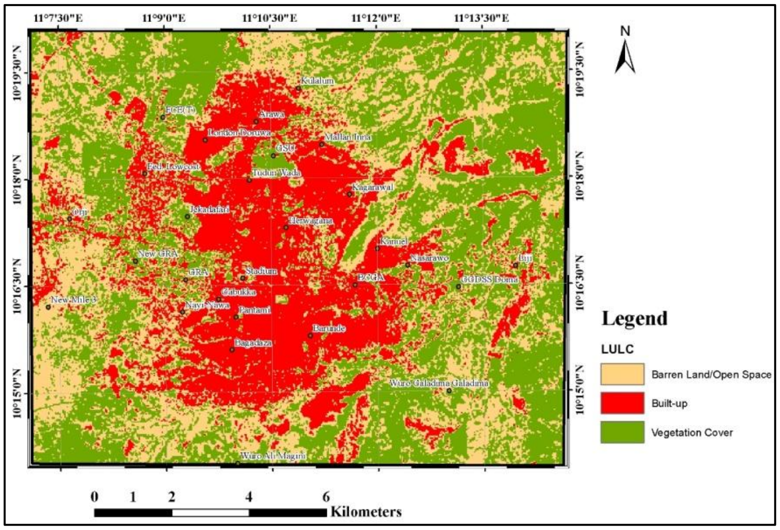

Figure 10: LULC Map of the Study Area

The LULC analysis provides insights into human activities and natural vegetation's role in flood dynamics, helping to identify areas where land management practices could reduce flood risk.

Valley Depth

Valley depth is a key factor in determining flood risk because it affects water storage capacity and flow dynamics. Deeper valleys, such as those in the 160-190 and 200-260 classes (covering 43.48% and 23.40% of the area, respectively), can store larger volumes of water, reducing the likelihood of surface flooding in adjacent areas (Figure 11). However, excessively deep valleys may also impede drainage, increasing the risk of flooding in low-lying regions (Johnson & Roberts, 2023).

Valley depth analysis helps in identifying areas where water is likely to accumulate, informing the development of flood management strategies that consider both water storage and drainage needs.

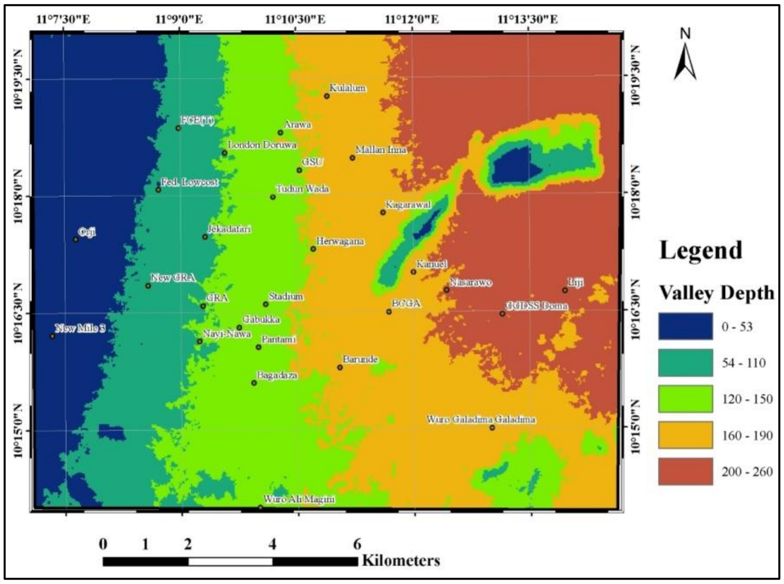

Figure 11: Valley Depth Map in the Study Area

Weighting of Flood Factors Using AHP

The Analytical Hierarchy Process (AHP) is a decision-making tool used to prioritize flood risk factors based on their relative importance. In this study, the AHP was used to assign weights to each flood factor, resulting in a comprehensive ranking of their influence on flood vulnerability (Figure 12).

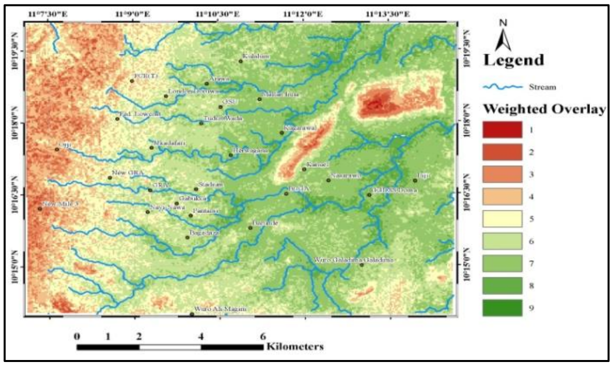

Figure 12: Flood Weighted Overlay – Higher weight Higher Flood Vulnerability

The Stream Power Index (SPI) and Valley Depth emerged as the most critical factors, with priorities of 19.70% and 19.60%, respectively. These factors highlight the importance of stream dynamics and landscape morphology in shaping flood risk. High SPI values indicate intense stream energy, leading to increased erosion and floodplain formation, while deep valleys contribute to water storage and flood propagation.

