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Geospatial assessment of flood vulnerability using remote sensing and GIS

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Abstract

Flooding has become one of the most frequent and devastating natural hazards worldwide, particularly in regions experiencing rapid urbanization, unregulated land use, and climate variability. Its impacts extend beyond the immediate destruction of property and infrastructure to long-term socio-economic disruptions, public health crises, and environmental degradation. Understanding spatial patterns of flood vulnerability is therefore essential for effective disaster risk management, sustainable urban planning, and community resilience building. Remote sensing and Geographic Information Systems (GIS) have emerged as powerful tools in this regard, providing high-resolution, multi-temporal data that can be integrated into vulnerability assessments. Through the use of satellite imagery and digital elevation models, remote sensing enables the identification of hydrological features, drainage networks, land cover changes, and flood-prone areas. When combined with ArcGIS, these datasets allow researchers to develop vulnerability indices by integrating biophysical and socio-economic variables such as slope, soil type, rainfall intensity, population density, and infrastructure distribution. ArcGIS-based spatial modeling provides a platform for mapping areas of high, medium, and low vulnerability, creating outputs that are both analytical and visually interpretable for decision-makers. Applying this integrated approach to flood-prone regions enables the development of precise vulnerability maps that can guide risk reduction strategies, emergency preparedness, and urban policy interventions. By capturing both natural and anthropogenic drivers, geospatial mapping enhances early warning systems, supports allocation of resources, and promotes evidence-based planning. The study underscores the necessity of mainstreaming geospatial technologies into flood risk management frameworks, ensuring that communities are better equipped to withstand the increasing threat of flooding.

Keywords: Flood Vulnerability; Geospatial Mapping; Remote Sensing; Arcgis; Risk Assessment; Disaster Management

1. Introduction

Flooding remains one of the most devastating natural hazards worldwide, displacing millions annually and inflicting severe damage on infrastructure, agriculture, and livelihoods [1]. Its consequences extend far beyond immediate economic losses, creating long-term socio-economic and environmental disruptions. The global intensification of flood events is linked to rapid urbanization, deforestation, and poor land-use planning, all of which amplify exposure and reduce the resilience of vulnerable populations [2]. Low-lying and riverine regions are particularly susceptible, with climate variability driving more frequent and intense rainfall that overwhelms drainage systems and natural floodplains [3].

In Nigeria, flooding has emerged as a recurring disaster, with Adamawa and Niger States serving as critical case studies. Both states are geographically prone to flooding due to their location along major rivers the Benue in Adamawa and the Niger in Niger State. Seasonal river overflows, combined with heavy rainfall, routinely inundate agricultural lands and residential areas. In Adamawa, repeated flooding along the Benue River has displaced thousands of households, eroded

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farmland, and disrupted regional trade routes [4]. Similarly, Niger State experiences persistent flooding in areas surrounding the River Niger, particularly in Mokwa and Lapai, where agricultural livelihoods are repeatedly undermined.

The impacts are unevenly distributed, as poorer rural communities often settle in high-risk floodplains due to limited alternatives. These populations face heightened vulnerability, lacking both resilient housing and sufficient infrastructure. The recurrent crises underscore the urgent need for systematic approaches that integrate geospatial mapping, early-warning systems, and governance strategies to identify hotspots and guide targeted interventions [5]. Such measures are essential not only to mitigate hazards but also to address the deep-seated inequalities that flooding exposes in Adamawa and Niger States.

1.1. Importance of geospatial technologies in flood risk studies

Geospatial technologies, particularly remote sensing and Geographic Information Systems (GIS), have transformed flood risk studies by providing accurate, timely, and spatially explicit information [3]. Remote sensing allows researchers to capture multi-temporal satellite imagery, enabling the monitoring of land-use changes, rainfall patterns, and surface water extent. These datasets are critical for detecting areas prone to inundation and for modeling hydrological processes across large regions [4].

GIS enhances the analysis by integrating diverse datasets, including elevation models, soil types, land cover, and socio-economic indicators. Through spatial analysis, GIS supports the generation of vulnerability indices, which combine hazard exposure, sensitivity, and adaptive capacity to provide comprehensive flood risk maps [7]. By visualizing these outputs, policymakers can identify areas of high risk and prioritize resource allocation for mitigation efforts.

The integration of geospatial technologies into flood studies is particularly important in contexts where traditional hydrological data are sparse or inconsistent. In many regions of the Global South, the absence of detailed ground measurements makes satellite-based and GIS-driven methods indispensable [5]. Moreover, these technologies provide scalable tools that can be applied at local, regional, and national levels.

For Nigeria and similar countries, the adoption of geospatial methods offers not only analytical insights but also practical benefits for disaster preparedness. Early warning systems, zoning regulations, and infrastructure planning can be improved when informed by spatially explicit flood risk assessments [2]. Thus, geospatial approaches bridge scientific innovation and practical governance in addressing flood vulnerability.

1.2. Objectives, scope, and contributions of the study

This study focuses on the geospatial mapping of flood vulnerability using remote sensing and ArcGIS, with a regional emphasis on flood-prone areas in Adamawa and Niger States. The primary objective is to develop vulnerability maps that combine both biophysical and socio-economic factors to identify the zones most at risk of recurrent flooding [6]. Specifically, the research seeks to:

Utilize satellite imagery and digital elevation models (DEM) to delineate hazard-prone areas along the River Benue in Adamawa and the River Niger in Niger State.

Apply ArcGIS-based spatial analysis to integrate environmental indicators such as slope, land cover, and rainfall with demographic and infrastructural factors to construct a composite vulnerability index.

Generate maps that classify high, medium, and low vulnerability zones, supporting targeted interventions in disaster preparedness and risk reduction strategies [3].

The scope of the study covers urban and peri-urban settlements along the floodplains of both states, where seasonal inundation disrupts livelihoods, agriculture, and transportation networks. Areas such as Yola and Numan in Adamawa, as well as Mokwa and Lapai in Niger State, are particularly emphasized due to their history of severe flooding and displacement of local populations [1]. By integrating remote sensing datasets with ground-level field observations and census-based socio-economic data, the study captures the multi-dimensional nature of vulnerability in these regions.

The contributions of this research are both methodological and practical. Methodologically, it demonstrates the effectiveness of integrating remote sensing with spatial modeling in ArcGIS to analyze flood risk [4]. Practically, it provides policymakers, planners, and emergency management agencies with vulnerability maps that guide disaster risk management, flood mitigation strategies, and community-based adaptation programs [7].

2. Theoretical and conceptual foundations

2.1. Concepts of flood vulnerability and resilience

Flood vulnerability refers to the degree to which individuals, communities, and systems are susceptible to harm from flood hazards. It encompasses both physical exposure to inundation and the capacity to cope with and recover from impacts. The concept is multidimensional, including biophysical factors such as topography, soil characteristics, and drainage conditions, as well as socio-economic dimensions like poverty, governance, and access to infrastructure [7]. For example, two communities within the same floodplain may face different levels of vulnerability depending on the resilience of their housing, availability of emergency response services, and livelihood options.

Resilience, in contrast, highlights the ability of a system to absorb disturbances and adapt without experiencing catastrophic breakdown. In the context of flooding, resilience is measured by how effectively communities prepare for, respond to, and recover from inundation events [6]. Resilient communities are characterized by adaptive infrastructure, diversified livelihoods, and robust governance institutions that promote equitable access to resources.

The interplay between vulnerability and resilience is central to flood risk assessment. While vulnerability captures susceptibility to harm, resilience emphasizes adaptive capacity. A household living in a flood-prone area with robust housing, insurance mechanisms, and strong community support may be less vulnerable than one in the same zone without these buffers [12].

The increasing relevance of resilience thinking is tied to the recognition that floods cannot be fully prevented. Instead, emphasis is shifting toward strategies that enhance communities' ability to withstand recurring flood events. This includes investment in resilient infrastructure, early warning systems, and social safety nets [10]. Understanding vulnerability and resilience in a combined framework ensures that flood risk assessments move beyond physical hazard exposure to include the social systems that shape outcomes.

2.2. Hazard-risk-vulnerability framework in geospatial science

Flood risk is commonly conceptualized as a function of three components: hazard, exposure, and vulnerability. The hazard dimension reflects the probability and magnitude of flood events, shaped by rainfall intensity, river discharge, and tidal surges [13]. Exposure captures the presence of people, infrastructure, and assets in flood-prone zones. Vulnerability represents the socio-economic and physical conditions that increase susceptibility to damage. Together, these components provide a holistic view of risk that informs both research and policy interventions [8].

Geospatial science operationalizes this framework by linking physical hazard data with socio-economic datasets. Digital Elevation Models (DEMs) help delineate flood-prone areas, while census data highlight population densities and settlement patterns. When integrated in GIS, these inputs generate spatially explicit risk maps that identify communities most at risk [11]. Such outputs not only quantify exposure but also reveal the spatial inequalities embedded in urban growth and land-use practices.

