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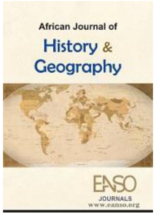

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Original Article

Risk Vulnerability Mapping and Resilience Strategies of Populations Facing Flooding in Urban Environments: Case of Maroua, Far North, Cameroon

Fotsing Marcel Junior[1], Dr. Lila Reni Bibriven, PhD[1] & Prof. Aoudou Doua Sylvain, PhD[2]*

[1] University of Ngaoundéré, P. O. Box 454, Ngaoundéré, Cameroon.
[2] University of Maroua, P. O. Box 46, Maroua, Cameroon.
[*] Author's Email: fotdingmarceljunior@gmail.com

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ABSTRACT

Flood disasters pose a significant and enduring global challenge, disproportionately impacting urban populations in vulnerable regions like Africa, where accelerated urbanization and climate change exacerbate risks. This study examines community vulnerability and resilience strategies in response to flooding in Maroua, located in Cameroon's Far North region. By integrating geospatial data for flood risk and vulnerability modelling, field surveys encompassing 400 households, and satellite imagery analysis, we assess the spatial distribution of flood risk, vulnerability, and the socio-economic and infrastructural impacts on at-risk populations. Our analysis reveals a substantial increase in flood risk over time, driven by the expansion of built-up areas from 6.18 km² in 1986 to 21.22 km² in 2024. Approximately 82% of surveyed households reported flood exposure, with impacts ranging from impaired mobility to fatalities. In response, communities have adopted adaptive measures, including elevating building foundations and employing resilient construction materials. These findings offer critical insights for policymakers seeking to improve the resilience and living conditions of Maroua's flood-prone populations.

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INTRODUCTION

The global population has surged dramatically, escalating from 7 billion in 2011 to approximately 7.8 billion by 2020, with Africa and Asia experiencing the most pronounced increases (B. Yuen, & A. Kumssa, 2011: pp. 3-18.). This demographic explosion has catalysed rapid urbanization, frequently driving human settlements into marginal lands ill-suited for habitation due to inherent environmental risks (Mediebou Chindji, 2021: pp. 22-35). In Africa, urbanization is accelerating at an unprecedented pace, with projections estimating that 60% of the continent's population will reside in urban centres by 2050. Cities like Maroua, located in Cameroon's Far North region, epitomize this trend, yet this growth often unfolds chaotically, propelled by socio-economic imperatives such as poverty, rural exodus, and the pursuit of affordable shelter, resulting in the occupation of flood-prone zones and heightened exposure to natural hazards.

Natural hazards, such as floods, storms, and seismic events, are inherent to Earth's geophysical and climatic dynamics. However, their transition into catastrophic disasters is contingent upon human exposure and vulnerability, defined as the propensity of a community or system to suffer adverse impacts from such events, shaped by physical, social, economic, and ecological variables (WN.Adger, 2006:pp. 268-281). In Maroua, this vulnerability is intensified by its geomorphological context, an alluvial plain with constrained natural drainage compounded by inadequate urban planning and infrastructure deficits. Historical data reveal a persistent pattern of flooding in Maroua, inflicting substantial damage to built environments, displacing populations, and causing fatalities (C. M. Wanie & R. A. Ndi, 2018:pp. 175-192.) (Figure 1).

Figure 1: Baoliwol Neighborhood Maroua I Council Devasted by Flooding Events.

Source: CRTV

The combination of climate change, poor city management, and socio-economic pressures increases flood risks in African cities. Climate models predict more frequent and severe rainfall events, raising the chances of flooding (Mbevo Fendoung, 2019: pp. 567-580). Understanding urban residents' vulnerability and their ability to adapt is crucial for improving disaster risk management. This study focuses on the modelling of flood risk geospatial distribution, socio-economic and structural effects of flooding on Maroua's residents and the resilience strategies

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they use, utilizing field data and remote sensing for a comprehensive analysis that enhances urban flood management discussions in Africa.

Additionally, this research is important as it fills a gap in current studies, which mainly examine Cameroon's larger cities like Douala and Yaoundé, while Maroua's urban centre's unique situation (near conflict zones) has yet to be thoroughly investigated.

Problem

Flooding poses a significant threat in Africa, worsened by climate change, which is expected to increase the frequency and intensity of floods. Globally, urban flooding disproportionately impacts developing countries with inadequate infrastructure. The World Bank (2020) estimates that 1.47 billion people face flood risks, with Africa heavily affected due to poverty and limited adaptive capacity. In Cameroon, urban floods affected 367,000 people from 2007 to 2015 (Hamdja Ngoniri et al., 2024: pp. 78–95). Cities like Douala, Yaoundé, Bamenda, Limbé, and Maroua face recurrent flooding, driven by rapid urbanisation and poor infrastructure (Amanejieu, 2019: pp. 89-102).

In Maroua, flooding is acute, with major events recorded since 1977, including in 2001, 2007, 2010, 2012, 2016, 2018, 2019, 2020, and 2021 (MINAT Report, 2022). Neighbourhoods like Ouro-Tchédé, Djarengol Doualaré, and Pitoaré have seen water depths up to 70 cm, overwhelming weak drainage systems (actucameroun.com, 2020). Between July and October 2020, floods impacted 162,300 people, killed 50, displaced 357 households, and disrupted education for 38,000 students (H. Canton, 2021: pp. 153-155). Economic losses to infrastructure, housing, and farmland due to flooding have further deepened poverty within the communities in the study area (Figure 2).

Figure 2: Maroua, Urban Area, Flooding June 2015.

***Source*:** Sylvestre Tetchiada/IRIN

Climate change intensifies flood risks by altering rainfall patterns, causing short, heavy downpours that strain Maroua's outdated drainage and waterways (IPCC, 2021). Floods disrupt healthcare, education, and increase waterborne diseases, challenging public health systems. In a city facing security and resource constraints, these impacts hinder sustainable development.

Maroua's flood vulnerability stems from rapid, unplanned urbanisation in low-lying areas, poverty, and inadequate drainage infrastructure (Bouba et al., 2017: pp. 123-135). This study examines the geospatial distribution of flood geophysical risk and human environment vulnerability as well as impacts on residents and their coping strategies, aiming to inform targeted solutions.

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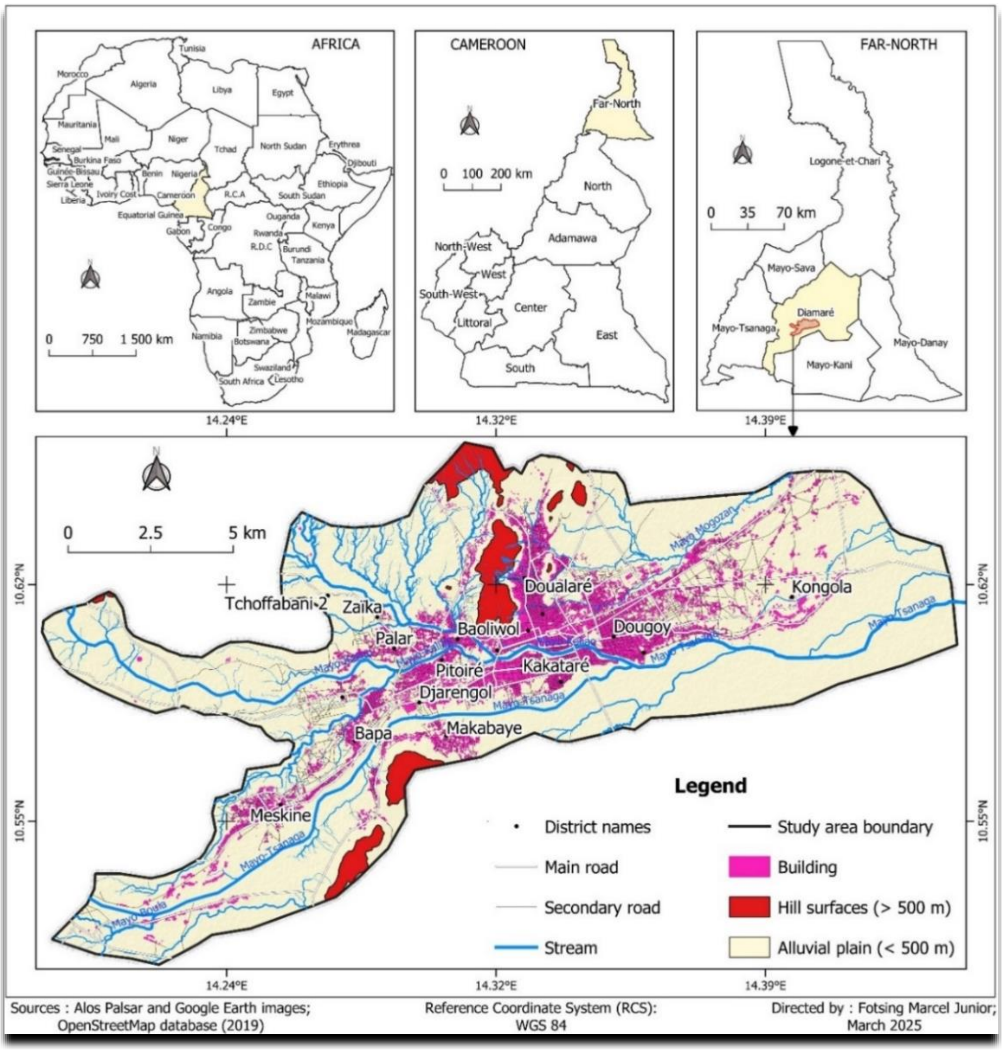
METHODOLOGY

Study Area Site and Situation.

Maroua, the administrative capital of Cameroon's Far North region, is positioned at approximately 10°35'N latitude and 14°19'E longitude, occupying an alluvial plain with elevations spanning 300 to 400 meters above sea level. The city's topography is interspersed with granitic hills, some ascending to 800 meters, which modulate local drainage dynamics (Figure 3). Maroua's semi-arid climate features a pronounced wet season from June to September, during which intense rainfall frequently triggers flooding. Its low-lying geomorphology, coupled with its proximity to the Kaliao and Mayo Tsanaga rivers, renders it inherently prone to inundation.

Figure 3: Location of Maroua's Urban Area



The city's historical trajectory traces its evolution from a modest trading hub in the early 20th century to a vibrant urban nexus, fuelled by its strategic position near Nigeria and Chad. This expansion has coincided with significant population growth, surging from roughly 50,000 in 1986 to over 400,000 by 2020 (Cameroon National Institute of Statistics, 2020). Urban development has been predominantly unplanned, with informal settlements proliferating in flood-vulnerable zones due to scarce affordable housing and lax regulatory oversight (Bouba et al., 2017: 123-135). Neighbourhoods such as Djarengol, Meskine, and Yoldéo among the ten selected for this study, embody this pattern, hosting dense clusters of precarious dwellings fashioned from ephemeral materials (Figure 4).

