EVALUATION OF CLIMATE CHANGE EFFECT ON RIVER NIGER IN LOKOJA AND NIAMEY, WEST AFRICA

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A THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL, FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA, NIGERIA IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF DOCTOR OF PHILOSOPHY (PhD) IN CLIMATE CHANGE AND HUMAN HABITAT

MAY, 2025

DECLARATION

I DOULLA NOUHOU Youssoufa declare that this thesis **"EVALUATION OF CLIMATE CHANGE EFFECT ON RIVER NIGER IN LOKOJA AND NIAMEY, WEST AFRICA"** is a documentation of my original research and it has not been presented for any other qualification anywhere. All the information and sources have been duly referenced.

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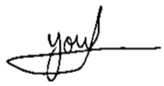

22/01/2026

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CERTIFICATION

This project entitled, **EVALUATION OF CLIMATE CHANGE EFFECT ON RIVER NIGER IN LOKOJA AND NIAMEY, WEST AFRICA** by DOULLA NOUHOU Youssoufa **(**PhD/SPS/FT/2021/13006) is in accord with the requirements governing the title of Doctor of Philosophy (Ph.D) of the Federal University of Technology Minna and is approved for its contribution to the advancement of scientific knowledge and literacy

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ABSTRACT

Climate variability has greatly impacted the riparian functionalities of diverse ecosystems; recent increases in flooding are linked to this phenomenon. Hence, the devastating floods and associated risks can only be managed holistically through a wide spectrum of engineering, societal, and institutional measures. Against this backdrop, this study evaluates and models the effects of climate change on the flood dynamics of the River Niger and explores adaptation strategies in Lokoja and Niamey, West Africa. To achieve this, the study analyses land use and land cover (LULC) patterns and their associated impacts, flood vulnerability, and risk distribution. It also develops flood profiles or scenarios under varying climate change projections, coupled with the proposition of flood risk management and adaptation strategies. The results reveal that between 1991 and 2021, Lokoja experienced significant urban expansion, with a 21.0% increase in built-up areas. Conversely, vegetation cover exhibited contrasting dynamics: shrubs and grasslands declined by 0.3%, and dense vegetation decreased by 0.6%. Simultaneously, agricultural land expanded by 8.0%. In Niamey (1991–2021), water bodies expanded by 14.66%, and agricultural lands grew by 18%. This pattern suggests a shift in land use toward intensive cultivation, leading to enhanced water retention. Human settlements increased by 312.88%, highlighting extensive urban development and a surge in urbanisation. Similarly, bare lands expanded by 21%, indicating significant soil exposure, partly due to vegetation loss and extensive land clearing. The findings further indicate that Niamey Metropolis is vulnerable to varying degrees of flood risk, with 26% of low-lying areas classified as high risk and 31% of the city center classified as moderate risk. In contrast, the scenario for Lokoja revealed that 41% of the city is at very high flood risk, with high-risk areas concentrated along the river. Analysis of extreme rainfall indices showed varying trends; however, no statistically significant changes were observed overall, except for the years 2011 and 2003 in Boubon, Niamey City, and Lokoja, respectively. Breakpoints were identified based on the RX1DAY statistic, indicating a short cycle of two years. In this context, the findings also reveal that flood risk management and adaptation through preventive measures both structural and non-structural achieved a high overall mean score of 3.32 in Lokoja. Education, awareness, and institutional policies also scored a mean of 3.32, while infrastructure restoration scored 3.30. For Niamey, infrastructure (notably the use of dykes) recorded a mean score of 2.03, and wetland restoration scored 2.02. Based on the overall findings, it suffices to conclude that a surge in urbanisation and increased human settlement in recent times has significantly amplified flood risks in both cities; flood risk in both cities can be classified as moderate (32%) spatially, while in Lokoja, the city center has an overall moderate risk (15%), with low-risk zones in the north and very high-risk pockets in the south; extreme rainfall patterns exhibit sporadic breakpoints, signaling high vulnerability induced by climate change; and infrastructure-based interventions, wetland restoration, and education/awareness programs emerge as the most viable frameworks for flood risk management and adaptation strategies. However, to avoid overgeneralisation, it is imperative to recommend the implementation of holistic catchment management planning for the transboundary River Niger. In addition to structural interventions, the development of an integrated flood-drought early warning system for flood defense has become necessary, given the complexities of climate variability. Thus, to complement these efforts, future studies should focus on the reliability-based design of flood defenses, optimisation of flood defense strategies, habitat or nature-based rehabilitation, development of integrated flood damage mitigation plans, and the advancement of flood simulation and risk analysis frameworks..