A critical strength of the hazard-risk-vulnerability framework is its adaptability across scales. It can be applied at the household level to examine micro-level adaptive capacity, or at regional and national levels to assess infrastructural resilience and policy gaps [9]. Figure 1 illustrates a conceptual framework for flood vulnerability mapping that integrates remote sensing with GIS to capture the hazard-risk-vulnerability relationship. By synthesizing multi-layered datasets, the framework provides both scientific rigor and practical utility in flood management.

This approach also enhances decision-making transparency. By visualizing risk zones, stakeholders including governments, NGOs, and local communities can engage in participatory planning and prioritize interventions where they are most needed [6]. Thus, the hazard-risk-vulnerability framework, when operationalized through geospatial science, provides an evidence base for building resilience and reducing disaster losses.

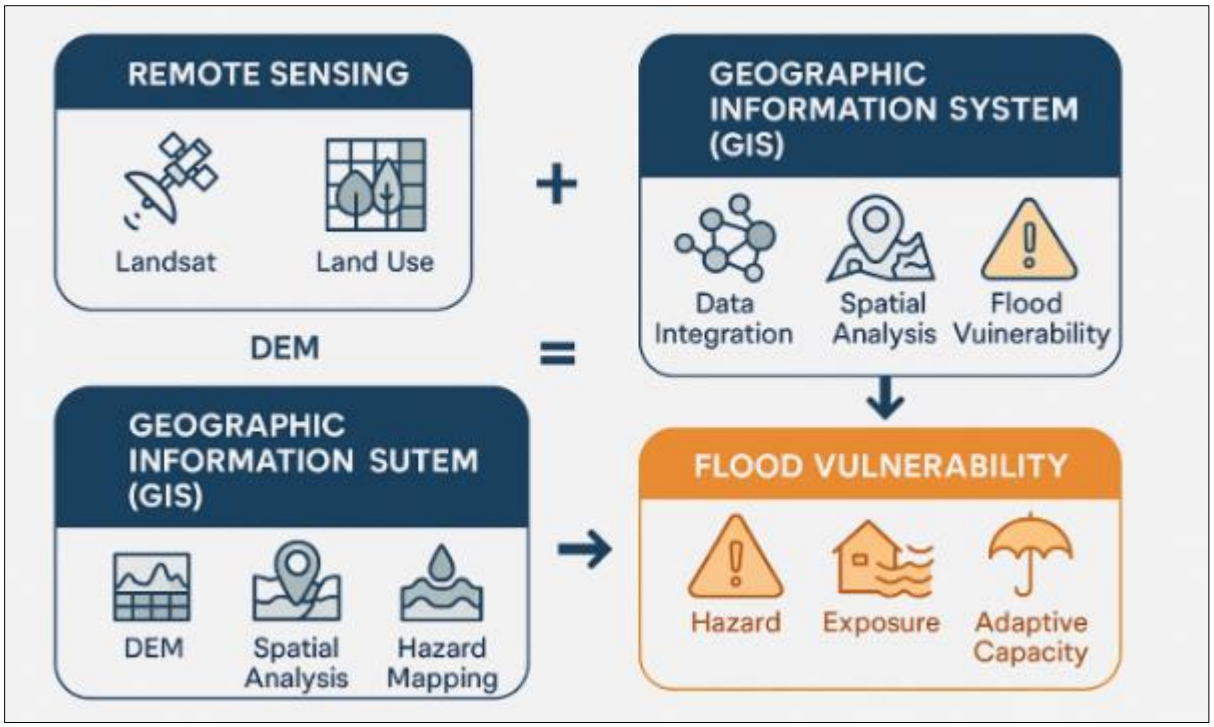


Figure 1 Conceptual framework of flood vulnerability mapping using remote sensing + GIS

2.3. Integration of remote sensing, GIS, and hydrological theory

The integration of remote sensing, GIS, and hydrological theory has advanced flood risk assessment by providing a comprehensive toolkit for analyzing both physical processes and social impacts. Remote sensing contributes temporal and spatial datasets that allow continuous monitoring of land use, rainfall patterns, and water surface changes. Multispectral imagery helps detect flooded zones, while radar systems penetrate cloud cover to capture flood extent even during heavy rainfall events [7].

GIS acts as the analytical environment where remote sensing outputs are combined with topographical and socio-economic datasets. Through spatial modeling, GIS can generate indices that quantify flood susceptibility based on slope, drainage density, soil type, and land cover [10]. When linked with census data, GIS also supports the mapping of social vulnerability, highlighting populations lacking adequate housing or infrastructure.

Hydrological theory underpins these tools by providing the process-based understanding necessary for interpreting data. Concepts such as runoff generation, infiltration capacity, and flood wave propagation explain why certain areas are more prone to flooding than others [12]. Integrating hydrological models with GIS enhances predictive accuracy, allowing simulations of how rainfall or land-use changes influence flood hazards.

This triad of methods supports a more holistic flood risk assessment. For instance, remote sensing may identify an expanding urban footprint, GIS may show that this growth encroaches on floodplains, and hydrological models may predict increased runoff leading to greater flood intensity [8]. By combining these perspectives, researchers and planners gain insights that transcend descriptive mapping and move toward predictive and prescriptive solutions.

The integrated approach also facilitates scalability. It can be applied to localized community assessments or expanded to national flood risk mapping initiatives [11]. As pressures from urbanization and climate variability intensify, the fusion of remote sensing, GIS, and hydrological theory represents a powerful methodology for anticipating risks and enhancing adaptive strategies [13].

3. Remote sensing and geospatial datasets for flood mapping

3.1. Satellite imagery for flood detection (Landsat, Sentinel, MODIS)

Satellite imagery has become indispensable for flood detection, providing temporal and spatial perspectives that ground-based monitoring alone cannot achieve. Among the most widely used platforms is the Landsat series, which has offered consistent medium-resolution imagery since the 1970s. Landsat's multispectral sensors capture changes in surface reflectance, enabling the identification of water bodies, inundated zones, and vegetation stress caused by flooding [15]. Its temporal archive allows for comparative analysis of historical flood patterns, making it ideal for long-term vulnerability studies.

Sentinel missions complement Landsat by offering higher spatial and temporal resolutions. Sentinel-1, in particular, uses synthetic aperture radar (SAR) to detect floodwaters even under cloud cover, a critical advantage during peak rainfall periods [16]. Sentinel-2 provides multispectral optical imagery that is effective for distinguishing between land cover categories affected by floods, such as agricultural fields, wetlands, and urban areas. The integration of Sentinel data with Landsat enhances both accuracy and reliability in flood detection.

MODIS, on the other hand, provides daily imagery at coarser resolutions, making it valuable for near real-time monitoring of extensive flood events [13]. Though it lacks the spatial detail of Sentinel or Landsat, MODIS is particularly suited for regional-scale assessments where frequent temporal coverage outweighs fine spatial detail.

The synergistic use of these satellite platforms enables researchers to capture both short-term flood dynamics and long-term changes in susceptibility. By combining their strengths, flood detection workflows achieve a balance between spatial precision and temporal frequency. This combination is especially relevant in regions like Adamawa and Niger States, where rapid urbanization and ecological stress increase flood vulnerability [17].

Thus, satellite imagery forms the first building block of flood vulnerability mapping, providing the raw datasets upon which geospatial and modeling techniques can be applied for detailed analysis.

3.2. Digital Elevation Models (SRTM, LiDAR) and terrain analysis

Digital Elevation Models (DEMs) play a pivotal role in flood studies, offering detailed representations of terrain that influence water flow, accumulation, and inundation patterns. DEMs provide the foundation for hydrological modeling, allowing researchers to calculate slope, drainage networks, watershed boundaries, and flow accumulation points [14]. By simulating these processes, DEMs make it possible to delineate areas most prone to flooding.

The Shuttle Radar Topography Mission (SRTM) is among the most widely used global DEMs. With a resolution of 30 meters, it provides reliable terrain data suitable for regional flood assessments [18]. Though limited in capturing small-scale features, SRTM remains valuable for identifying major flood-prone zones such as river valleys, low-lying coastal areas, and broad floodplains.

LiDAR (Light Detection and Ranging) DEMs offer far greater accuracy and spatial detail. With resolutions reaching sub-meter levels, LiDAR data enable fine-scale mapping of urban infrastructure, drainage channels, and embankments [12]. This makes them especially useful for urban flood modeling, where micro-topographic variations significantly affect inundation dynamics. However, the high cost and limited availability of LiDAR constrain its use in many developing regions.