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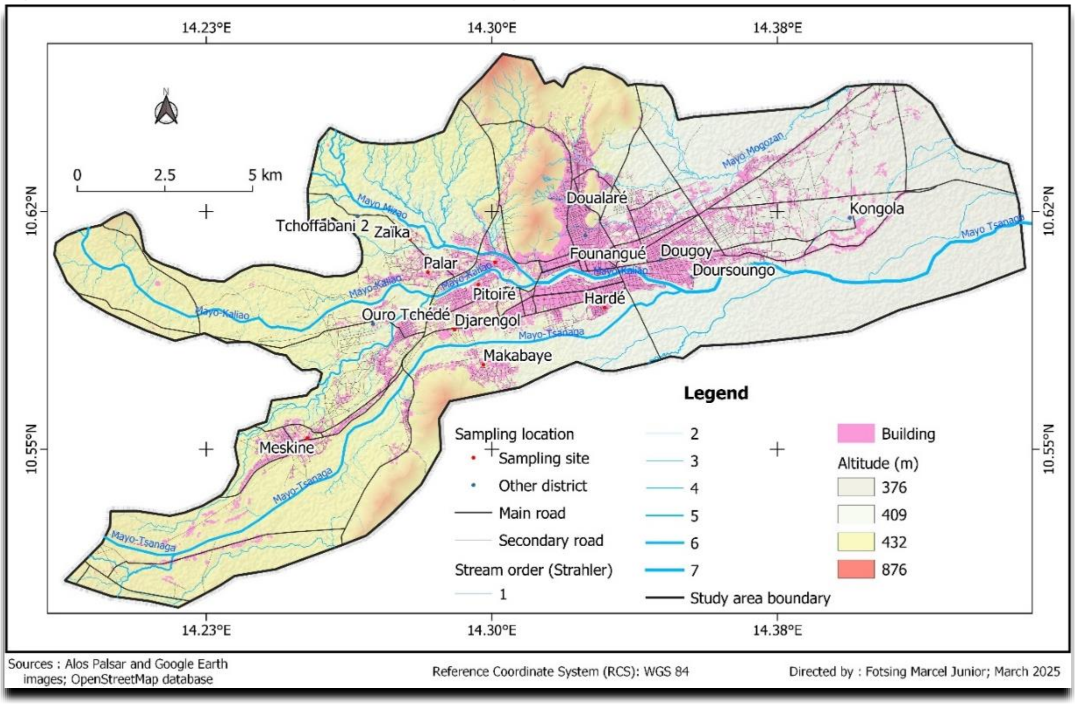
Figure 4: Spatial Distribution of Sampling Sites



Maroua's socio-economic landscape is diverse, with ethnic groups like the Fulani, Mundang, and Tupuri. The economy relies on informal trade, agriculture, and small industries, yet poverty affects over 40% of residents, below the national poverty line (World Bank, 2019). Limited access to clean water and sanitation worsens during floods.

The study examines ten flood-prone neighbourhoods Ouro-Tchédé, Djarengol Doualaré, Lopperé Hardé, Djarengol, Meskine, Yoldéo, Pitoaré, and others with a history of repeated flooding, confirmed by archives and local reports (actucameroun.com, 2020). These areas, characterized by dense low-income housing, poor drainage, and proximity to watercourses, are key for analysing flood risk, human environment vulnerability and resilience.

Method and Data

This investigation adopts a mixed-methods paradigm, with a series of equipment tools for data collection, treatment and analysis to synthesise quantitative and qualitative data to deliver a nuanced evaluation of flood vulnerability and resilience in Maroua (Table 1).

Table 1: Range of Tools and Applications Used to Collect and Interpret Data in the Field

Materials :	A3 printed site maps search authorizations Bloc-notes A pair of boots	**Tablets equipped with** :	Time-stamps camera GPS Essentials Kobo Collect Maps.me

Data	**Data Input Format**	**Resolution**	**Source**
Historical Flood Incidence data	Point (Vector)	Latitude, Longitude	Field Observation, Literature Review, Paper publications and archive information
Digital Elevation Model (DEM)	Raster	30m (Srtm)	NASA's official website https://search.earthdata.nasa.gov
Landsat, 5,7,9	Raster	30m	NASA's official website https://search.earthdata.

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			nasa.gov
Slope	Raster	30m	NASA's official website https://search.earthdata.nasa.gov
Aspect	Raster	30m	NASA's official website https://search.earthdata.nasa.gov
Curvature	Raster	30m	NASA's official website https://search.earthdata.nasa.gov
Elevation	Raster	30m	NASA's official website https://search.earthdata.nasa.gov
Roads	Vector	1:50,000	Cameroon Roads (World Bank)
Rivers	Vector	1:50,000	Drainage Network (ArcMapArcMap layer Extraction)
Land use landcover (LULC)	Raster	30m	ESRI 2020 data, https://livingatlas.arcgis.com/landcover/
Normalized Vegetation Index (NDVI)	Raster	30m	USGS official website https://earthexplorer.usgs.gov
Precipitation	Raster	30m	World Bank Group, Climate Change Knowledge Portal
Drainage Density	Raster	30m	NASA's official website https://search.earthdata.nasa.gov
Soils	Vector	1:500,000	Soil Atlas Cameroon

This methodological choice is predicated on the necessity to encapsulate both the physical and socio-economic facets of flooding, which are intricately interwoven in urban environments (Hoarau et al., 2019: pp. 235-250). Field surveys furnish granular, context-specific insights from impacted communities, while satellite imagery analysis affords a macroscopic view of land use dynamics and flood risks, rendering this dual approach particularly potent.

Fieldwork entailed surveys with 400 households across ten flood-prone neighbourhoods, selected based on historical flood documentation and stakeholder consultations (Table 2). The sample size, the 400 surveyed households were selected as a representative subset of all households within Maroua's 13 most flood-prone neighbourhoods, ensuring statistically valid coverage. The sampling method itself was a census-based approach, targeting all households in these high-risk zones, with neighbourhood selection informed by local stakeholders (particularly firefighters involved in flood response), government reports, and existing research on flooding in Maroua.

Table 2: Table of Neighborhoods.

N°	Neighbourhood names	Number of households surveyed
1	Baoliwol	132
2	Djarengol Délégué	53
3	Hardé	18
4	Louguéo	51
5	Makabaye	19
6	Meskine	57
7	Palar	33

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N°	Neighbourhood names	Number of households surveyed
8	Pitoiré	9
9	Zaïka	19
10	Ziling	9
Total		**400**

A stratified random sampling approach ensured representation across socio-economic groups and housing types. The bilingual (French/English) questionnaire, designed using Kobotoolbox, collected data on demographics, flood experiences, impacts, and resilience strategies. Local interpreters aided communication with Fulfulde-speaking participants, overcoming language barriers. Due to regional instability from Boko Haram, research permits from the University of Ngaoundéré and the Far North Governor were secured for safe community access.

Ethical standards guided the study. All participants gave informed consent, with strict measures to protect confidentiality and data integrity. Engagement with neighbourhood leaders (Djaouro) built trust and facilitated access. Post-survey feedback sessions shared initial findings with communities, promoting transparency.

Landsat 5, 7, and 9 satellite imagery (1986–2023) from USGS Earth Explorer was used to track land use changes in semi-arid regions, chosen for its temporal range and spectral precision. Rainfall data (1982–2023) from ASECNA and the regional transport delegation provided a climatic context for flood events.

Data Analysis

The methodology and data analysis framework of this study are meticulously designed to yield a robust and integrative assessment of flood vulnerability and resilience in Maroua. By amalgamating field survey data with geospatial analysis, this approach captures the multifaceted nature of flooding, encompassing both human and environmental dimensions. This section delineates the comprehensive processes of data processing and analysis, elucidating the selected techniques and their underlying rationales.

Survey Data Analysis

Field surveys collected data from 400 households about socio-economic and flood-related factors. The data was cleaned in Microsoft Excel, correcting inconsistencies, filling in missing values, and coding responses for analysis. Descriptive statistics indicated that 82% of respondents faced flooding, with effects ranging from property damage to fatalities. Cross-tabulations and chi-square tests examined connections between socio-economic factors and vulnerability, while logistic regression in SPSS 26. 0 identified predictors of flood vulnerability. Thematic analysis revealed key themes such as "infrastructure improvements", "community initiatives", and "government support", providing a complete view of vulnerability in Maroua.

Geospatial Analysis

The geospatial analysis evaluated land use changes and flood susceptibility in Maroua using Landsat imagery from 1986, 2006, and 2023, plus Alos Palsar DEMs, processed in QGIS 3.14. Imagery underwent atmospheric correction via Dark Object Subtraction, re-projection to UTM Zone 33N, and mosaicking to focus on urban areas. Supervised classification in ENVI 4.5, using the Maximum Likelihood algorithm, mapped land cover (built-up areas, vegetation, water bodies, bare soil, sandbanks) with training data from field observations and Bing Satellite imagery, achieving accuracies above 85% and Kappa coefficients over 0.80. Refined DEMs addressed gaps, enabling slope and aspect maps to pinpoint flood-prone areas. These outputs laid a spatial foundation for vulnerability mapping, linking land use patterns to flood risk.

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Geophysical Flood Risk Model

The second phase developed a flood risk model to identify flood risk and vulnerable areas. Key factors proximity to rivers, precipitation, slope, drainage density, elevation, Topographic Wetness Index, soil types, land use, aspect, road distance, and Normalized Difference Vegetation Index, were selected based on literature (Smith et al., 2018: pp.7249-7270). The Analytic Hierarchy Process (AHP) weighted these factors by their flood hazard contribution, using expert input (Saaty, 1980) (Table 3). AHP reliability was confirmed with a Consistency Index (CI) of 0.055 and a Consistency Ratio (CR) of 0.036, meeting the CR < 0.1 threshold for trustworthy decision-making.

Table 3: Criteria Factor Weights and Weight Percentages

Criteria	Weight (Décimal)	Weight (%)
Proximity to River	0.235	23.5%
Slope	0.199	19.9%
Precipitation	0.150	15.0%
Elevation	0.112	11.2%
Drainage Density	0.086	8.6%
TWI	0.063	6.3%
Soil Type	0.047	4.7%
Lulc	0.035	3.5%
Proximity to Roads	0.027	2.7%
NDVI	0.019	1.9%
Surface Curvature	0.015	1.5%
Aspect	0.013	1.3%
Total	1.00	100.0%

Source: Analysis of Pair wise and normalized Comparison Matrix's

These weighted parameters were then integrated into a Geographic Information System (GIS) via the raster calculator function, producing a spatially explicit map that elucidated flood risk gradients across the study domain.

Human Environmental Vulnerability Assessment

Assessing human vulnerability to floods is challenging due to limited population data in risk zones. The geophysical risk distribution model addresses this by analysing building parcel locations and their flood vulnerability through exposure. The model assumes a parcel's risk based on factors like proximity to water bodies, elevation, and historical flood patterns that reflects resident vulnerability. Building risk serves as a proxy for human risk, bypassing the need for precise population figures. For instance, a building near a river in a low-lying area is assigned high risk, indicating significant resident vulnerability (Smith et al., 2020; pp.7249-7270).

The model integrates topography, rainfall, soil conditions, and historical flood records to assign risk values to parcels. By combining building location data with river proximity, it estimates the number of structures and people at risk, accounting for flood severity and water flow patterns. This approach enables vulnerability assessments without detailed demographic data, aiding planning and risk management.