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DEDICATION

To my family, expecialy my beloved mother, whose unwavering love, sacrifices and prayers have been the foundation of my success, whose support has made every challenge an opportunity, and to my friends, who have inspired, guided and supported me, your impact is engraved on every page of this work. To those who seek truth through science and build a better future through knowledge. To those who dare to dream, explore and push back the boundaries of knowledge.

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LIST OF ABBREVIATIONS

ABN/ NBA: Autorité du Bassin du Niger/ Niger River Authority

AGRHYMET: Centre Régional de Formation et d'Application en Agrométéorologie et Hydrologie Opérationnelle

AHP : Analytical Hierarchy Process

CAH: Cadre d'Action de Hyōgo

C.V: Coefficient de Variation

DEM: Digital Elevation Model

EEA: European Environment Agency

ETCCDI: Climate Change Detection and Indices Experts

FAO: Food and Agriculture Organisation of the United Nations / Organisation des Nations Unies pour l'Alimentation et l'Agriculture

GCMs: General Circulation Models

GEV: Generalised Extreme Value

GHG: Greenhouse Gases

GIEC: Groupe d'experts intergouvernemental sur l'évolution du climat

GIS: Geographic Information System

HEC-HMS: Hydrologic Modeling System

HEC-RAS: Hydrologic Engineering Centers River Analysis System

IPCC: Intergovernmental Panel on Climate Change

LULC: Land Use and Land Cover

NDVI: Normalized Difference Vegetation Index

NDWI: Normalised Difference Water Index

NIHSA: Nigerian Hydrological Services Agency

NIMET: Nigerian Meteorological Agency

NIWA: National Inland Waterways Authority

OCHA: United Nation Office for the Coordination of Humanitarian Affaires

SAI: Standardised Anomaly Index

SAP: Système d'Alerte Précoce

SDGs: Sustainable Development Goals

SQ-Mk: Sequential Mann-Kendall

SRTM: Shuttle Radar Topography Mission

SWAT: Soil and Water Assessment Tool

TWI: Topographic Wetness Index

UNFCCC: United Nation Framework Convention on Climate Change

UNEP: United Nation Environment Programme

USGS: United States Geological Survey

UNDP: United Nation Development Program

UNDRR: United Nations Office for Disaster Risk Reduction

WASCAL: West African Science Service Centre on Climate Change and Adaptation

Land Use

WGS: World Geodetic System

WMO: World Meteorological Organisation

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the Study

As humanity finds itself cornered by an unprecedented climate crisis, it is striking to observe that the future now hinges on the capacity to reverse the relentless trajectory of human-induced environmental disruption. Sweltering heatwaves, apocalyptic droughts, devastating cyclones, and unrelenting floods are multiplying, painting a dystopian landscape where nature, altered by humanity's excesses, turns against us (Barros *et al*., 2014; Brooks, 2013). This chilling reality transforms human survival into a challenge as urgent as it is daunting. The scientific community identifies climate change as a primary driver of this escalation, intensifying the frequency and severity of natural disasters, and deeming it one of the greatest global challenges to human development (IPCC, 2022). These phenomena profoundly damage ecosystems, livelihoods, and the environment, disproportionately affecting the world's poorest regions. Marginalised communities, though least responsible for greenhouse gas emissions, face acute threats to water resources and agriculture, particularly in climate-sensitive areas such as the Niger River Basin, where economies rely heavily on rain-fed farming (Paltsev *et al*., 2013 ; Serdeczny *et al*., 2016)

Moreover, the intensification of climate hazards exacerbates damage to infrastructure and natural systems, compounding economic and environmental losses (United Nations, 2009). Climate change, fuelled by anthropogenic greenhouse gas emissions, has heightened hydrological instability, manifesting in erratic rainfall patterns, prolonged droughts, and extreme precipitation. These disruptions disproportionately impact regions like sub-Saharan Africa, where rising temperatures (≈0.5°C cover 50–100 years) and altered rainfall cycles worsen water security and destabilise agricultural economies (Lebel, 2020; IPCC, 2022). Projections indicate a 1.5–2°C temperature rise by 2050, amplifying flood risks as intense rainfall overwhelms inadequate drainage systems, particularly in low-lying areas (Ofoegbu and Chirwa, 2019). The Niger River Basin exemplifies this crisis: sudden floods devastate crops, infrastructure, and livelihoods while fostering disease outbreaks (Valentin *et al*, 2016).