Terrain analysis based on DEMs is often coupled with hydrological indices such as the Topographic Wetness Index (TWI), which quantifies the tendency of terrain to accumulate water. These indices, when integrated with rainfall and land cover data, enhance the predictive accuracy of flood models. Figure 2 illustrates how DEM-derived terrain attributes, when combined with land-use overlays, can generate detailed maps of flood-prone zones.

The comparative use of SRTM and LiDAR highlights the trade-offs between accessibility and precision. In contexts where resources are limited, SRTM provides sufficient input for regional studies, while LiDAR offers superior detail for site-specific planning. Both datasets underscore the importance of terrain in understanding flood vulnerability, reinforcing the role of DEMs as a cornerstone of geospatial flood analysis [16].

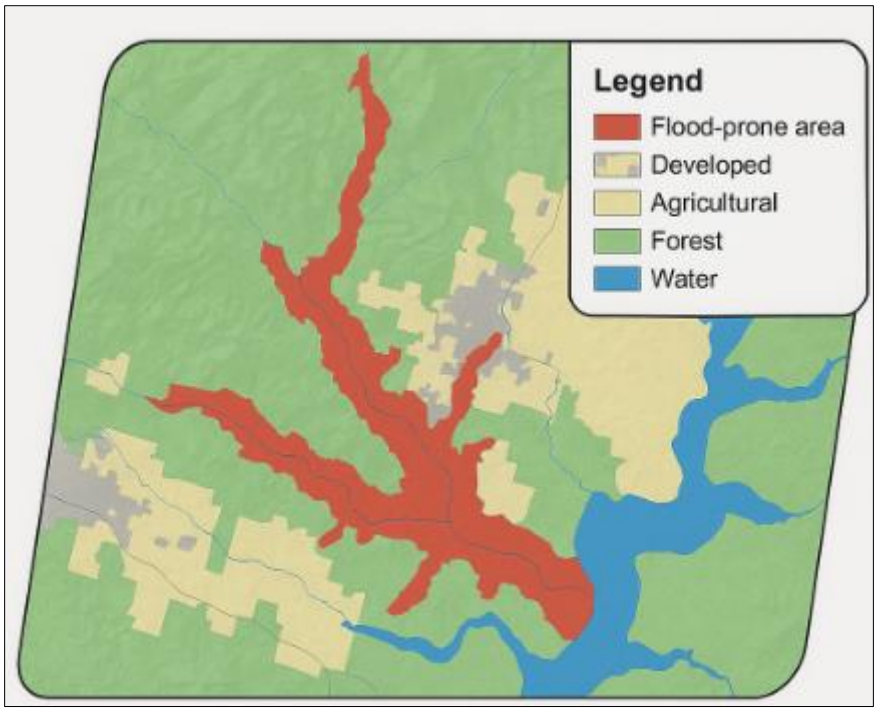


Figure 2 Sample flood-prone area map generated from DEM + land use overlays

3.3. Land use/land cover mapping for flood susceptibility

Land use and land cover (LULC) mapping is vital for assessing flood susceptibility because human activities strongly influence hydrological processes. In many flood-prone regions, urban expansion reduces natural infiltration zones, replacing permeable soils with impervious surfaces such as roads and paved housing plots. This shift increases surface runoff and frequently overwhelms drainage systems, intensifying flood risk [15]. Agricultural practices, particularly unsustainable farming on riverbanks, deforestation for fuelwood, and wetland encroachment, further weaken the natural water retention capacity of landscapes in Adamawa and Niger States [13].

Remote sensing offers powerful tools for classifying LULC across these regions. Data from Landsat and Sentinel imagery enable identification of major categories including built-up areas, farmlands, forests, grasslands, and wetlands. Temporal analysis reveals how changes in these categories contribute to heightened vulnerability. For instance, in Adamawa, deforestation along the Benue River and conversion of wetlands into settlements have coincided with recurrent seasonal floods. Similarly, in Niger State, expansion of farming into floodplains around Mokwa and Lapai has reduced natural buffers, amplifying exposure to flooding events [12].

ArcGIS provides the analytical capacity to process LULC classifications by integrating spectral indices, supervised and unsupervised classification methods, and accuracy assessments. These outputs can be combined with hydrological models, elevation data, and socio-economic indicators to construct composite flood vulnerability profiles. **Table 1** summarizes commonly used remote sensing datasets and their specifications for flood mapping, highlighting how spatial resolution, revisit frequency, and spectral capabilities determine their suitability for flood risk studies in Adamawa and Niger.

LULC mapping thus bridges human activity with environmental susceptibility, linking biophysical processes to socio-economic pressures. It provides a critical spatial foundation for designing adaptive land-use strategies and targeted interventions that reduce flood risks in vulnerable communities [18].

Table 1 Remote sensing datasets and their specifications for flood mapping with focus on Sentinel and SRTM

Dataset	Sensor / Platform	Spatial Resolution	Temporal Resolution	Key Parameters for Flood Mapping	Strengths	Limitations
Sentinel-1 (SAR)	C-band Synthetic Aperture Radar (ESA Copernicus)	10 m (Ground Range Detected)	6–12 days (global coverage, orbit-dependent)	Backscatter intensity, coherence change, flood extent detection (all-weather, day/night)	Cloud-penetrating, sensitive to water surfaces, high revisit for flood dynamics	Speckle noise; requires preprocessing; may misclassify wet soils as water
Sentinel-2 (MSI)	Multispectral Instrument (ESA Copernicus)	10 m (VNIR), 20 m (Red Edge, SWIR), 60 m (atmospheric bands)	5 days (combined constellation)	NDWI, MNDWI, land cover classification, vegetation–water interaction	High spectral resolution; useful for flood extent + land use mapping	Cloud cover limits use during storms; less effective at night
SRTM DEM	Shuttle Radar Topography Mission (NASA/USGS)	~30 m (1 arc-second, global)	One-time mission (2000; global coverage)	Elevation data, slope, hydrological modeling, floodplain delineation	Global coverage, free access, widely used in hydrology and flood hazard models	Vertical accuracy varies (±16 m globally, better in flatter regions); outdated
Ancillary (e.g., Landsat 8 OLI/TIRS)	Multispectral + Thermal Infrared (NASA/USGS)	30 m (optical), 100 m (thermal)	16 days	NDWI, land cover classification, historical flood trend analysis	Long archive (since 1970s), valuable for multi-decadal flood studies	Lower temporal frequency; cloud issues; not as high-res as Sentinel-2

3.4. Integrating socio-economic datasets with geospatial layers

Flood vulnerability cannot be understood through biophysical factors alone; socio-economic conditions are equally significant. Communities with low income, inadequate infrastructure, and limited access to resources are disproportionately affected, even when exposed to the same flood hazard [17]. Integrating socio-economic datasets with geospatial layers allows researchers to capture this multidimensional vulnerability.

Key socio-economic indicators include population density, housing quality, income levels, literacy rates, and access to emergency services. These variables, when mapped alongside hazard and exposure datasets, provide composite indices of vulnerability [14]. For instance, densely populated informal settlements located in floodplains are at higher risk than sparsely populated high-income neighborhoods in the same zone.

GIS facilitates this integration by providing a platform where demographic and socio-economic statistics can be spatially joined with hydrological and environmental datasets. This enables the generation of vulnerability maps that highlight not just where flooding is likely to occur, but also who is most at risk. Such outputs are vital for equitable disaster risk reduction, ensuring interventions target the most vulnerable populations [16].

The integration of socio-economic layers also improves the interpretability of flood maps for policymakers. While hazard maps alone show physical risk, combined maps reveal the social dimensions of exposure. This supports more inclusive and socially just flood management policies [12].

Moreover, the use of socio-economic data strengthens the link between academic research and practical governance. Policymakers require not only technical assessments but also socially relevant evidence to allocate resources and design interventions. By embedding socio-economic conditions into geospatial models, researchers bridge this gap, producing outputs that inform both scientific understanding and real-world decision-making [18].

4. Arcgis workflows for flood vulnerability mapping

4.1. Spatial analysis of topographic and hydrological variables

Topography and hydrology are fundamental determinants of flood vulnerability, as they shape how water accumulates, flows, and disperses across landscapes. Within a GIS environment, Digital Elevation Models (DEMs) provide the core dataset for calculating slope, elevation, and flow accumulation, all of which reveal areas with heightened susceptibility to inundation [19]. Low-lying regions, particularly along river basins and coastal floodplains, emerge as the most exposed, while areas of steep slope tend to facilitate rapid runoff.

Hydrological variables such as drainage density, stream order, and catchment boundaries further refine flood risk analysis. By delineating watershed networks, researchers can model how rainfall events translate into surface flow, identifying points where river channels are likely to overflow [17]. Terrain indices like the Topographic Wetness Index (TWI) quantify the propensity of particular areas to retain water, providing valuable insights into soil saturation and waterlogging potential [22].