Drainage Density also received significant priority (16.90%), emphasizing the role of stream networks in influencing surface runoff and flood risk. Elevation, Slope, and TWI were assigned moderate priorities, reflecting their roles in modulating runoff and water accumulation.On the other hand, LULC, Soil, and Geology received lower priorities, indicating their lesser influence compared to other factors. However, these factors still play a role in shaping flood dynamics by affecting surface permeability, infiltration rates, and land surface characteristics.The AHP decision matrix provided a structured approach to assess and prioritize flood factors, informing the development of targeted flood mitigation strategies.

Flood Prone Areas in the Study Area

The study categorizes flood vulnerability in the area into five distinct levels: Very Low, Low, Moderate, High, and Very High. Very Low Vulnerability areas, covering 6.84% of the region, are the least susceptible to flooding, requiring minimal flood risk management efforts. Low Vulnerability areas account for 25.64% and, while relatively safe, still need monitoring and basic flood prevention measures. Moderate Vulnerability areas, making up 26.68% of the study area, face a moderate risk of flooding and necessitate preparedness and mitigation measures to handle potential localized flood events. High Vulnerability, encompassing 34.98% of the area, indicates significant flood risk, demanding robust flood management strategies to protect infrastructure and human settlements. Very High Vulnerability areas, comprising 5.85% of the region, are at the greatest risk and require immediate attention with comprehensive flood mitigation strategies to safeguard lives, property, and the environment.

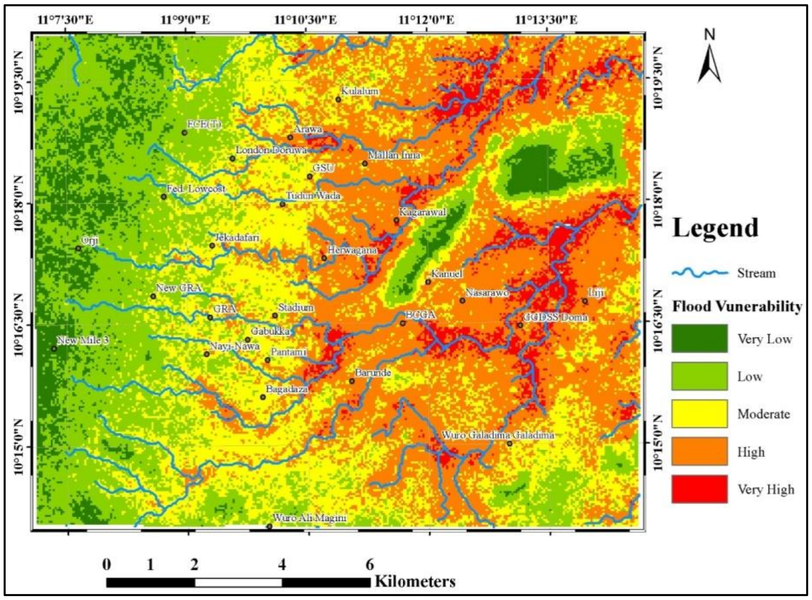

Figure 13: Flood Vulnerability Map of The Study Area

The spatial distribution of these vulnerability levels, as shown in the Figure 13, reveals critical patterns in flood risk across the study area. The majority of high and very high vulnerability areas are located in low-lying regions, valleys, and areas with high stream density, which are particularly prone to flooding due to their geomorphologic characteristics, high potential for water accumulation, and limited drainage capacity. This spatial analysis highlights the need for targeted flood risk management strategies in the most vulnerable areas, including the implementation of flood defenses, improved drainage systems, land use planning, and community preparedness programs. Additionally, the analysis underscores the importance of integrating flood risk assessments into urban planning and development projects to minimize the impact of future flood events.

Conclusion

The geospatial assessment of flood-prone areas in Gombe Local Government Area offers a detailed evaluation of flood risks. Utilizing geospatial tools, the study effectively identifies areas with varying degrees of flood vulnerability, underscoring the importance of tailored flood management strategies. The research emphasizes that high and very high vulnerability areas require immediate attention through improved infrastructure, enhanced drainage systems, and comprehensive flood mitigation measures.

The study's findings are crucial for guiding local authorities, policymakers, and stakeholders in making informed decisions about flood risk management. By integrating flood risk assessments into urban planning and development projects, the study promotes a proactive approach to minimizing flood-related impacts and ensuring sustainable development in the region.

Recommendations

Establish an advanced flood mapping and monitoring system to accurately identify flood-prone areas and track changes in flood vulnerability over time. This system will be instrumental in guiding interventions and resource allocation. Prioritize the enhancement of drainage systems, particularly in high and very high vulnerability zones, to reduce water accumulation and mitigate flood risks. Upgrading existing drainage infrastructure and constructing new systems where needed should be a key focus.

Implement community-focused education and preparedness programs to raise awareness about flood risks and encourage the adoption of flood-prevention measures. These programs should include training on emergency response and sustainable land use practices. Design and construct flood defense structures, such as levees, floodwalls, and retention basins, in areas identified as highly vulnerable to flooding. These defenses will play a crucial role in protecting lives, properties, and infrastructure.

Incorporate flood risk assessments into all urban planning and development initiatives. This includes enforcing zoning regulations that restrict construction in flood-prone areas and ensuring that new developments are resilient to flood risks. Deploy early warning systems that provide real-time information on flood risks, allowing communities to take necessary precautions and minimize the impact of flooding. Promote land use practices that reduce flood risks, such as reforestation, wetland conservation, and the regulation of urban sprawl. These practices will help maintain natural water flow and prevent excessive water accumulation in vulnerable areas.

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