Flooding is a direct consequence of climate-linked hydrological extremes, highlighting the vulnerability of regions lacking resilient infrastructure and governance. According to Dilley *et al*., (2005), over a third of the global land is flood-prone, impacting roughly 82% of the world's population. The increased frequency and severity of flooding represent a critical manifestation of climate change, particularly in regions with low resilience, such as West Africa. Heavier rainfall, attributed to warmer atmospheric conditions, has triggered recurrent flash floods, destroying infrastructure, displacing populations, and sparking epidemics (Lebel, 2020). The Niger River Basin epitomises this crisis, where projected increases in extreme rainfall under climate scenarios (IPCC, 2022) threaten to worsen flooding in flat, poorly drained areas with inadequate infrastructure (Ofoegbu and Chirwa, 2019). These events underscore glaring climate injustice: marginalised communities, least responsible for emissions, bear the brunt of hydrological chaos.

The Lower Mekong Basin illustrates similar challenges, grappling with climate variability, rapid urbanisation, and human-induced hydrological shifts. This region, vital for 60 million people in Cambodia and Vietnam, faces escalating flood risks, as shown by Perera *et al*., (2017). Flood severity has surged alarmingly, with inundated areas projected to expand by 24–35 % by century's end. Catastrophic water volumes threaten the Mekong Delta's rice paddies a source of over 50% of Vietnam's national output while extreme rainfall and river discharge jeopardise local livelihoods. In Nepal's West Rapti

Basin, climate change has intensified monsoons, increasing flood frequency by 30% since 2000 (Perera *et al*., 2017). Rural households where 70 % are rely on subsistence farming, lose 40–60% of annual income due to crop destruction and livestock losses (UNDP, 2022).

Ideally, water resource management in the Congo River Basin would integrate sustainable planning accounting for climate impacts. Yet the region mirrors challenges seen elsewhere: climate change, urbanisation, and hydrological mismanagement. Increasing extreme rainfall raises flood risks, with a projected 94% rise in heavy precipitation days by 2071 to 2100 (RCP8.5 scenario), triggering devastating flash floods in northern and western areas (Karam *et al*., 2022).

Over the past two decades, sub-Saharan Africa particularly the Sahel has endured catastrophic floods exacerbated by West African monsoon variability and climate change. These events compound the vulnerability of populations already weakened by historic droughts (1970s–1980s) and recurrent food crises. In Niger, where floods are the most frequent disaster, they intensify multiple emergencies: between 2018–2020, floods claimed dozens of lives, destroyed thousands of homes, and affected over 360,000 people (OCHA, 2024). Niger River floods and runoff in fossil valleys (Dallols) threaten infrastructure, crops, and human security, with over one million recently impacted amid critical food insecurity.

In neighbouring Nigeria, floods driven by poor urban planning and waste management cause major socio-economic harm. Blocked drains and construction in floodplains have led to colossal losses, undermining sustainable development goals. Both countries urgently require integrated risk management: resilient infrastructure, land-use planning, and early-warning systems are vital to mitigate mounting disasters in a Sahel where climate extremes demand coordinated and sustainable responses.

The escalating frequency and intensity of Niger's floods aggravated by climate change and insufficient local risk data necessitate urgent, science-based solutions. This study addresses the absence of a risk-assessment framework tailored to Niger and Nigeria's socio-environmental context. While tools like Geographic Information Systeme (GIS) and remote sensing have proven effective globally for mapping flood hazards, prioritising risks, and designing mitigation strategies (Behanzin *et al.*, 2015 ; Al-Omari *et al.*, 2024),their application in the region remains limited. Existing hydrological models (Shim *et al.*, 2018; Jafarzadeh *et al.*, 2021;) and machine-learning techniques (Grimes *et al.*, 2003) offer unparalleled potential for predicting flood patterns and simulating climate impacts, yet these innovations remain underutilised in the Niger Basin.