GIS-based spatial analysis integrates these parameters, producing layered outputs that capture both macro- and micro-scale flood risks. For example, the coupling of DEM-derived flow paths with rainfall intensity data helps simulate likely flood zones under extreme precipitation events [20]. Such analyses form the backbone of vulnerability mapping, ensuring that hydrological and topographic realities are embedded within broader flood risk assessments (Figure 4).

4.2. Weighted overlay and multi-criteria analysis for vulnerability indices

Flood vulnerability is inherently multidimensional, requiring the integration of diverse biophysical and socio-economic factors into a composite framework. Weighted overlay analysis and multi-criteria decision analysis (MCDA) within ArcGIS provide structured approaches to synthesizing these variables. In this method, each criterion such as slope, land use, soil permeability, population density, or proximity to rivers is assigned a weight based on its relative importance to flood risk [18].

The assignment of weights often draws on expert judgment, literature reviews, or statistical techniques such as Analytical Hierarchy Process (AHP). By normalizing values across multiple layers, GIS allows these variables to be combined into a single vulnerability index [21]. The result is a spatially continuous surface that categorizes areas into high, medium, or low flood vulnerability zones.

For instance, a steep slope may reduce vulnerability weight, while dense informal settlements in floodplains receive higher weightings. ArcGIS then calculates a composite score for each spatial unit, highlighting priority zones for risk mitigation. Table 2 provides an example of how criteria are weighted and scored in a multi-criteria flood vulnerability analysis, showing the balance between environmental and socio-economic variables.

The strength of weighted overlay lies in its flexibility and transparency. Policymakers can adjust weights to reflect local realities, such as emphasizing infrastructure resilience in urban areas or agricultural exposure in rural zones [23]. Furthermore, the visual outputs produced are intuitive, making them accessible to both experts and non-technical stakeholders.

By transforming complex datasets into actionable vulnerability indices, MCDA ensures that flood risk assessments are not fragmented but holistic, accounting for the interplay between natural processes and human systems [16]. This approach provides an evidence base that directly supports flood preparedness, land-use planning, and disaster risk management.

Table 2 Criteria weights and scoring used in multi-criteria flood vulnerability analysis

Criteria	Indicator Description	Weight (%)	Scoring Range (1–5)	Rationale for Inclusion
Slope	Derived from DEM; flatter areas accumulate runoff	20%	1 = >15% slope (low risk) 5 = 0–2% slope (very high risk)	Gentle slopes increase flood susceptibility
Land Use / Land Cover	Built-up, agriculture, forest, wetlands	20%	1 = Forest 3 = Agriculture 5 = Built-up/wetlands	Impervious surfaces and wetland encroachment elevate risk
Soil Permeability	Soil infiltration capacity (sandy vs. clayey soils)	15%	1 = High infiltration (sand) 5 = Low infiltration (clay)	Low permeability soils increase runoff
Rainfall Intensity	Average annual rainfall (mm)	15%	1 = <1000 mm 3 = 1000–2000 mm 5 = >2000 mm	Heavy rainfall intensifies flood hazard
Proximity to Rivers	Distance buffer zones from major rivers/streams	10%	1 = >5 km 3 = 1–5 km 5 = <1 km	Closer proximity increases flood exposure
Population Density	People per km^2; proxy for exposure	10%	1 = <500 3 = 500–2000 5 = >2000	Higher densities amplify potential impacts
Drainage Infrastructure	Availability/quality of stormwater drainage	10%	1 = Well-structured 3 = Partial 5 = Absent	Poor drainage increases flood vulnerability

4.3. Integration of hazard, exposure, and adaptive capacity layers

A comprehensive flood vulnerability framework must integrate hazard, exposure, and adaptive capacity layers. Hazard represents the probability and intensity of flood events, typically modeled through hydrological and rainfall datasets. Exposure reflects the assets, infrastructure, and populations located within flood-prone zones, while adaptive capacity measures the ability of these populations to prepare for, respond to, and recover from floods [20].

Within ArcGIS, hazard layers might include flood inundation maps derived from DEMs and hydrological models, while exposure layers incorporate census data, road networks, and critical infrastructure. Adaptive capacity layers add a social dimension, capturing indicators such as literacy rates, healthcare access, and community preparedness programs [22]. When combined, these layers create a multi-dimensional picture of vulnerability that extends beyond physical inundation.

The integration process often uses spatial overlay techniques to intersect hazard and exposure, while adaptive capacity serves as a moderating factor. For example, a densely populated area exposed to high flood hazard may be classified as highly vulnerable if adaptive capacity indicators are weak, but only moderately vulnerable if robust coping mechanisms exist. Figure 3 illustrates the ArcGIS workflow for flood vulnerability analysis, showing how these inputs progress from raw data layers to composite vulnerability maps.

This tri-layered integration ensures that risk assessments capture not only where floods are likely to occur, but also who is affected and how well they can respond [17]. By embedding social resilience within spatial analysis, GIS workflows advance from purely biophysical assessments toward socio-technical frameworks that align with real-world complexities [19].

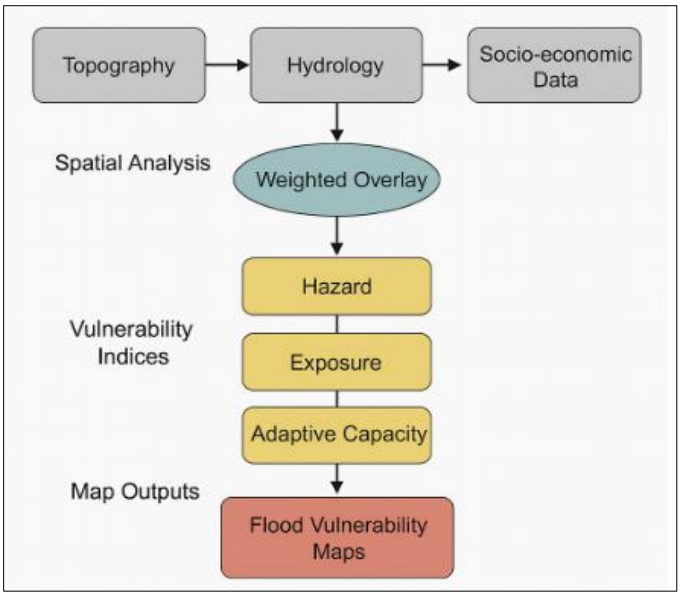


Figure 3 ArcGIS workflow for vulnerability analysis (from input to map outputs)

4.4. Validation of vulnerability maps with historical flood events

Validation is a critical step in ensuring the reliability of flood vulnerability maps. Without comparison to real-world events, geospatial models risk producing theoretical outputs that lack practical utility. Historical flood records derived from field surveys, disaster reports, or remote sensing imagery provide the benchmark for validating vulnerability assessments [21].

One common approach is to overlay modeled vulnerability zones with documented flood extents from past events. If high-vulnerability areas correspond with actual flood-affected zones, the model is considered reliable. Conversely, significant mismatches prompt recalibration of input weights, criteria, or data sources [18]. Remote sensing data, particularly SAR imagery from Sentinel-1, is increasingly used to delineate historical flood extents for validation purposes [16].

Community-based validation also strengthens accuracy. Local knowledge of flood frequency, duration, and impacts complements technical datasets, ensuring that vulnerability maps reflect lived realities. Incorporating such participatory methods bridges the gap between scientific modeling and community engagement [23].

Validation is not merely a technical exercise but an iterative process that enhances trust and usability. Maps that have been tested against historical events gain greater credibility among policymakers and practitioners, increasing the likelihood of their integration into planning frameworks [22]. Thus, validation ensures that flood vulnerability maps are not static products but adaptive tools aligned with evolving realities.

5. Empirical assessment of flood vulnerability in Adamawa and Niger states

5.1. Study area: climate, hydrology, and socio-economic context

Adamawa and Niger States represent two of Nigeria's most flood-prone regions, shaped by unique climatic, hydrological, and socio-economic conditions. Both states experience a tropical wet-and-dry climate, with distinct rainy and dry seasons. Annual rainfall ranges from 1,000 to 1,600 millimeters in Niger and 900 to 1,200 millimeters in Adamawa, with the wettest periods occurring between June and September [25]. Intense rainfall, combined with low-lying floodplains and riverine corridors, contributes significantly to recurrent flooding.

Hydrologically, the River Benue in Adamawa and the River Niger in Niger State dominate their respective landscapes. These rivers sustain agriculture, fisheries, and transportation, but they also act as major flood conduits during peak rainfall [23]. In Adamawa, areas such as Yola and Numan are highly susceptible to overflows from the Benue, while in Niger State, towns like Mokwa and Lapai regularly contend with inundation from the Niger and its tributaries. Poor or

poorly maintained drainage infrastructure in peri-urban settlements further amplifies flood hazards, as stormwater frequently overwhelms both natural and artificial channels.