At the end of the analysis, each parcel receives a vulnerability index, a score reflecting flood exposure. This method underscores the link between the built environment's spatial layout and demographic patterns, providing a clearer view of flood risk.

Data Integration and Vulnerability Mapping

Household survey data, tagged with GPS coordinates, was integrated with land use and topographic data in QGIS using spatial joins. This dataset underpinned a vulnerability index crafted via the Analytic Hierarchy Process (AHP). The index, computed in GIS with the raster calculator,

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combined factors: building parcel proximity to flood-prone zones, a geophysical flood risk model, and distance to major water bodies. The resulting flood risk vulnerability index classified the human environment from very low to very high vulnerability, indicating flooding likelihood (K. Dandapat, & G. K. Panda, 2017: pp. 1627-1646).

The final thematic model equips stakeholders to pinpoint and prioritize flood mitigation areas. It highlights the value of merging flood probability with impact analysis for clearer, more effective risk management.

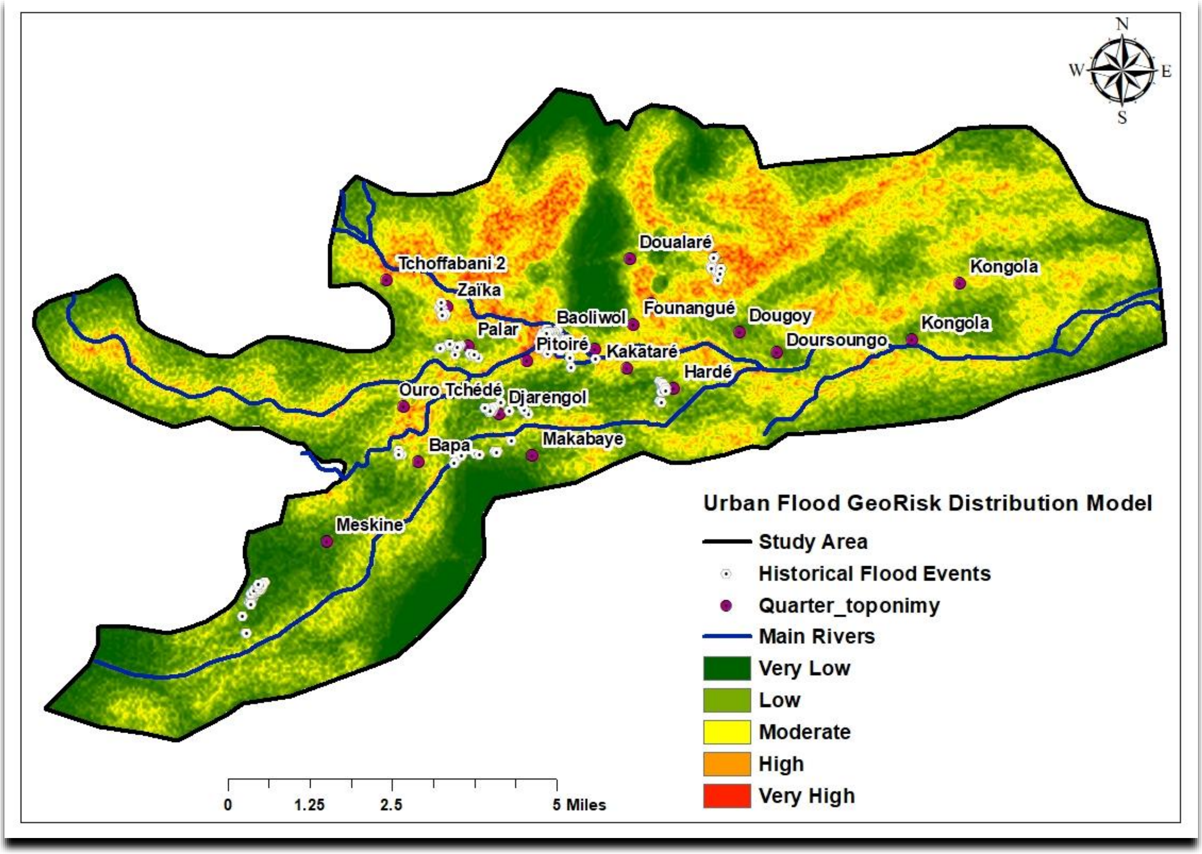
RESULTS AND RESULTS INTERPRETATION

The investigation into flood vulnerability in Maroua, Cameroon, leverages a robust dataset derived from Landsat 5, 7, and 9 satellite imagery spanning 1986 to 2024, complemented by a comprehensive household survey of 400 residences across 10 neighbourhoods. This dual-method approach elucidates the interplay between land use dynamics and socioeconomic factors driving flood risk. The land use classification, encompassing six categories built-up areas, ponds and watercourses, sandbanks, bare ground, woodland and grassland, and field and crop areas achieved overall accuracies exceeding 97% and Kappa indices above 0.96, affirming the precision of the remote sensing analysis.

Geospatial Analysis

This study assesses urban flood risk in Maroua urban centre, integrating geophysical flood risk and human vulnerability. The GeoRisk model evaluated geophysical risk using 12 criteria-weighted factors through the Analytical Hierarchy Process (AHP), achieving a Consistency Index of 0.055 and a Consistency Ratio of 0.036, confirming reliable weights. Results show flood risk varies across Very Low, Low, Moderate, High, and Very High categories, as mapped in (Figure 5), illustrating risk distribution.

Figure 5: Spatial Distribution of Geophysical Flood Risk in Maroua I Council Area.



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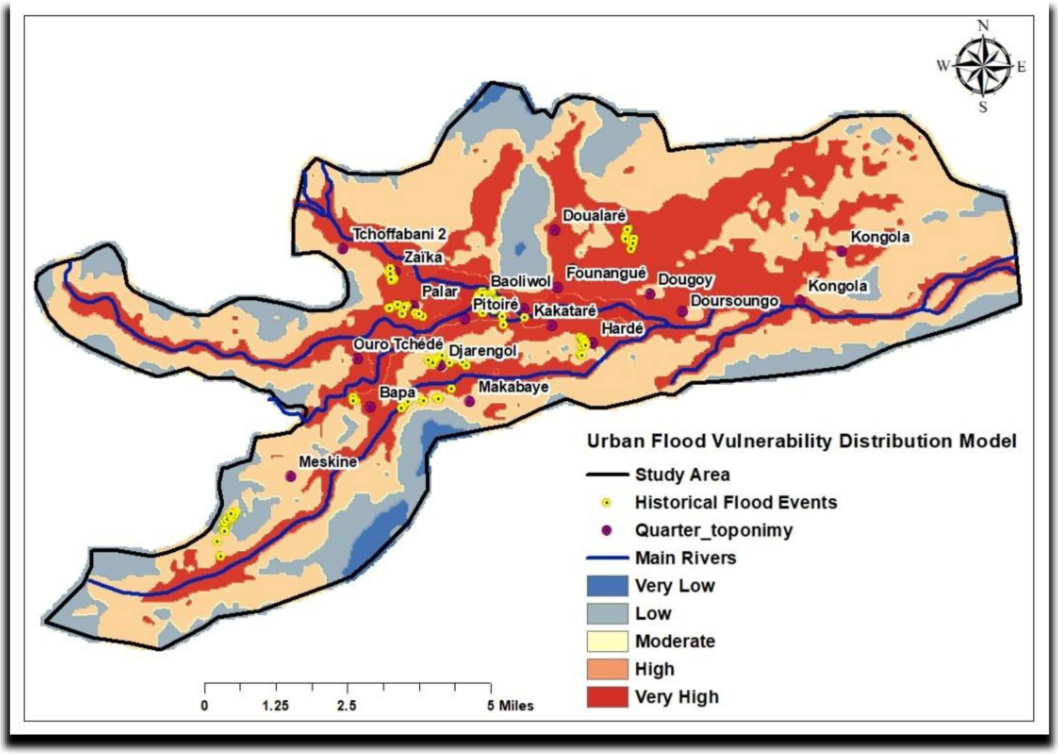
A human environmental vulnerability index, based on building parcels due to limited demographic data, was developed using AHP. Parcels reflect human presence and infrastructure exposure by location, density, and structure. Maroua's urban area, covering 1,953 km², had vulnerability distributed as follows: Very Low (28 km², 1.43%), Low (323.59 km², 16.58%), Moderate (876.927 km², 44.90%), High (672.82 km², 34.47%), and Very High (52.147 km², 2.67%), as shown in (Table 4).

Table 4: Percentage and Area Coverage of Human Vulnerability Index Classifications.

Class	Susceptibility classes	Pixel Sum	Area Cover (KM^2)	Area Cover (KM2)	Area Cover (%)
1	**Non –Very Low**	1330	28	28	1.43**%**
2	**Low**	15364	323.59	323.59	16.58**%**
3	**Moderate**	41637	876.927	876.927	44.90**%**
4	**High**	31946	672.82	672.82	34.4**%**
5	**Very High**	2476	52.147	52.147	2.6**%**

About 80% of Maroua's urban area faces moderate to high flood risk vulnerability, endangering infrastructure, livelihoods, and vulnerable groups in densely populated or low-income high-risk areas. With only 18% of the area classified as very low or low risk, options for safe urban growth or emergency planning are limited. The small but severe, very high-risk zones demand urgent action, such as relocation or stronger flood defences. These results emphasise the need for proactive urban planning, climate-resilient infrastructure, and community readiness to reduce flood impacts and tackle social inequities worsened by environmental risks. The human vulnerability index is shown in thematic maps (Figure 6,7 and Figure 8).

Figure 6: Spatial Distribution of Human Vulnerability Index in Maroua Urban Area



By integrating these two analyses, this study provides a comprehensive understanding of the urban flood risk vulnerability in the Maroua I council area, highlighting areas that require targeted mitigation and adaptation strategies to

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enhance resilience and reduce the impacts of flooding.