This research pursues two objectives. Firstly, it seeks to bridge knowledge gaps by integrating spatial analysis, climate projections, and historical hydrological data such as declining Niger River flows since 1970 (Mahe *et al.*, 2011) and increased post-2000 seasonal rains flooding (Cassé, 2016) to map current and future flood risks. Secondly, it analyses how climate change amplifies flood dynamics in this transboundary basin, where studies on water-resource vulnerability remain scarce. Combining remote sensing, GIS, and climate modelling, the study will produce risk maps, identify vulnerability factors (such as urban encroachment on floodplains), and propose adaptation measures to enhance community resilience. The ultimate aim is to equip policymakers and communities with data-driven tools, bridging the gap between scientific innovation and on-ground action in a region where climate extremes outpace preparedness.

1.2 Statement of the Research Problem

Flooding is a major global challenge, the effects of which differ considerably from region to region due to geographical, socio-economic and institutional differences. Storm surges and rising sea levels threaten low-lying and coastal areas, while inland regions are affected by river overflows and intense rainfall. In West Africa, particularly in the River Niger basin, the situation is becoming increasingly serious. In an optimal scenario, flood risk management in the Niger River Basin would involve resilient communities and ecosystems capable of adapting to climatic extremes. These communities would benefit from robust institutional frameworks integrating climate-smart spatial planning, early warning systems, and adaptive infrastructure. Sustainable land-use practices such as reforestation, wetland preservation, and regulated urban expansion would enhance natural water absorption capacity, thereby reducing runoff and soil erosion (Descroix *et al*., 2013).

Transboundary cooperation among West African nations would harmonise flood risk policies, leveraging advanced hydrological models and localised climate projections to anticipate future scenarios under varying emission trajectories (Taylor *et al*., 2017 ; G.Panthou *et al*.,2018). Agricultural practices would prioritise soil conservation and flood-resistant crops, while urban development would adhere to zoning laws avoiding high-risk areas. Communities would access real-time flood risk data, participatory disaster preparedness programmes, and diversified livelihoods to reduce dependence on flood-vulnerable activities. Finally, ecosystems such as the Niger River's wetlands would be protected as natural flood buffers, ensuring biodiversity conservation and long-term socio-ecological resilience (Valentin *et al,* 2016; Massazza *et al*., 2021).

Floods in the Niger River Basin, particularly in urban centres, have intensified due to climate change and human activities. Rising temperatures have disrupted rainfall patterns, increasing flash floods and river overflows (G.Panthou *et al*., 2018). Rapid population growth and unregulated urbanisation have degraded natural barriers like wetlands and forests, while unsustainable farming practices exacerbate soil erosion and runoff (Descroix *et al*., 2013). Local governments lack resources for spatial planning and flood mitigation, often prioritising immediate needs such as healthcare and electrification over long-term risk reduction (Tiepolo and Braccio, 2020). Furthermore, the absence of data on local vulnerability patterns hampers the development of targeted adaptation strategies (Henstra *et al.*, 2019).

Floods, devastating phenomena with multidimensional impacts, now ravage lives, infrastructure, and entire ecosystems while undermining human security. Across sub-Saharan Africa, these disasters reached critical proportions in 2024, resulting in a human toll of 1,526 deaths, 1.4 million affected in Niger, and 1.3 million in Nigeria. By September 2024, floods had destroyed 16,375 homes and displaced 211,000 people, primarily in Niger's Zinder (80,534 victims), Maradi (28,847), and Agadez (31,222) regions (OCHA, 2024). The intensification of urban flooding stems from a combination of climatic disruptions and anthropogenic pressures. Rising temperatures have destabilised rainfall regimes, triggering more frequent flash floods and river overflows (G.Panthou *et al*., 2018). Concurrently, unplanned urbanisation and intensive agriculture have destroyed wetlands and forests, accelerating soil erosion and destructive runoff (Descroix *et al*., 2020a). This crisis is exacerbated by institutional failures: local governments, torn between competing priorities (such as healthcare and electrification), neglect of spatial planning and risk-reduction investments (Tiepolo and Braccio, 2020). Worse, the lack of precise data on local vulnerabilities, whether through updated risk maps or predictive models, impedes targeted adaptation strategies.

In summary, floods in the Niger Basin epitomise a vicious cycle where climatic hazards, demographic pressures, and political inertia mutually reinforce one another, leaving millions exposed to escalating risks.