Socio-economic conditions add another layer of vulnerability. Adamawa's population, exceeding 4 million, and Niger's, with over 5 million residents, are rapidly expanding into floodplains and riverbanks, often through informal housing development [24]. These settlements lack resilient construction, planned drainage, and adequate access to public services, exposing households to repeated displacements. Agricultural communities are particularly affected, as farmland losses directly threaten food security and local livelihoods.

The economic importance of both states heightens the disruptive effects of flooding. Adamawa serves as a regional hub for cross-border trade with Cameroon, while Niger State hosts critical hydroelectric infrastructure such as the Shiroro and Kainji dams [26]. Flood events in these areas disrupt not only local economies but also national power supply, agricultural production, and trade routes. Understanding the interplay of climatic, hydrological, and socio-economic factors is thus essential for assessing and mitigating flood vulnerability in Adamawa and Niger States.

5.2. Flood hazard mapping using rainfall, DEM, and soil data

Flood hazard mapping integrates climatic and environmental datasets to delineate areas most prone to inundation. In Adamawa and Niger States, rainfall is a primary hazard driver, as both regions experience intense wet-season precipitation linked to West African monsoon dynamics. Spatial interpolation of rainfall records, through techniques such as inverse distance weighting (IDW) and kriging, allows the creation of rainfall intensity surfaces across the states [27]. These surfaces reveal distinct gradients, with Adamawa's eastern zones along the River Benue and Niger's western lowlands near the River Niger consistently registering higher rainfall intensities. Such regions emerge as recurrent flood hazard hotspots.

Digital Elevation Models (DEMs) provide terrain inputs crucial for hazard delineation. Using Shuttle Radar Topography Mission (SRTM)-derived DEMs, researchers can compute slope, flow direction, and flow accumulation indices to model drainage pathways and identify flood-prone basins [22]. Settlements along the Benue floodplain in Yola and Numan, as well as areas near Mokwa and Lapai in Niger, exhibit low slopes and high flow accumulation, classifying them as high-hazard zones. DEM analysis also highlights artificial obstructions such as roads and embankments that redirect water and generate localized flooding risks.

Soil characteristics contribute significantly to flood susceptibility. In both states, clay-dominated soils with poor infiltration capacity intensify runoff during peak rainfall, while sandy soils in upland areas offer higher infiltration and lower accumulation potential [25]. Integrating soil datasets into GIS workflows helps identify zones where infiltration is inadequate, particularly in peri-urban settlements with compacted soils.

By synthesizing rainfall, DEM, and soil datasets, composite hazard maps can be generated to assign relative risk levels across communities. Table 3 illustrates a flood hazard classification scheme grouping settlements into high, medium, and low categories based on integrated indicators. Such classifications not only support technical assessments but also provide accessible tools for policymakers, emergency managers, and communities to prepare and implement mitigation strategies [24].

Table 3 Flood risk classification (high, medium, low) by community clusters in Adamawa and Niger States

Risk Level	Community Clusters (Adamawa State)	Community Clusters (Niger State)	Key Contributing Factors
High	Yola, Numan, Lamurde (along River Benue floodplain)	Mokwa, Lapai, Baro (near River Niger floodplain)	Low slope terrain, high flow accumulation, clay soils, river overflows, poor drainage infrastructure
Medium	Gombi, Hong, Demsa (upland–river transition zones)	Bida, Agaie, Katcha (peri-urban floodplain margins)	Moderate rainfall intensity, partial drainage, mixed soil infiltration, expansion into wetlands
Low	Mubi, Michika, Madagali (upland zones)	Kontagora, Shiroro, Suleja (higher elevation areas)	Higher slopes, sandy soils, better natural drainage, lower direct exposure to river flooding

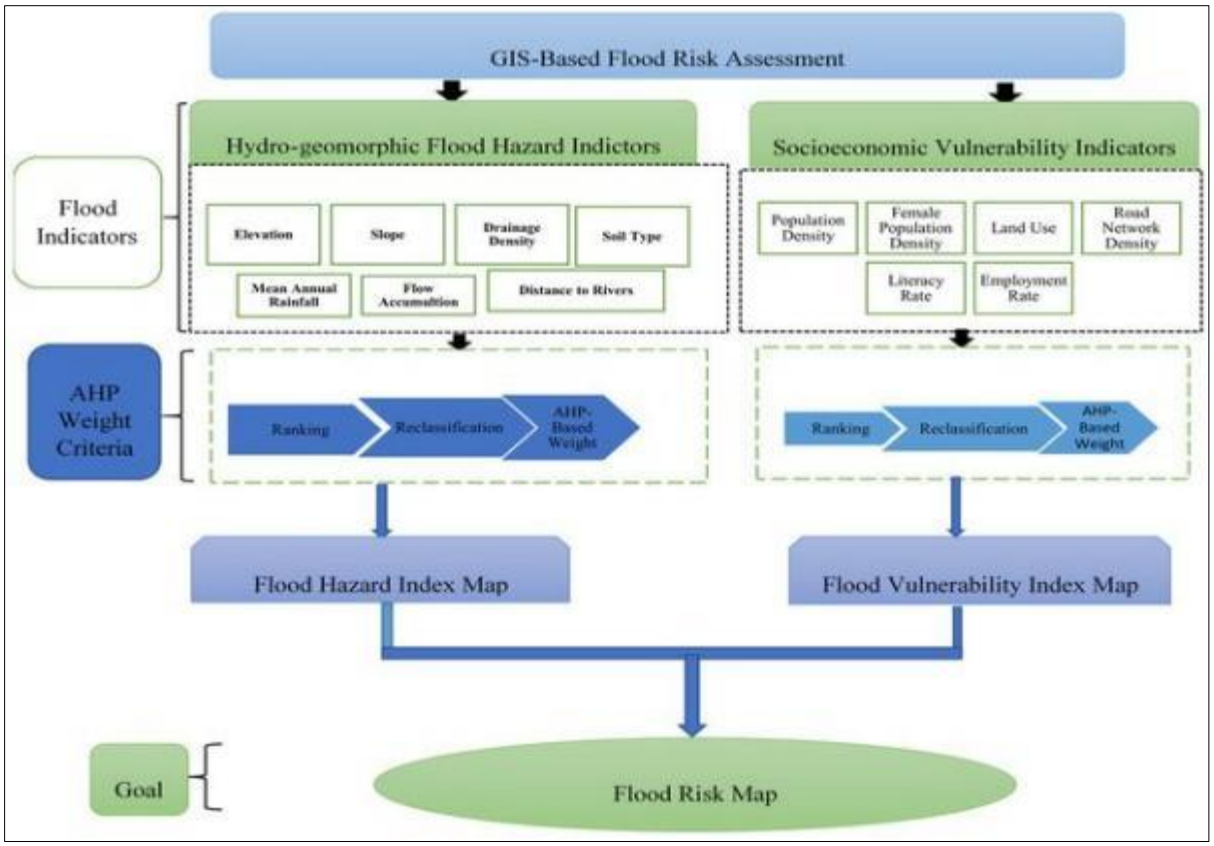


Figure 4 GIS Flood Risk Assessment

5.3. Vulnerability mapping integrating exposure and sensitivity indicators

While hazard mapping delineates the physical susceptibility of landscapes, vulnerability mapping integrates the human and infrastructural dimensions of flood risk. Exposure indicators include population density, settlement quality, and proximity to rivers or floodplains. In Adamawa, communities such as Yola South and Numan experience high exposure due to their location along the River Benue floodplain, where dense settlements and limited drainage infrastructure heighten risk [26]. Similarly, in Niger State, towns like Mokwa and Lapai face high exposure along the River Niger, where seasonal overflows repeatedly threaten housing, farms, and local markets. High exposure in such zones correlates with greater potential losses, particularly where dwellings are constructed with fragile materials such as mud or poorly reinforced blocks.

Sensitivity indicators complement exposure by reflecting how populations and infrastructure respond to hazards. Factors such as income levels, literacy rates, and access to healthcare significantly shape community resilience. Rural agricultural households with limited income in Adamawa, or fishing-dependent communities in Niger, have reduced capacity to prepare for or recover from floods [23]. Infrastructure sensitivity compounds this, with underdeveloped drainage systems, limited road connectivity, and inadequate flood defenses leaving communities more vulnerable to prolonged disruption.

ArcGIS supports the integration of these indicators using weighted overlay analysis, allowing the production of vulnerability maps that categorize communities into high, medium, and low vulnerability classes. **Figure 5 and 6** illustrates an example of such outputs for Adamawa and Niger, highlighting clusters of flood-prone settlements along river corridors and critical socio-economic hotspots such as markets, schools, and health centers. These spatial outputs reveal inequities in risk, with poorer communities disproportionately concentrated in high-vulnerability zones.