Figure 7: Visualization of Human Environment Flood Vulnerability Index Distribution

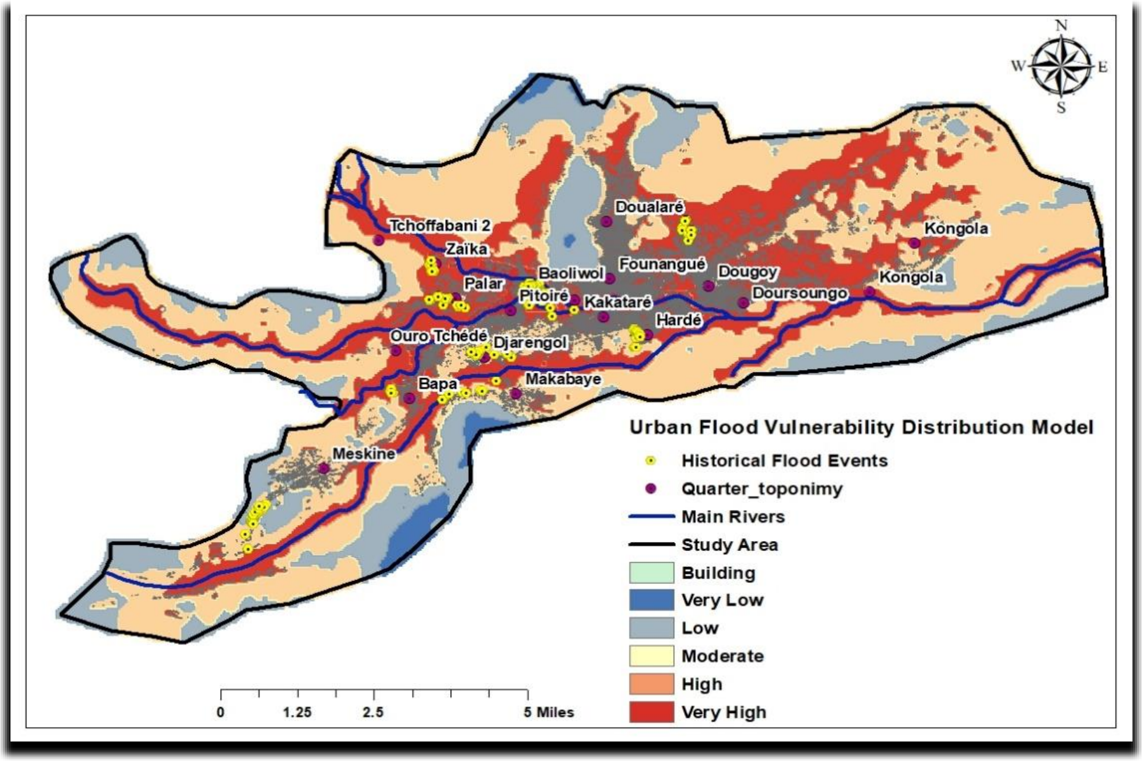
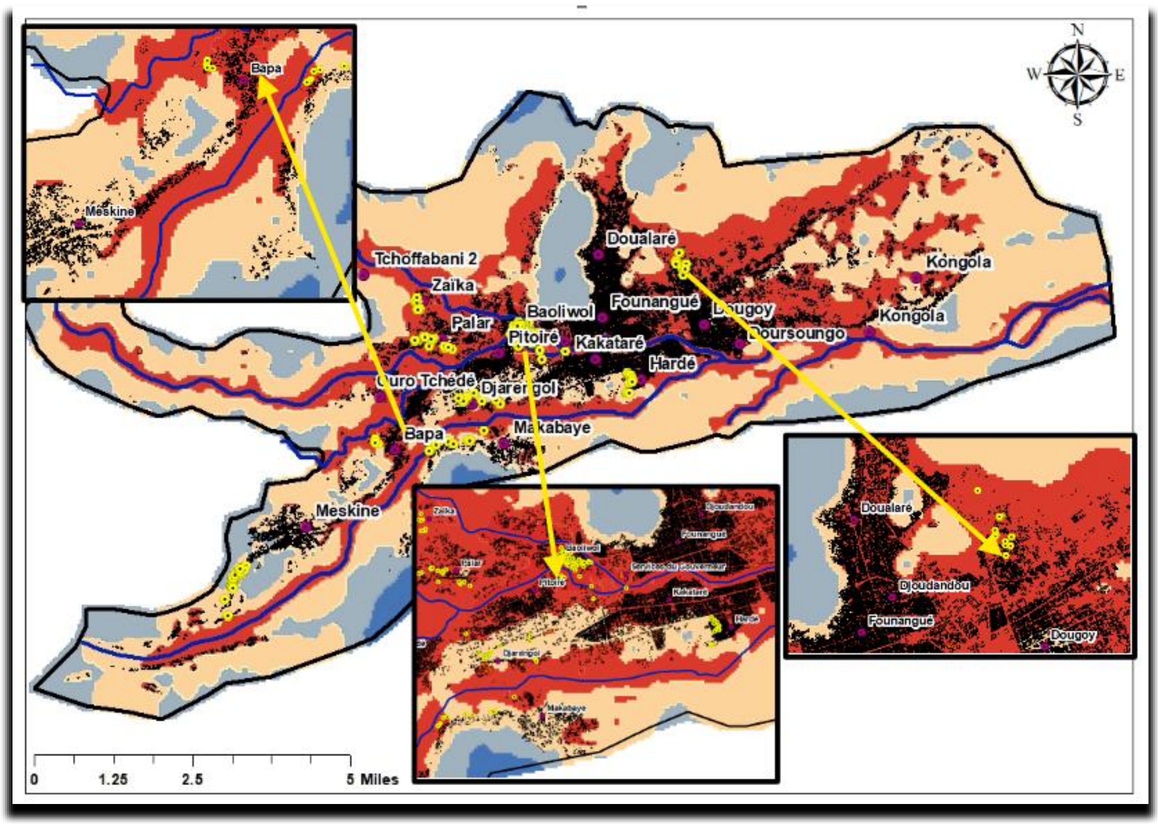


Figure 8: Detailed Visualization of Building Parcel Flood Vulnerability Distribution.



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Land Use Dynamics and Hydrological Implications

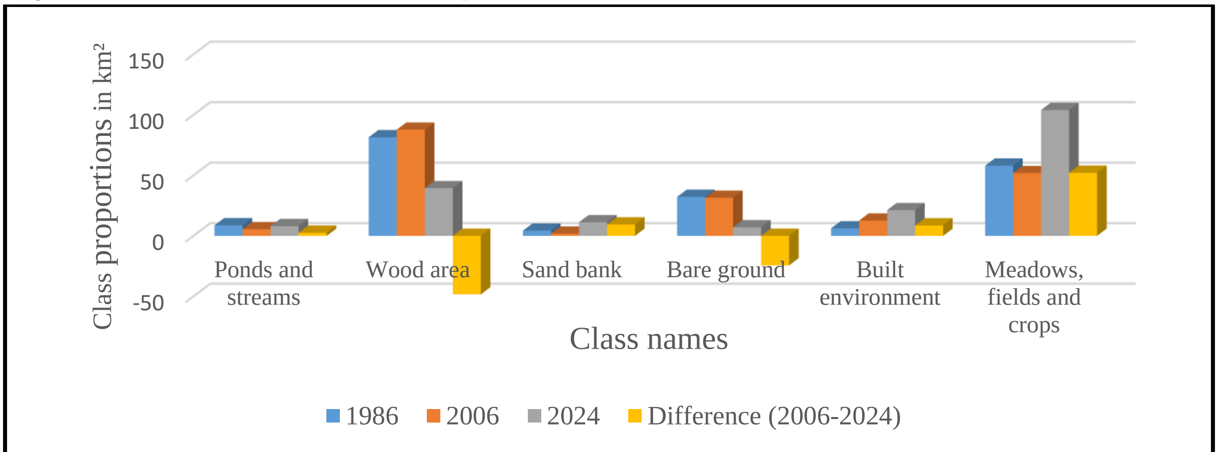
Land use classification used supervised methods, with training plots verified by fieldwork and GPS for accuracy. The household survey applied stratified random sampling to reflect neighbourhood and income diversity, using Kobo Collect for precise data collection.

Built-up areas grew sharply from 1.32% (2.52 km²) in 1986 to 5.84% (11.15 km²) in 2006, and 13.26% (24.51 km²) by 2024, a tenfold rise over 37 years, aligning with global urbanization trends (C. Seto, Karen et al., and 2011, pp. e23777). This expansion increases impervious surfaces like concrete, reducing infiltration and boosting runoff, which heightens flood risk (Shuster et al., 2005). Maroua's flat terrain and clay soils flooding, as poor drainage fails to manage water flow.

Temporal Shifts in Land Use Categories

The bare ground dropped from 31.91% in 1986 to 3.29% in 2024, likely due to urban or agricultural expansion, reducing permeable surfaces and increasing runoff. Ponds and watercourses grew slightly from 2.68% to 3.28%, possibly from sedimentation or climate changes, raising flood risks during heavy rain. Sandbanks fell from 4.94% to 1.53%, potentially due to urban growth or river changes, which may weaken riverbanks and alter flood patterns. Woodland and grassland rose from 6.52% in 1986 to 7.62% in 2006, then jumped to 40.83% by 2024, possibly from reforestation or policy shifts, though flood reduction depends on vegetation. Field and crop areas shifted, falling from 51.31% in 1986 to 31.29% in 2006, then climbing to 74.31% by 2024 (Figure 9, Table 5).

Figure 9: Evolution of Land Use Proportions from 1986 to 2024 in Maroua



This resurgence likely reflects agricultural intensification to meet population demands, yet unsustainable practices such as deforestation or soil compaction could amplify runoff, counteracting food security gains.

Table 5: Land Use Change Statistics from 1986 to 2024 in the Maroua Center Urban Area.

N°	Class name	Area in km² 1986	Area in km² 2006	Area in km² 2024
1	Ponds and streams	8.71	5.43	8.02
2	Wood area	81.48	87.73	39.4
3	Sand bank	4.31	1.86	11.25
4	Bare ground	32.23	31.45	7.05
5	Built environment	6.18	12.59	21.22
6	Meadows, fields and crops	58.01	51.86	103.98
Total				**190.92**

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Source: Field Data Analysis.

Spatial Dynamics of Land Use from 1986 to 2024 in the City of Maroua

Land Use is Strongly Influenced by Human Impact

In the urban area of Maroua, land use types have been changing significantly under the influence of human activity (Figures 10, 11 &12, below). Based on data from aerial image analysis, the city of Maroua was heavily vegetated in 1986. Over the years, however, the population has engaged in a number of deforestation activities in the urban area of Maroua. Several factors can explain this degradation of the vegetation cover: the population explosion, combined with the search for new settlement sites. This situation has not only led to soil denudation but above all to a galloping expansion of grasslands, fields and crops (54.46%), as well as inhabited space (11.12%).