Floods, a global challenge with region-specific dynamics pose a growing threat in West Africa's Niger River Basin, where geographical, socio-economic, and institutional vulnerabilities converge. These shifts, worsened by rapid urbanisation and unsustainable land-use practices such as deforestation, agricultural expansion, and soil-degrading farming, have paralysed natural hydrological buffers, amplifying runoff and erosion (Descroix *et al*., 2011). The consequences are catastrophic: cascading risks like soil loss and infrastructure damage exacerbate food insecurity and displacement, disproportionately affecting marginalised communities. Limited capacity for integrated spatial planning, alongside competing priorities in healthcare and electrification, sidelines proactive flood risk management. Local governments lack frameworks to reconcile urban growth with climate resilience, while fragmented data on vulnerability patterns obstruct targeted adaptation.

Previous research on the Niger Basin by Valentin *et al* (2016), Oguntunde *et al*., (2017), Amogu *et al.*, (2010) and Massazza *et al*., (2021) identified a concerning rise in floods, attributed to hydrological factors (increased runoff, extreme floods) and anthropogenic drivers (land-use changes, unplanned urbanisation). However, these studies exhibit gaps: while they demonstrate that heightened runoff in the Sahel is more linked to land-use changes than climatic variability (confirming the Sahelian Paradox), they neglect spatial analyses integrating climate, demographics, and infrastructure, downplay transboundary issues and socio-urban vulnerabilities, and inadequately explore future scenarios combining climatic and human pressures. Existing work focuses predominantly on hydrological and rainfall trends, overlooking the effects of hydraulic infrastructure and local adaptation strategies. These limitations restrict their utility for proactive risk management.

This study addresses these gaps by focusing on Niamey (Niger) and Lokoja (Nigeria), two flood-prone urban centres emblematic of the basin's challenges. Through a multidisciplinary lens, it analyses two decades of land-use changes, maps socio-spatial risk patterns, and models future flood scenarios under varying climate trajectories. By integrating community insights with geospatial tools, the research proposes context-specific adaptation strategies—such as wetland restoration and enhanced early warning systems—to bridge the gap between technical solutions and population needs. Ultimately, the findings aim to inform resilient urban planning, safeguard ecosystems, and prioritise equity in disaster risk reduction, offering a blueprint for sustainable adaptation in West Africa's evolving climate landscape.

1.3 Research Questions

The study is designed to address the following basic questions:

(i) How does the land use and land cover influence surface flood dynamics?

(ii) Which areas are most vulnerable to flood and what is the associated flood risk?

(iii) What is the trend in extreme rainfall based on historic rainfall events?

(iv) What can be the most effective integrated flood risk management strategies for mitigating current and projected flood risks in the River Niger basin, taking into account the stress factors involved?

1.4 Aim and Objectives

The study aim is to evaluate and model the effect of climate change on River Niger Flood dynamics and adaptation strategies in the Lokoja and the region of Niamey, West Africa focusing in flood risk analysis and mitigation.

Based on the aim, the specific objectives of the study are to:

(i) Analyse land use land cover pattern and their associated impacts;

(ii) Determine flood vulnerability and risk distribution;

(iii) Develop flood scenarios under varying climate change projections, and

(iv) Propose flood risk management or adaptation strategies.

1.5 Justification of the Study

In the not-too-distant future, it is expected that the results from this study would play a key role in improving flood management policies in the River Niger basin, particularly in Lokoja (Nigeria) and Niamey (Niger), where urban populations were facing increasing flood risks. Key players such as Nigeria's National Emergency Management Agency (NEMA), UNEP and the SAP (Système d'Alerte Précoce) could find the data to refine policies such as the ECOWAS Flood Risk Management Action Plan (2020-2025), ensuring that they are adapted to local vulnerabilities. In addition, the study could enable Niger and Nigeria to harmonise their cross-border water management policies, strengthening regional cooperation to reduce shared risks.

Improved Operational Performance: The results from this study are expected to enhance the operational effectiveness of flood management by addressing systemic challenges such as uncontrolled urban run-off and inadequate disaster response.