Vulnerability mapping underscores that flooding is not only a hydrological hazard but also a socio-economic challenge. The convergence of exposure and sensitivity in marginalized groups highlights the need for targeted interventions. By linking spatial and social indicators, vulnerability maps provide decision-makers with a strong evidence base for prioritizing resources toward the most at-risk communities [27].

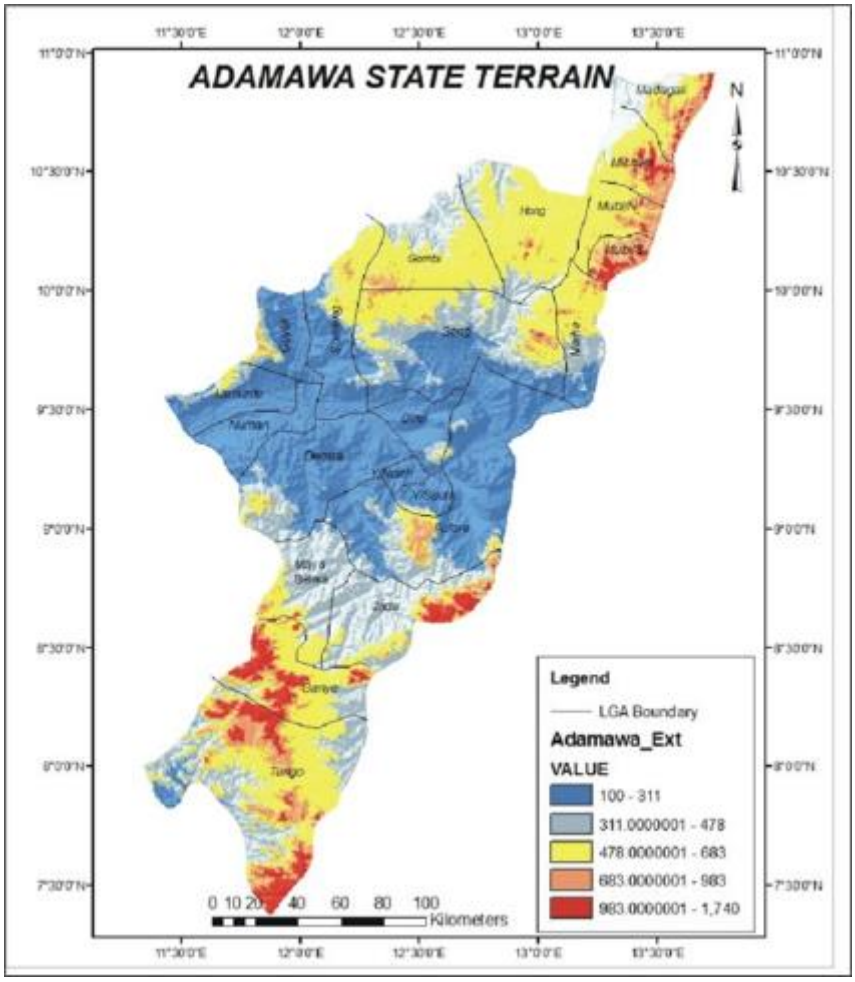
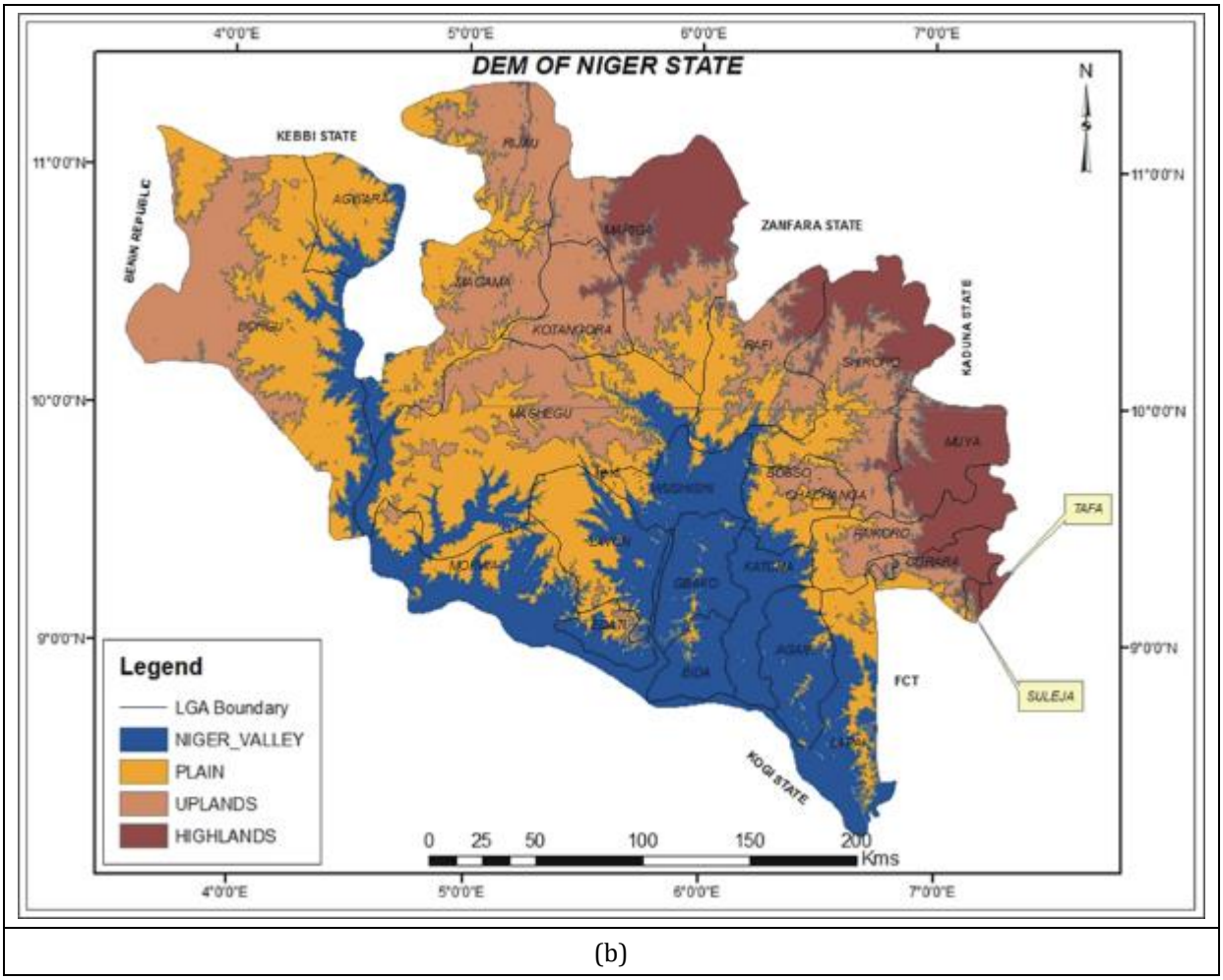


Figure 5 Vulnerability maps of flood-prone zones in Niger [28]



(b)

Figure 6 Vulnerability maps of flood-prone zones in Adamawa [27]

5.4. Risk zoning and identification of flood-prone communities

Flood risk zoning synthesizes hazard and vulnerability outputs to classify areas based on overall risk. Risk is conceptualized as the intersection of hazard, exposure, and sensitivity, which means that even moderate hazards can produce severe impacts if vulnerability is high [22]. Conversely, communities with higher adaptive capacity may experience reduced risk despite proximity to significant hazards.

GIS workflows facilitate the integration of hazard and vulnerability indices into composite risk maps that delineate high, medium, and low-risk zones. In Adamawa State, high-risk zones are concentrated along the River Benue floodplains in Yola, Numan, and Lamurde, where low-lying terrain combines with dense settlements and fragile infrastructure [25]. In Niger State, high-risk zones are evident around Mokwa, Lapai, and Baro, which experience recurrent inundation from the River Niger. Medium-risk zones include upland communities in Gombi (Adamawa) and Bida (Niger), where rainfall intensity is substantial but moderate elevation and adaptive coping strategies provide partial protection. Low-risk zones are found in elevated areas such as Mubi and Michika in Adamawa, or Kontagora and Suleja in Niger, where higher slopes, permeable soils, and better drainage reduce overall susceptibility [24].

Community-level risk classification adds granularity to zoning by recognizing differences even within the same category. For instance, a planned residential neighborhood in Yola with concrete housing and raised foundations may face less functional disruption compared to nearby informal settlements built on mud blocks along the same floodplain [26]. Such differentiation highlights that vulnerability is not homogeneous and that socio-economic conditions strongly mediate risk.