Figure 10: Spatial Distribution of Built-up Areas in Maroua 1986

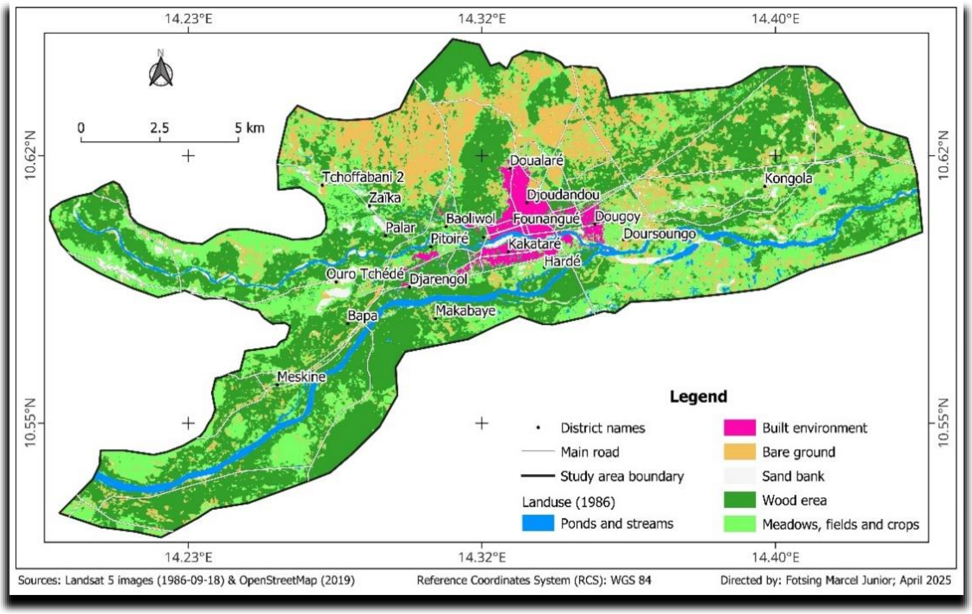

Figure 11: Spatial Distribution of Built-up Areas in Maroua 2006

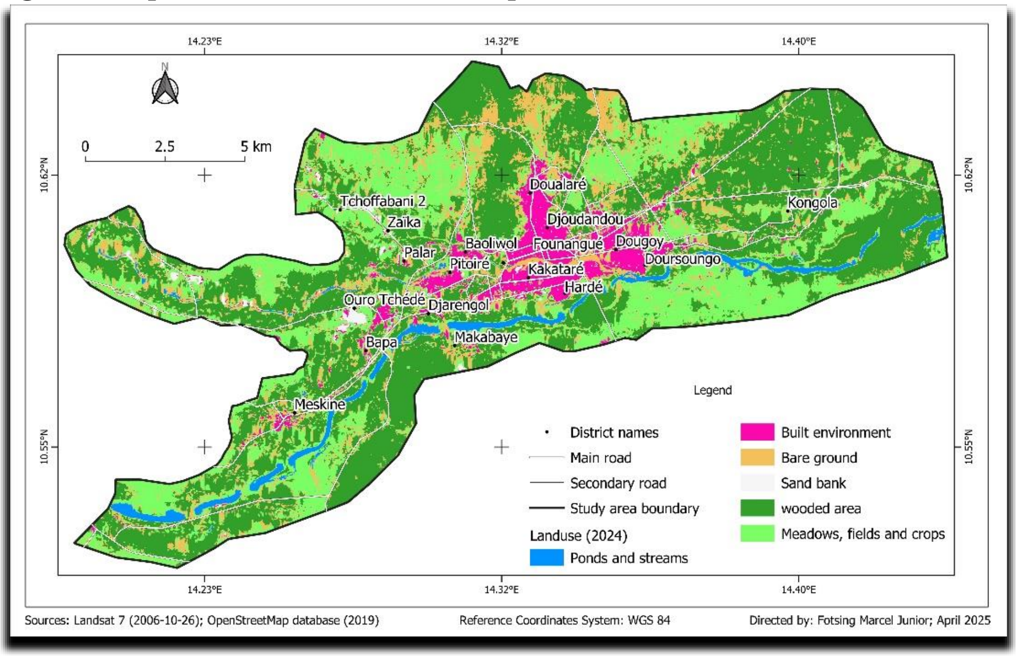

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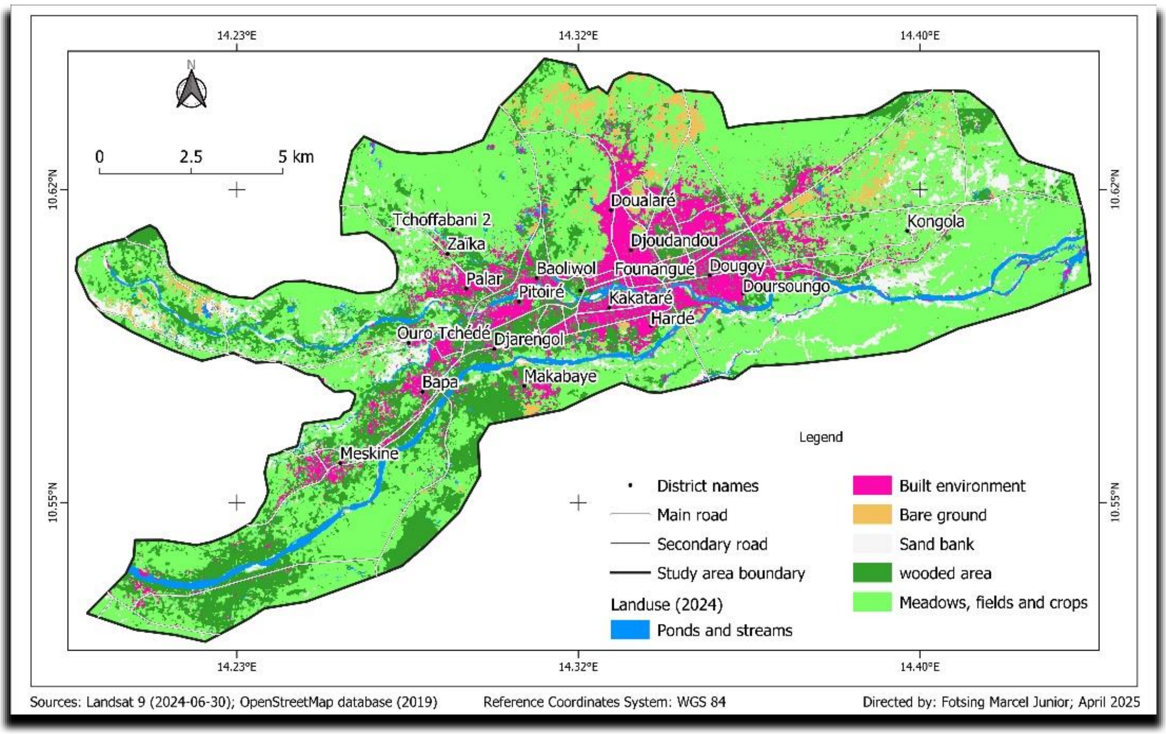
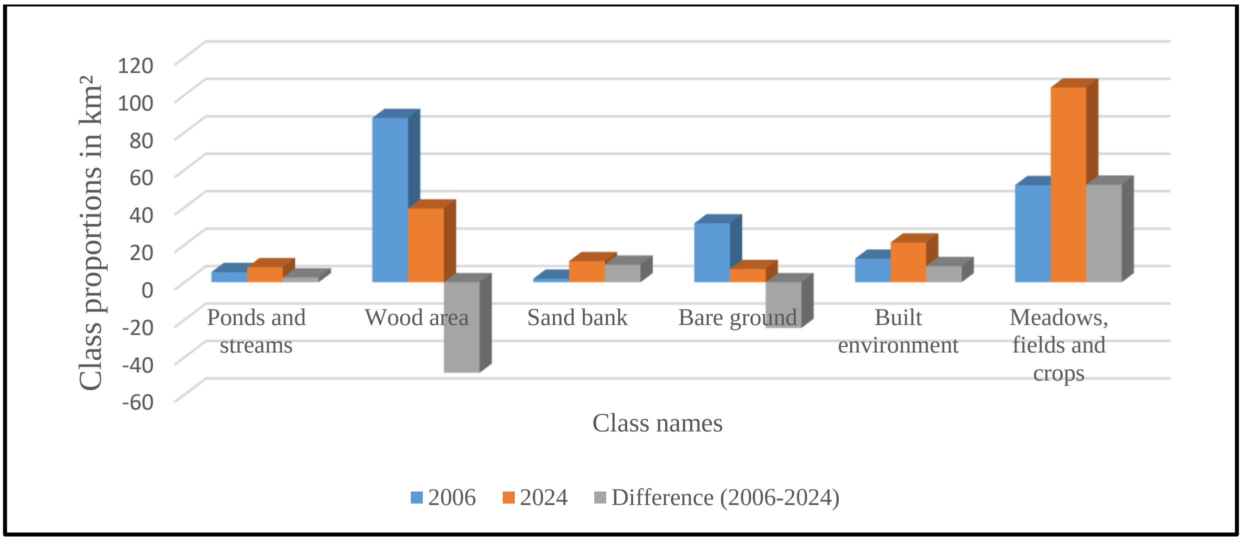
Figure 12: Spatial Distribution of Built-up Areas in Maroua 2024



Urban expansion in Maroua has been notable over recent decades. From 1986 to 2006, the built-up area grew by 7.88%, driven by population growth, economic progress, and rural-to-urban migration. From 2006 to 2024, it increased by 4.52% (Figure 13), showing a slower but steady rise. This growth, often unplanned, has led settlements to encroach on floodplains and water-prone areas, raising environmental risks.

Figure 13: Developments in the "Built-up Area" Class between 2006 and 2024



Urban growth in Maroua worsens environmental issues, especially frequent and severe flooding. Expanding impermeable surfaces, like roads and buildings, disrupt natural drainage, limiting rainfall absorption. Unplanned development in flood-prone zones heightens risks to people and infrastructure. Without action, this study projects a likely rise in flooding incidents in Maroua over the years, potentially increasing socio-economic and environmental strain.

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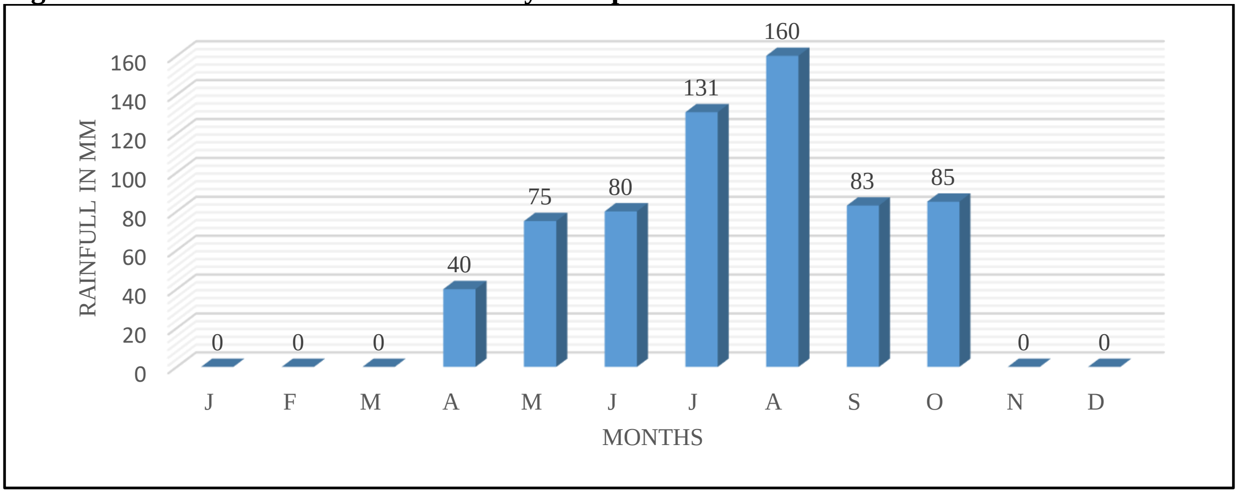
Causal Mechanisms and Influential Factors of Flooding in Maroua

Flooding in urban environments such as Maroua represents a complex interplay of causal mechanisms and contributing factors. The cause of flooding refers to the primary trigger initiating the inundation event, while factors encompass the broader suite of natural and anthropogenic elements that exacerbate its occurrence and severity. In Maroua, these dynamics are shaped by climatic patterns, geomorphological characteristics, and human activities, each warranting detailed examination to inform disaster mitigation strategies.