Flood risk zoning outputs serve as vital decision-making tools. They provide spatial clarity for prioritizing interventions such as embankment construction, drainage rehabilitation, or planned relocations. Additionally, zoning supports participatory planning by enabling communities to engage directly in disaster risk reduction strategies [23]. Ultimately,

flood risk zoning transforms geospatial data into actionable governance instruments, bridging the gap between scientific knowledge and policy implementation while guiding targeted adaptation strategies in Adamawa and Niger States [27].

6. Socio-economic and environmental implications

6.1. Impacts of flooding on housing, infrastructure, and livelihoods

Flooding has severe consequences for housing, infrastructure, and livelihoods, disrupting both physical assets and socio-economic stability. In Adamawa and Niger States, urban housing structures, particularly in informal settlements, are disproportionately affected due to their location on floodplains and their poor structural quality. Walls constructed from mud or unreinforced blocks often collapse under prolonged water exposure, leading to displacement and property losses [23]. High-income residential areas may also experience damage, but stronger construction materials and insurance mechanisms mitigate long-term impacts.

Infrastructure disruption compounds these challenges. Roads are frequently submerged, making them impassable for days and disrupting transport systems critical for trade and commuting [27]. Public facilities such as schools, hospitals, and markets suffer functional paralysis, further straining urban resilience. For instance, health facilities face surges in demand during flood events as waterborne diseases such as cholera and typhoid spread rapidly [25]. The collapse of drainage systems and the inundation of power installations aggravate service delivery failures, creating cascading effects on productivity.

Livelihoods, particularly in agriculture and informal urban economies, are also deeply impacted. Farmers lose crops and livestock to inundation, while urban traders experience losses when market areas are flooded. Daily wage earners dependent on street-level commerce are especially vulnerable, as floods halt business operations and erase income streams [22]. The intersection of physical damage and livelihood disruption underscores flooding as both an environmental and economic crisis. These impacts highlight the urgency of using geospatial analysis to identify high-risk zones, enabling proactive measures to protect housing, infrastructure, and livelihoods before flood events occur [26].

6.2. Environmental degradation and land-use pressures

Flooding accelerates environmental degradation and places immense pressure on land use in Adamawa and Niger States. Recurrent inundation along the River Benue and River Niger strips fertile farmlands of essential nutrients, reducing crop yields and threatening food security in predominantly agrarian communities [24]. Sediment deposition alters river channels, leading to siltation that reduces water flow capacity, thereby amplifying the intensity and frequency of subsequent flood events. Wetlands and riparian zones, which serve as natural buffers in both states, are increasingly encroached upon by settlements and farming. Their loss diminishes ecological resilience, as wetlands provide crucial flood attenuation by absorbing excess water and reducing peak discharge impacts.

Deforestation compounds these challenges. In Adamawa, vegetation clearance for fuelwood and farmland expansion reduces natural infiltration, accelerating runoff and soil erosion [22]. In Niger State, rapid settlement growth around peri-urban towns such as Bida and Mokwa has replaced vegetated floodplains with impervious surfaces. Urban expansion intensifies runoff by sealing surfaces with asphalt and concrete, channeling rainfall into poorly maintained or inadequate drainage systems. This often results in artificial flooding hotspots that persist even during moderate rainfall events.

Flooding also introduces significant pollution risks. Floodwaters mix with agricultural residues, solid waste, and in some cases untreated sewage, spreading contaminants into rivers, streams, and lowland areas [26]. Such contamination disrupts aquatic ecosystems and undermines public health by exposing populations to waterborne diseases. The River Benue in Adamawa and River Niger in Niger State have both experienced declining water quality due to waste deposition following major flood events.

Geospatial mapping highlights these cumulative pressures, revealing how land-use changes intersect with ecological vulnerability [27]. By overlaying LULC datasets with flood hazard zones, planners can identify where degradation most exacerbates flood susceptibility. These insights underscore the urgency of adopting sustainable land management practices that balance development with ecological preservation, ensuring that human activity does not further erode natural resilience in Adamawa and Niger States.

6.3. Community vulnerability, inequality, and displacement

Flooding magnifies existing inequalities, leaving the most vulnerable communities disproportionately affected. Informal settlements located along riverbanks, wetlands, and coastal zones face the highest levels of exposure, yet residents often lack the resources to relocate or invest in protective infrastructure [25]. Many of these communities consist of low-income households dependent on precarious livelihoods, making recovery from floods slow and incomplete.

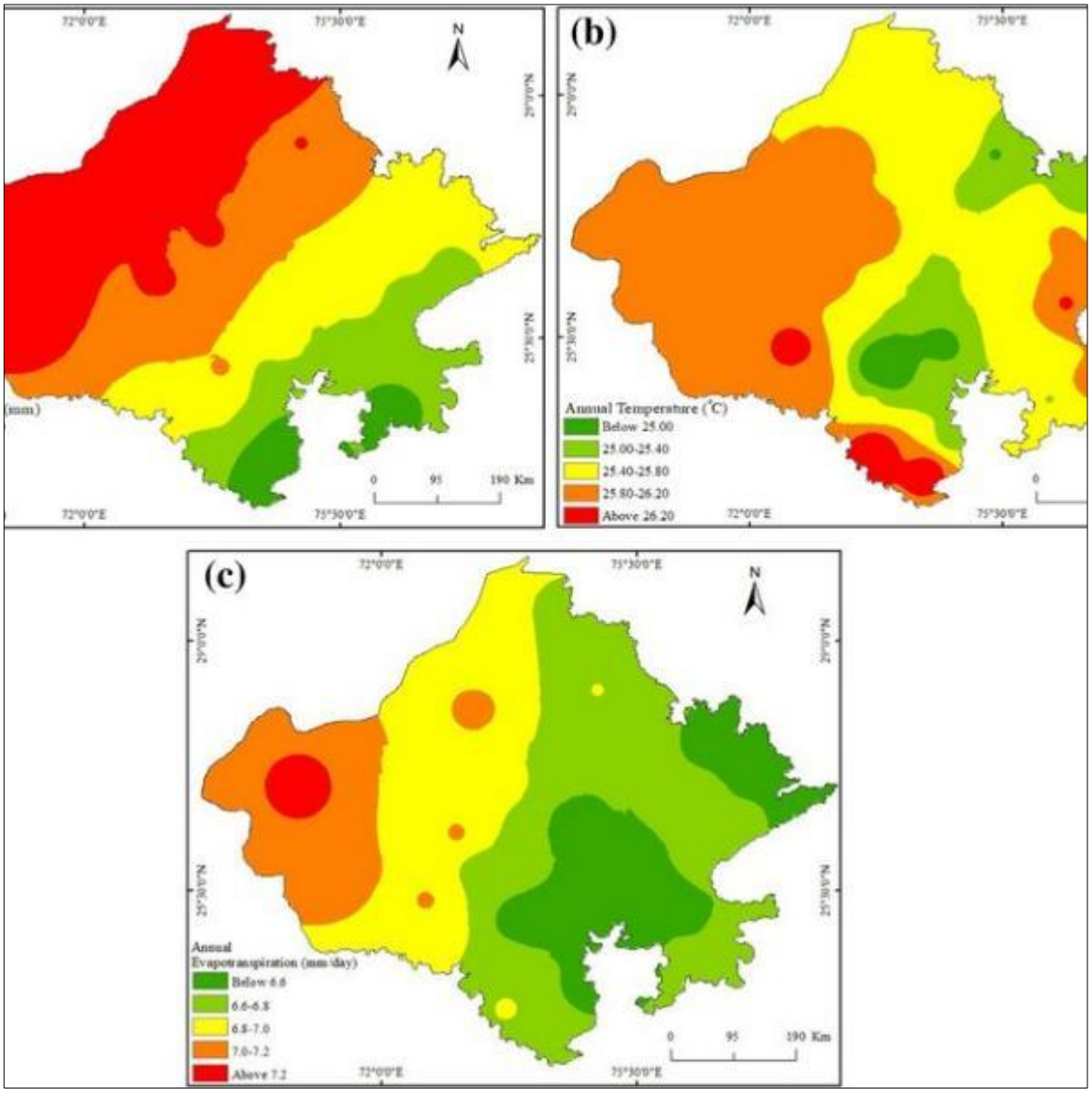


Figure 7 Overlay of socio-economic vulnerability indicators with mapped flood zones [28]

Inequality manifests not only in exposure but also in adaptive capacity. Wealthier groups may access insurance schemes, government compensation, or private relocation options, while poorer households face displacement without support systems [23]. As a result, floods deepen socio-economic divides, perpetuating cycles of poverty. Displacement further compounds vulnerability, as families forced from their homes often move into temporary shelters or overcrowded urban areas, creating secondary risks of disease outbreaks and social instability [22].