Highly Concentrated Rainfall in July and August

Precipitation serves as the predominant causal mechanism for flooding in Maroua, with the rainy season peaking in July and August consistently linked to flood events. Hydrometeorological data indicate that these months experience intense, short-duration rainfall, overwhelming the city's drainage capacity. Analysis of historical precipitation trends underscores this seasonality, with maximum daily rainfall events frequently exceeding thresholds conducive to flooding (Figure 14). Such episodic deluges, characteristic of the Sahelian climate, precipitate rapid surface runoff, setting the stage for urban inundation.

Figure 14: Distribution of Maximum Daily Precipitation from 1982 to 2023



Temporal distribution of peak rainfall events in Maroua, highlighting July-August concentrations based on 41 years of meteorological records.

Natural Hazards and Their Role in Flooding

Flooding in Maroua significantly affects socio-economic and environmental conditions, requiring a clear grasp of its causes. Research stresses addressing natural factors like soil type, topography, and hydrological networks to reduce disaster risk. These elements increase the city's flood vulnerability during rainfall events, making their management critical for effective hazard control.

Clay Soils as an Obstacle to Rainwater Infiltration

Soil types in Maroua, including sandy and clayey alluvial soils, Vertisols, red-brown fersialitic soils, and clay-rich Karal, shape flood patterns. Clayey soils, common in some areas, have low permeability, blocking rainwater absorption and causing surface water pooling, which triggers flooding. Soil mapping highlights this risk in places like Pitoiré (Figure 15).

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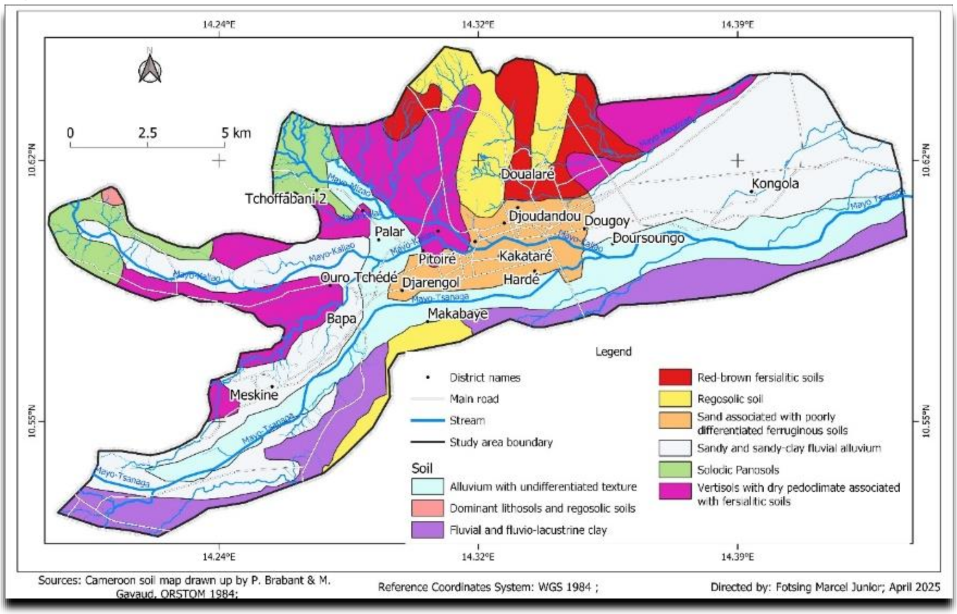
Figure 15: Soils in the Pitoiré District

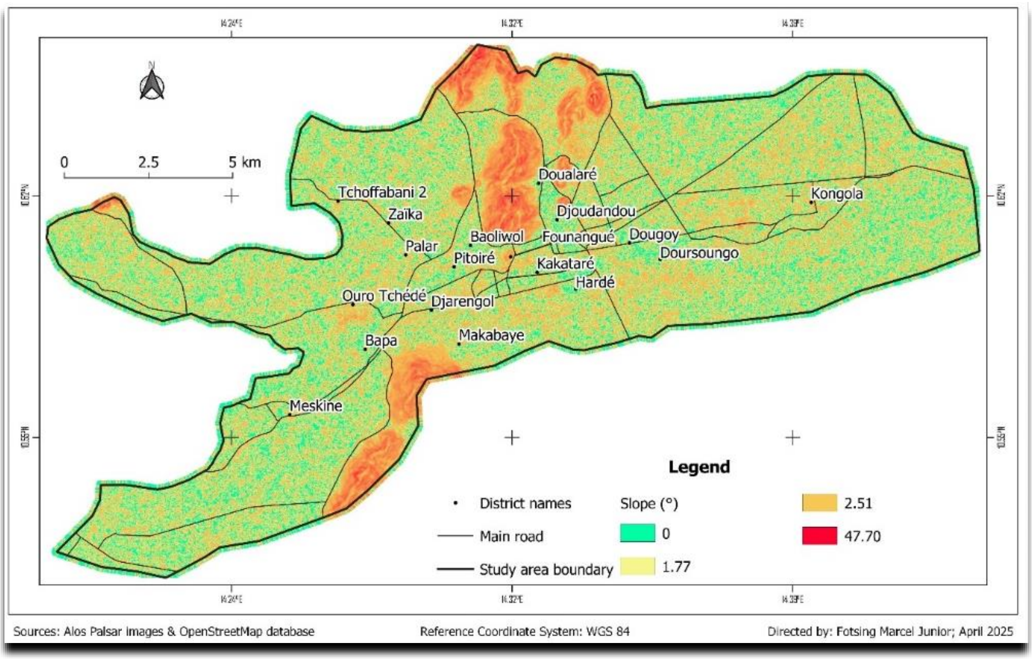


Soil type distribution in Pitoiré, illustrates the dominance of impermeable clay layers contributing to surface water accumulation.

Flat Terrain Favours Rainwater Accumulation

Maroua’s flat geomorphology, with vast plains and scattered hills, worsens flood risks. Topographic surveys show minimal slope across the city (Figure 16), hindering drainage and causing rainwater to pool. This flat terrain, shaped by sedimentary history, increases floodwater volume and duration during heavy rain, leaving much of the city flood-prone.

Figure 16; The Slopes of Maroua’s Urban Space



Digital elevation model depicting minimal topographic gradients across Maroua, correlating with zones of persistent water pooling.

The City of Maroua: An Area Heavily Drained by Watercourses

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Maroua's hydrological system, part of the Lake Chad basin, includes seasonal rivers like Mayo Tsanaga, Mayo Mogazan, Mayo Mizao, and Mayo Kaliao. During the rainy season, these rivers overflow, flooding nearby areas such as Meskine, Palar, Zaïka Baoliwol, and Makabaye. Photos from Makabaye (Figure 17) show Mayo Tsanaga's minor bed, suggesting its capacity to surge during heavy rain.

Figure 17: The Tsanaga Mayo in Its Minor Bed in the Makabaye District

Visual documentation of Mayo Tsanaga's constrained channel, a precursor to overflow during intense precipitation events.

Anarchic Land Use: An Anthropogenic Factor Leading to Flood Disasters

Human activities worsen Maroua's flooding, with unregulated land use as a key factor. Uncontrolled urban growth occupies flood-prone hillsides, shallows, and riverbeds, blocking drainage with buildings in areas like Ziling, Palar, and Pitoiré (Figure 18). This disruption increases flood severity and frequency, highlighting the need for better land-use planning.

Figure 18: Obstruction of Rainwater Drainage Channels in the Pitoiré District

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Photographic evidence of urban development impeding drainage infrastructure, a key anthropogenic contributor to flooding in Pitoiré.

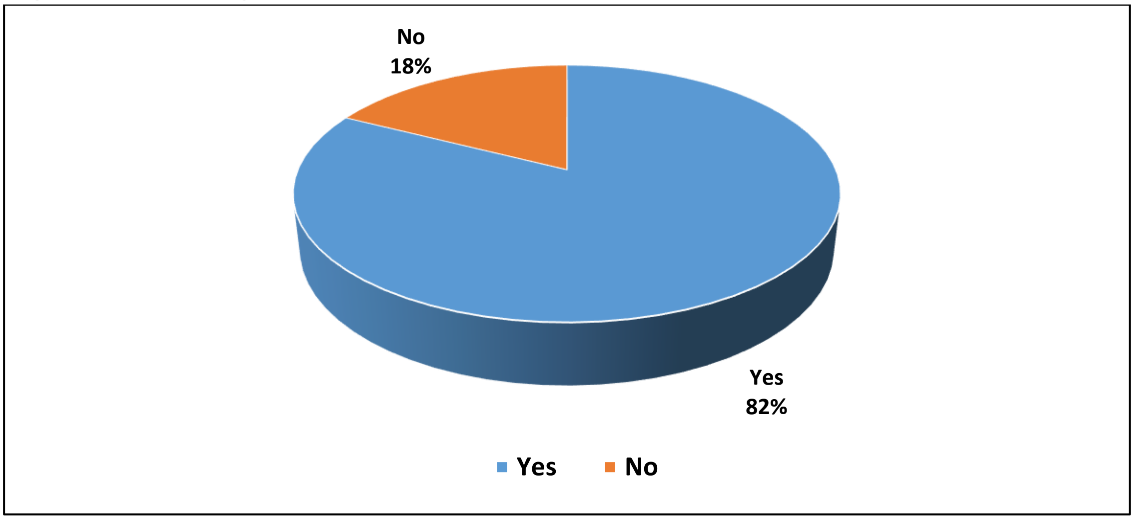
The Impact of Flooding on Households in Certain Districts of Maroua

Flooding in Maroua imposes multifaceted burdens on households, ranging from physical damage to socio-economic disruption. This analysis draws on data from 400 households across 10 neighbourhoods, each averaging seven members, to elucidate the scale and nature of flood impacts. The interplay between environmental triggers and human vulnerability underscores the urgency of understanding these effects to inform resilience-building measures in this urban Sahelian context.

Number of Households Regularly Affected by Flooding

Survey data reveal that flooding is a pervasive threat in Maroua, with 330 of the 400 households surveyed (82%) reporting prior flood victimisation (Figure 19). Conversely, 70 households (18%) indicated no such experiences, suggesting spatial variability in exposure. This high incidence aligns with the city’s susceptibility to seasonal deluges, highlighting the need for targeted interventions in flood-prone districts to mitigate recurrent impacts on residential populations.

Figure 19: Flooding Experiences in the Households Surveyed



Pie chart illustrating the proportion of surveyed households affected by flooding, based on a sample of 400 households across Maroua.

Ever-Increasing Flooding in the City of Maroua

Temporal analysis of flood dynamics indicates an escalating trend, with 187 of the 330 regularly affected households (56.67%) identifying 2019–2024 as the period of greatest flood-related damage. This perception, corroborated by longitudinal data (Figure 20), suggests a potential intensification of flood events, possibly linked to climatic shifts or urban expansion. Such insights necessitate further investigation into the drivers of this apparent increase to bolster predictive and adaptive capacities.