Figure 5 illustrates how socio-economic vulnerability indicators overlay with mapped flood zones, showing that high-risk areas frequently coincide with marginalized communities. Such visualizations underscore the spatial justice dimensions of flood risk, where those least able to adapt bear the greatest burden [26].

Displacement also disrupts social networks that serve as informal safety nets. In contexts where state support is limited, community ties provide crucial resilience. Flood-related dislocation weakens these networks, reducing both immediate coping capacity and long-term recovery potential [27]. By highlighting these patterns, geospatial analysis not only identifies physical risk zones but also illuminates the social inequities embedded within flood vulnerability. These findings point toward the need for inclusive planning that integrates marginalized communities into flood resilience strategies, ensuring that adaptation measures are equitably distributed across society.

7. Policy implications and governance strategies

7.1. National disaster risk frameworks and institutional response

National disaster risk frameworks form the cornerstone of coordinated flood management, shaping institutional responses to recurrent hazards. In Nigeria, disaster governance has been centralized through agencies such as the National Emergency Management Agency (NEMA), which is tasked with disaster preparedness, response, and recovery. State-level emergency agencies also exist, but their effectiveness varies depending on resources, political will, and coordination mechanisms [32]. Despite the institutional architecture, gaps persist in translating policies into actionable strategies, particularly at the local government level where flood impacts are most acute.

Flood management frameworks often prioritize emergency response rather than proactive risk reduction. This approach leads to reactive measures such as temporary relief and shelter provision, which, while necessary, do not address root causes of vulnerability [29]. A more integrated strategy would emphasize pre-disaster planning, resilience building, and community empowerment. Institutions are increasingly recognizing the importance of integrating climate variability and urbanization patterns into disaster risk frameworks, but implementation is constrained by funding limitations and weak data systems [33].

The institutional response to floods highlights both strengths and limitations. While coordination during major flood disasters has improved through partnerships with international organizations, the lack of systematic geospatial integration reduces the precision of interventions. Strengthening frameworks requires embedding geospatial tools and datasets into disaster management cycles, ensuring that vulnerability hotspots are identified and addressed before disasters occur [28].

7.2. Integrating geospatial mapping into policy and planning

Geospatial mapping offers transformative potential for integrating scientific evidence into policy and planning. By providing spatially explicit vulnerability maps, decision-makers can prioritize investments in infrastructure, housing, and drainage systems in areas of highest risk. In Nigeria, however, geospatial analysis is often underutilized due to limited technical capacity, inconsistent data availability, and weak collaboration between research institutions and government agencies [34].

ArcGIS-based flood mapping enables policymakers to visualize the intersection of hazard, exposure, and socio-economic vulnerability. For example, overlaying settlement maps with floodplain data helps planners identify informal housing clusters that require either upgrading or relocation [30]. Similarly, integrating rainfall and DEM datasets with urban plans allows engineers to design drainage systems that align with topographic realities rather than arbitrary layouts.

The inclusion of geospatial methods in policy frameworks also strengthens accountability. Spatial outputs are tangible, easily communicated, and provide transparent evidence for decision-making. When vulnerability maps are made public, communities gain access to critical knowledge about their risks, fostering participatory planning [28]. International experiences show that geospatial data integration improves disaster risk reduction outcomes by linking scientific insights with practical governance instruments [35].

Incorporating geospatial mapping into urban and rural planning also bridges sectoral divides. Ministries responsible for housing, environment, water resources, and transport can coordinate around shared spatial evidence, reducing duplication and improving resource allocation [29]. For flood governance to be effective, mapping must move from research outputs to institutionalized policy tools that inform planning at all scales.

7.3. Recommendations for resilient urban and rural flood governance

Building resilient flood governance in Adamawa and Niger States requires attention to both urban and rural contexts, as the drivers of vulnerability vary significantly. In urban centers such as Yola in Adamawa and Minna in Niger State, challenges stem from rapid population growth, informal settlement expansion, and strained infrastructure. Governance

strategies in these cities should prioritize upgrading drainage networks, enforcing zoning regulations to restrict development on floodplains, and investing in nature-based solutions such as wetland and riparian zone restoration [31]. Public–private partnerships can further mobilize resources for resilient infrastructure, minimizing physical damages and economic disruptions.

In rural areas, governance must focus on safeguarding livelihoods. Farming communities along the River Benue in Adamawa and River Niger in Niger State depend heavily on timely flood warnings and adaptive practices such as crop diversification and adoption of flood-tolerant seed varieties. Strengthening rural flood infrastructure including embankments, levees, and community-based early warning systems enhances resilience while ensuring food security [30]. Community engagement remains essential, as rural populations often rely on indigenous knowledge and collective coping networks for responding to flood events [28].

Cross-cutting priorities include integrating geospatial mapping into governance frameworks, enhancing institutional capacity through targeted training, and building robust data infrastructures that improve forecasting and planning [34]. Ensuring equity is also critical: flood management strategies must involve marginalized groups including women, smallholder farmers, and low-income households decision-making processes to address socio-spatial disparities [32].

Resilient governance requires a transition from reactive crisis response to anticipatory planning. This involves incorporating climate projections, evolving land-use patterns, and socio-economic transitions into long-term policies [35]. By bridging urban and rural priorities through a geospatially informed governance framework, Adamawa and Niger States can reduce the human and economic toll of flooding while advancing sustainable and inclusive development pathways [29].

8. Conclusion

8.1. Summary of key findings

This study examined flood vulnerability in Adamawa and Niger States through the integration of remote sensing, GIS, and hydrological approaches, highlighting how geospatial technologies provide powerful tools for hazard and risk analysis. Key findings reveal that the combination of satellite imagery, Digital Elevation Models, land use/land cover data, and socio-economic indicators produces comprehensive vulnerability maps that go beyond physical hazard assessments to incorporate social dimensions of risk. Flood hazard was found to be particularly high in low-lying coastal areas and floodplains, where rainfall intensity, terrain characteristics, and poor soil infiltration converge to amplify inundation risks. Vulnerability was exacerbated by rapid urbanization, informal settlements, inadequate drainage systems, and socio-economic inequalities that restrict adaptive capacity.

The integration of hazard, exposure, and adaptive capacity layers enabled a more holistic understanding of flood risk. By validating outputs with historical flood events, the study demonstrated the accuracy and reliability of geospatial workflows in identifying high-risk communities. Findings underscore that flooding in Adamawa and Niger States is not only an environmental phenomenon but also a socio-economic challenge, deeply tied to patterns of inequality, urban growth, and environmental degradation. This approach provides actionable insights for disaster preparedness, sustainable planning, and equitable risk governance.

8.2. Research limitations

While the study demonstrates the value of geospatial methods, several limitations must be acknowledged. First, the reliance on secondary datasets such as SRTM DEMs and satellite imagery introduces issues of resolution and accuracy. While adequate for regional analyses, these datasets may not capture fine-scale variations in urban micro-topography or localized drainage patterns. Higher-resolution data such as LiDAR would improve precision but remain costly and inaccessible in many developing contexts.

Second, socio-economic indicators were drawn from census and secondary sources, which may not reflect current realities in rapidly changing urban environments. Informal settlements, in particular, are often underrepresented in official data, creating potential gaps in vulnerability assessments. Similarly, community-level indicators such as coping strategies and local resilience mechanisms were not fully integrated, limiting the ability to capture social dynamics in detail.

Third, the validation process was constrained by limited historical flood records. While remote sensing provided useful benchmarks, comprehensive ground-based validation would enhance the robustness of outputs. Finally, the study's

geographic scope focused on Adamawa and Niger States, meaning findings may not be directly generalizable to other regions with different climatic, hydrological, or socio-economic conditions. Addressing these limitations would further strengthen the reliability and applicability of geospatial flood vulnerability studies.

Future directions

- Future research pathways in geospatial flood vulnerability studies

Future research on geospatial flood vulnerability should emphasize both methodological innovation and contextual integration. Methodologically, high-resolution datasets such as LiDAR and drone photogrammetry can improve terrain modeling, particularly in dense urban settings where micro-topography drives flood pathways. Advances in radar remote sensing, especially synthetic aperture radar, enable near real-time flood monitoring under cloud cover, strengthening early warning systems. Machine learning also holds potential for automating land use classification, predicting flood dynamics, and integrating diverse datasets into adaptive risk models.

At the contextual level, integrating community-based knowledge through participatory GIS can capture local coping strategies and resilience mechanisms. Incorporating social vulnerability indicators, such as healthcare access and governance, ensures more holistic assessments. Comparative and longitudinal studies across regions with differing hydrological regimes and socio-economic pressures would enhance transferability. Finally, linking geospatial outputs to policy through zoning, infrastructure planning, and disaster preparedness ensures research informs actionable resilience strategies and equitable adaptation.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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