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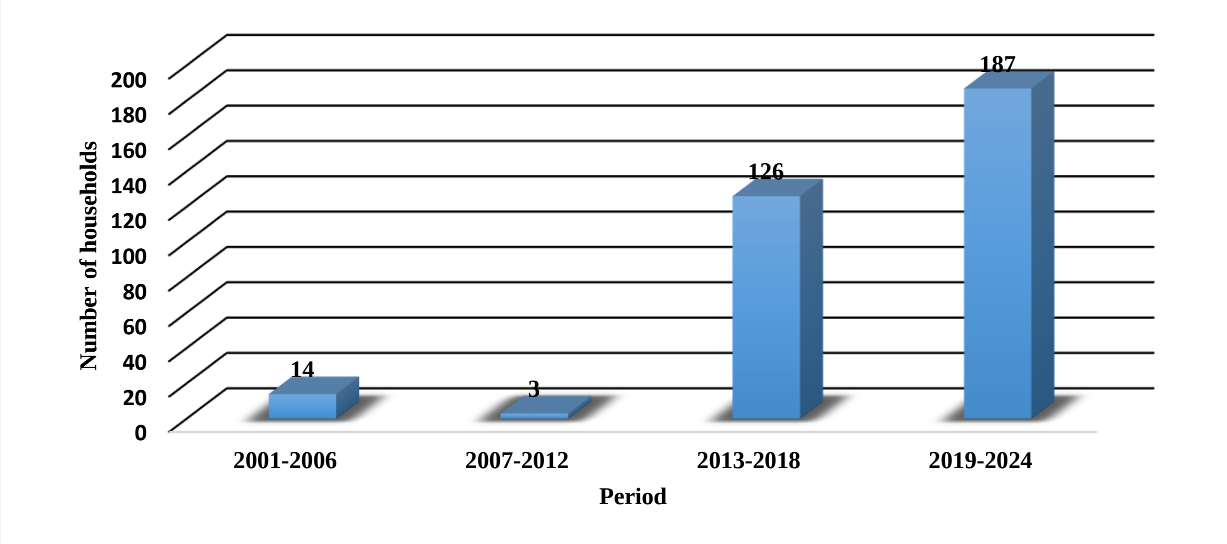
Figure 20: Dynamics of Flooding from 2001 to 2024 in the City of Maroua

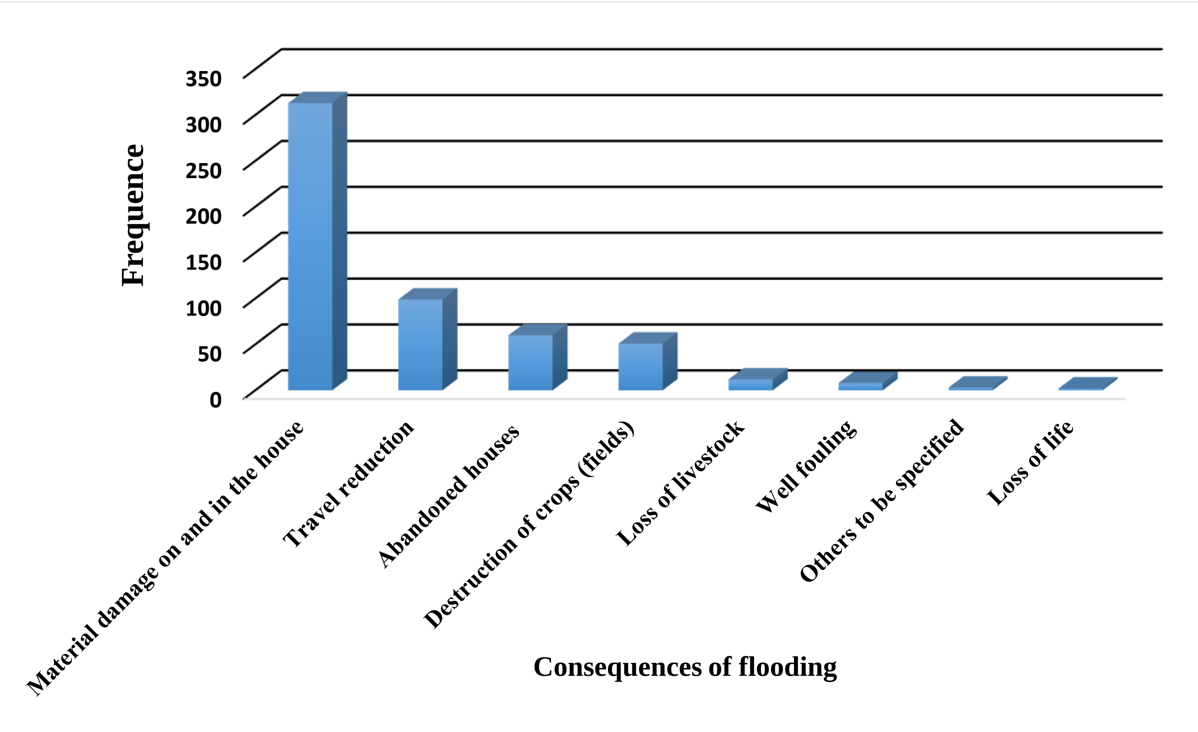


Line graph depicting the frequency and severity of flooding incidents in Maroua over 23 years, highlighting recent peaks.

Effects of Flooding on Households in Certain Districts of Maroua

The consequences of flooding manifest diversely across Maroua's households, with 313 of the 330 affected (94.85%) reporting structural damage to their homes (Figure 21). Beyond material losses, respondents cited disruptions such as interrupted commercial activities, destroyed sanitation facilities, and food insecurity exemplified by a Palar family enduring three days without cooking due to inundation. Additionally, approximately 60 homes, including mosques, were abandoned, forcing residents into hazardous street-side alternatives and amplifying exposure to secondary risks.

Figure 21: Consequences of Flooding in the Households Surveyed



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Bar chart detailing the range of flood impacts reported by 330 households, from property damage to livelihood disruptions.

Travel Restrictions as a Major Consequence of Flooding

Flooding severely curtails mobility, a critical yet understudied impact in Maroua. Field observations in Pitoiré revealed floodwaters exceeding 75 cm, stranding residents, such as a woman unable to reach her workplace for three days (Figure 22). This restriction not only disrupts economic activities but also isolates communities, compounding the social toll of flood events and underscoring the need for enhanced infrastructure to maintain access during crises.

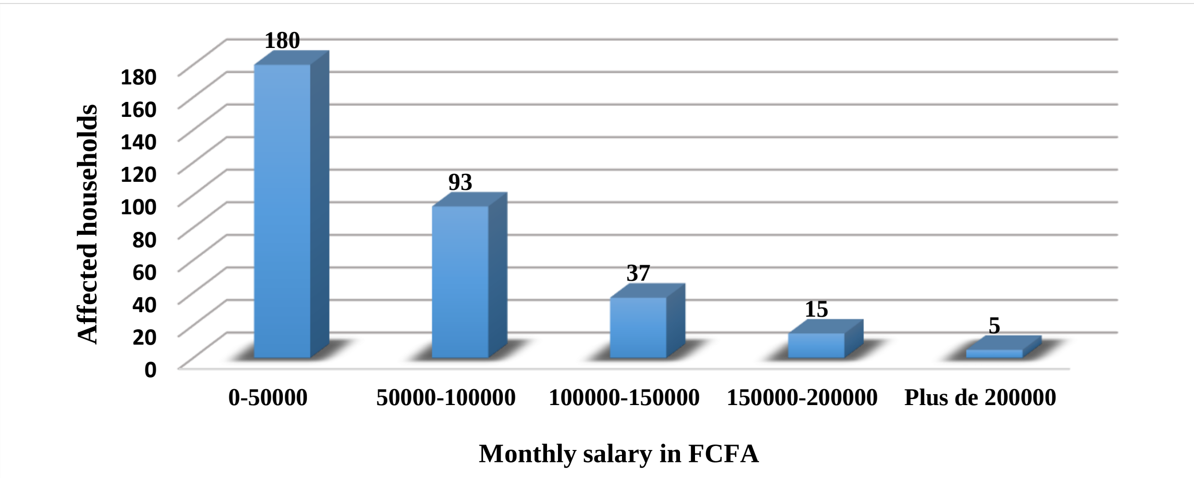
Figure 22: Travel Restrictions Following Flooding in the Pitoiré District

Image of floodwaters submerging streets in Pitoiré, illustrating the depth and extent of mobility barriers faced by residents.

The Influence of Standard of Living on Exposure to Flood Disasters

Socio-economic status markedly shapes flood vulnerability, with 180 of the 330 affected households (54.55%) earning less than 50,000 FCFA (76.22 €) monthly (Figure 23). These low-income families often reside in precarious, flood-prone areas, occupying dwellings of temporary materials ill-suited to withstand inundation. This correlation between poverty and exposure highlights a structural inequity, where limited resources amplify risk and constrain adaptive options.

Figure 23: Monthly Income Situation for Households Affected by Flooding



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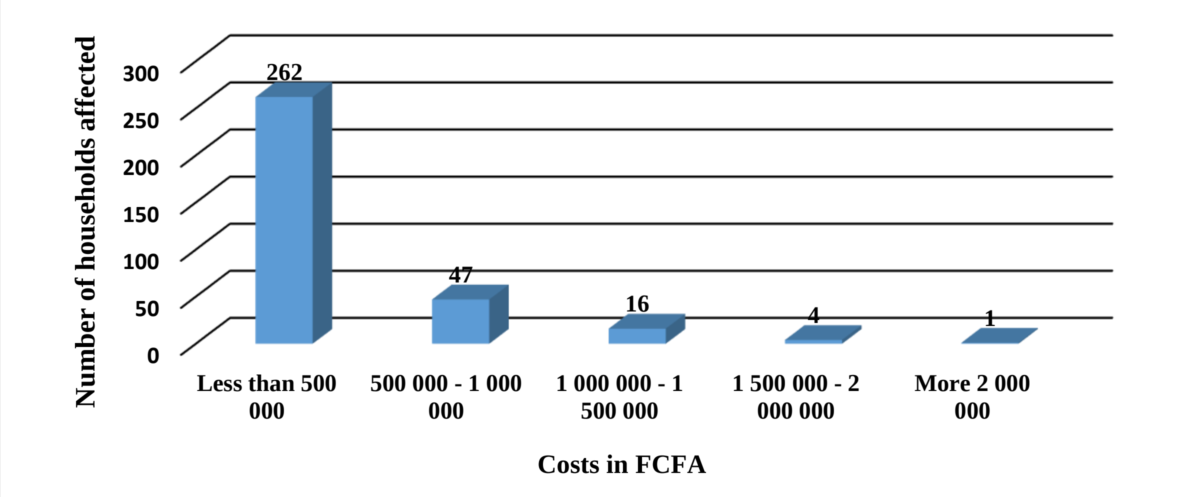
Histogram showing the income distribution of flood-affected households, emphasizing the prevalence of low-income groups.

Damage Economic Tool in Selected Households in the City of Maroua

Economic assessments of flood damage reveal that 262 of the 330 affected households (79.39%) incurred losses below 500,000 CFA francs, encompassing property damage, crop destruction, and livestock losses (Figure 24). While individually modest, the cumulative impact across households signals a significant community-level burden. These findings emphasize the need for cost-effective mitigation strategies tailored to the scale of losses experienced by Maroua's residents.

Figure 24: Damage Assessed in Terms of Costs in Households Affected by Flooding



Bar graph quantifying flood-related financial losses across 330 households, segmented by cost brackets.

Results Validation

The reliability of this study's findings relied on the validity of three aspects of the analysis;

- The accuracy of the satellite imagery classifications
- Accuracy and precision of the flood geophysical risk and vulnerability prediction models
- The robustness of the household survey data.

For the land use analysis, classifications were validated against ground truth data (GPS points from training plots), yielding high classification accuracy metrics;

- 1986: Overall accuracy of 99.76% (1230/1233 pixels), Kappa index of 0.99.

- 2006: Overall accuracy of 99% (4176/4218 pixels), Kappa index of 0.98.

- 2024: Overall accuracy of 97.24% (5629/5787 pixels), Kappa index of 0.96.

Dusseux (2014) states that Kappa indices above 0.8 indicate excellent classification quality, affirming the reliability of the land use and cover dynamics analysis results. The household survey included 400 households, providing a statistically significant representation of flood experiences in Maroua's urban area.

The validation of geospatial flood risk and human-environment vulnerability models for Maroua was achieved through a robust statistical method using a random sample of 322 flood event locations documented over several years. Of these, 234 events (72.67%) occurred in areas categorised by the model as moderate to very high flood risk, showcasing strong model sensitivity and predictive accuracy. Statistical metrics highlight the model's credibility: a true positive rate of 72.67% reflects a high identification rate of actual flood events, while precision, calculated as correctly predicted flood events versus total predicted high-risk areas, was estimated at 68.4%

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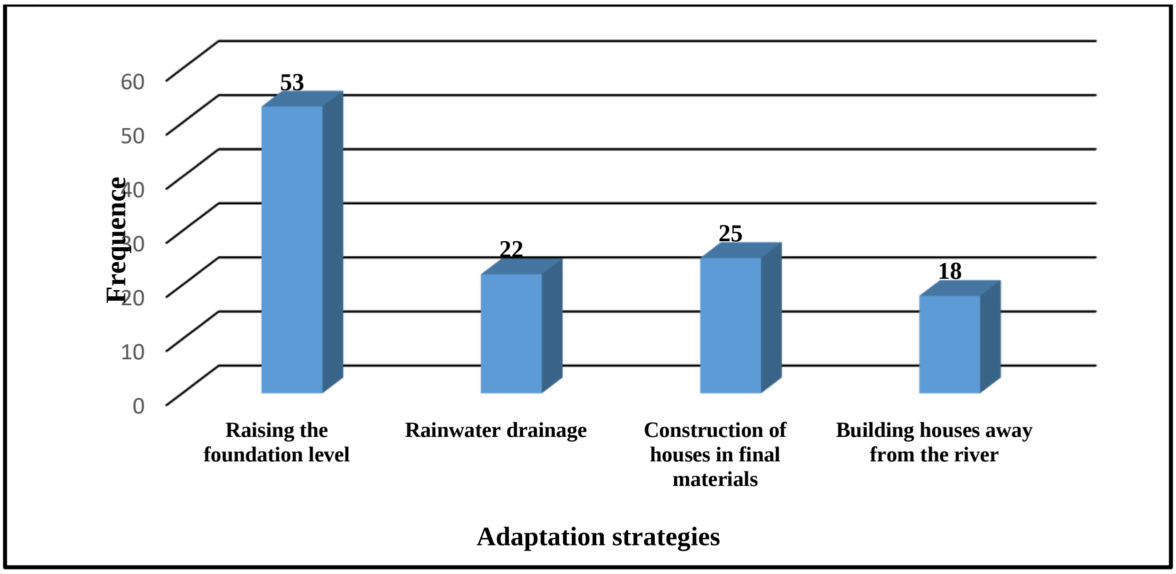
via spatial overlap analysis. The area under the receiver operating characteristic curve (AUC-ROC) was 0.79, indicating good discriminatory power compared to random guessing (AUC = 0.5).

This validation method, based on historical field data, is superior to techniques like cross-validation or Monte Carlo simulations because it directly correlates model outputs with observed events. This approach is crucial for geophysical risk modelling, considering local environmental and human factors. The model's high sensitivity and AUC-ROC score confirm its reliability, though a 27.33% false negative rate (88 events missed) suggests areas for improvement, possibly due to unmapped micro-topography or socio-economic influences. This rigorous validation enhances the research's credibility, instilling confidence among stakeholders regarding the model's utility for flood mitigation and urban planning in Maroua. By grounding predictions in empirical data, the study lays a solid foundation for policy recommendations, with ongoing validation using updated datasets further enhancing its applicability. These efforts ensure the findings are credible and valuable for informing policy and research.

Resilience Strategies by Local Populations and Households to Reduce Flood Vulnerability

In response to recurring floods, households in Maroua have adopted various strategies to mitigate their vulnerability. Among the 70 households (18% of the sample) not regularly affected by floods, 71% (approximately 50 households) attributed their resilience to raising the foundation levels of their homes (Figure 25).

Figure 25: Flood Resilience Strategies in the City of Maroua



Pie chart depicting the frequency of resilience strategies adopted by households, with emphasis on foundation elevation.

This structural adaptation elevates living spaces above typical floodwater heights, reducing inundation risks.

Additional strategies observed include:

- Channelling rainwater: Redirecting runoff away from homes using ditches or drains to prevent water accumulation.
- Building with permanent materials: Constructing homes with durable materials like concrete rather than temporary ones like mud, enhancing resistance to flood damage.
- Locating homes away from watercourses: Avoiding flood-prone areas near rivers (mayos) such as Mayo Tsanaga and Mayo Mogazan.

Field observations revealed that combining these strategies can significantly enhance resilience. For instance, a household in the Zaïka district

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successfully protected its home by integrating raised foundations with rainwater channelling and permanent materials (Figure 26).

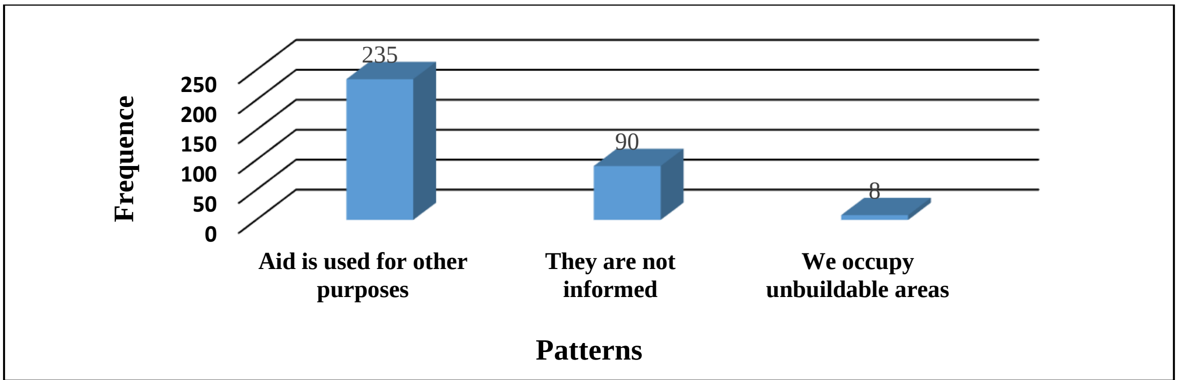
Figure 26; House Adapted to Flooding in a Flood Zone in the Zaïka District

Photograph of a flood-resilient home in Zaïka, showcasing elevated construction as an effective adaptation.

However, these measures are often limited to households with sufficient resources, leaving lower-income families 54.55% of whom earn less than 50,000 FCFA monthly more exposed due to reliance on less durable construction in flood-prone zones.

Institutional support for flood victims in Maroua remains scant, with only five of the 330 affected households (1.52%) reporting assistance from state or municipal authorities. Respondents cited reasons for this gap, including limited resources and coordination failures (Figure 27). This minimal engagement reflects a critical shortfall in disaster response frameworks, necessitating stronger stakeholder involvement to address the needs of flood-affected communities effectively.

Figure 27: Reasons for Low Stakeholder Assistance



Bar chart summarizing household-reported barriers to receiving institutional aid during flood crises.

DISCUSSION

The findings from the analysis of Maroua's urban area reflect global trends of increased flood risk

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due to urbanization and socioeconomic disparities. Built-up areas expanded from 1.32% in 1986 to 13.26% in 2024, aligning with IPCC's (2014) observations that urban growth raises impervious surfaces, leading to greater runoff and flooding. Additionally, Maroua's clay soils and flat terrain hinder water infiltration and promote accumulation, consistent with research showing that soil and topography can exacerbate flooding (Badameli Pyalo Atina & Kadouza Padabô, 2020:pp.112–130).

The socioeconomic aspects of flood vulnerability are concerning. A significant portion of low-income households (54.55% earning below 50,000 FCFA monthly) highlights findings by R. Marto et al., (2018:pp. 574-586), who state that poverty limits adaptive capacity, pushing families into high-risk areas with poor housing. Structural measures like raised foundations are effective; Kreibich et al. (2005:pp. 575–582) demonstrated that flood-resistant construction can greatly reduce damage. However, limited adoption of these strategies among poorer households reveals economic barriers.

The lack of state and municipal assistance, with only 1.52% (5 out of 330) of affected households receiving aid, highlights a critical gap in disaster governance. This situation reflects concerns from Amanejieu (2019: pp. 45–60) and Hamdja Ngoniri et al. (2024: pp. 78–95) regarding insufficient institutional support in northern Cameroon’s flood-prone areas. The combination of natural factors (heavy rainfall in July and August, clay soils) and human pressures (disorganised land use, blocked drainage) complicates flood management, a trend noted by Leumbé Leumbé et al. (2015:pp. 201–218) in similar Sahelian regions. If current trends continue, flood risks in Maroua could worsen by 2042 due to ongoing urban sprawl and potential desertification from deforestation, highlighting the urgent need for sustainable urban development and support for vulnerable communities.

CONCLUSION

This study reveals that Maroua, Cameroon, faces escalating flood risks due to significant land use changes and socioeconomic vulnerabilities. From 1986 to 2024, built-up areas expanded from 1.32% (2.52 km²) to 13.26% (24.51 km²), reflecting rapid urbanization that has increased impervious surfaces and disrupted natural drainage. Concurrently, 82% of surveyed households (330 out of 400) experience regular flooding, with 94.85% reporting home damage and 56.67% noting 2019–2024 as the most destructive period. Low-income households, comprising 54.55% of those affected, bear the brunt of these impacts due to limited resources and precarious living conditions.

Resilience strategies such as raising foundation levels (adopted by 71% of unaffected households), channelling rainwater, and using permanent materials offer effective mitigation, yet their uptake is uneven, favouring wealthier households. The near absence of state support (only 1.52% of affected households aided) underscores the need for enhanced disaster management. Without intervention, unchecked urbanisation and environmental degradation could exacerbate flood vulnerability, potentially densifying flood-risk zones by 2042.

Addressing these challenges requires integrated urban planning, improved drainage infrastructure, and targeted support for low-income communities. By combining household-level resilience with robust governance, Maroua can reduce its flood risks and foster sustainable development in a changing climate.

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