Contribution to the Body of Knowledge: This research filled critical gaps in the existing literature on flood risk in West Africa, particularly in the River Niger basin, where data on localised climate impacts and transboundary risk dynamics were scarce. It introduced innovative methodologies, combining geospatial analysis with socioeconomic vulnerability indicators, to produce comprehensive flood risk assessments. The study also deepened understanding of the interactions between land-use changes such as deforestation or urban expansion and climate variability, which exacerbate flooding. By projecting future flood scenarios under different climate models, it has contributed to global discussions on adaptation to climate change, providing a replicable framework for other vulnerable regions in Africa. In addition, the development of a transboundary risk index has provided a new tool for assessing shared vulnerabilities in international river basins, fostering interdisciplinary research in hydrology, climatology and human geography. These results have been disseminated through scientific journals, policy briefs and regional workshops, ensuring their impact in both academic debate and practical decision-making. The study is useful for developing strategic climate action in Niger and Nigeria to adapt to and mitigate the impacts of climate change. It will encourage research on flood impacts and adaptation options in climate change studies. In Addition, the Impact of climate change scenarios on the frequency of extreme flooding at the local levels could also be projected.

This study provided the necessary knowledge required by policymakers, river engineers and flood managers to practical manage river basins against increasing flood risks while ensuring sustainable development. The relevant stakeholders willing to contribute to the improvement of their environment will be able to use the results of this study to identify the most vulnerable areas settling, By extension, the finding could be useful for the appropriate use and management of water resources in the transboundary basin of the river Niger.

Future Research: While this study has provided important answers, it has also highlighted the need for further interdisciplinary research to strengthen long-term resilience. For example, more detailed socio-economic analyses would be needed to quantify the indirect impacts of flooding, such as disruption to livelihoods or mental health crises in displaced populations. Integrating high-resolution climate data with local hydrological models could improve the accuracy of flood forecasts, particularly in regions where data is scarce. In addition, the effectiveness of community-based adaptation strategies such as nature-based solutions (e.g. wetland restoration) or early warning systems would require long-term evaluation to identify best practices. Future studies should also explore the role of governance structures in flood management, examining how decentralised policies or cross-sectoral collaboration strengthen institutional capacity. Finally, it is essential to assess the equity implications of adaptation measures, to ensure that they do not further marginalise already vulnerable groups, such as low-income households or female-headed families.

Regional Collaboration and Implications: The study has fostered collaboration between regional and international stakeholders, strengthening collective efforts to address flood risks. By sharing harmonised databases with organisations such as ICPAC (IGAD Climate Prediction Centre) and AGRHYMET, it has contributed to the development of early warning systems adapted to West African climatic conditions. Sub-regional bodies, such as the SADC Drought Monitoring Centre and ACMAD, have used the results to align flood management strategies with broader climate resilience initiatives, such as drought preparedness programmes. At a local level, the research has enabled municipal governments and NGOs to design context-specific interventions, such as flood-resistant housing or rainwater harvesting systems. It has also strengthened the role of platforms such as the ECOWAS Commission in the exchange of knowledge between Niger and Nigeria, facilitating joint investment in infrastructure such as cross-border flood barriers. These collaborations have not only improved regional stability, but have also positioned West Africa as a proactive player in global discussions on adapting to climate change.

1.6 Description of Study Area

1.6.1 Location of the study area

This study was conducted in two cities particularly located along the River Niger: the city of Niamey (Niger) (Figure1.1) and Lokoja (Nigeria) (Figure 1.2) 1068 km apart in the far east of west Africa. Niamey represents the political and administrative capital of Niger with a total area of 240 km^2. Niamey is the most populous city in Niger and is located in the western part of the country between 3° 20'00 and 13°35'00 latitude North and 2°00'00 and 2°15'00 longitude East. It is located in the western part of the country and is surrounded by the Tillabéri region in the north and Dosso in the south. The town is located on the banks of the Niger River, which divides it into two parts: the right and left banks, and is subdivided into five municipalities. On the other hand, Lokoja is located near the confluence of the River Niger with its tributary, the River Benue. It is the main town of Kogi State in Nigeria (29,833 km²) with an area of 3180 km²; it is located between 7°45'0 to 7°53'30" North latitude and 6°43'0" to 6°51′30″ longitude. It is bordered in the north by Niger State and surrounded by Kabba and Koton Karfe, respectively to the west and east and south by Okehi and Adavi. Figure 1 and 2 show the study area in terms of the respective attributes mentioned.

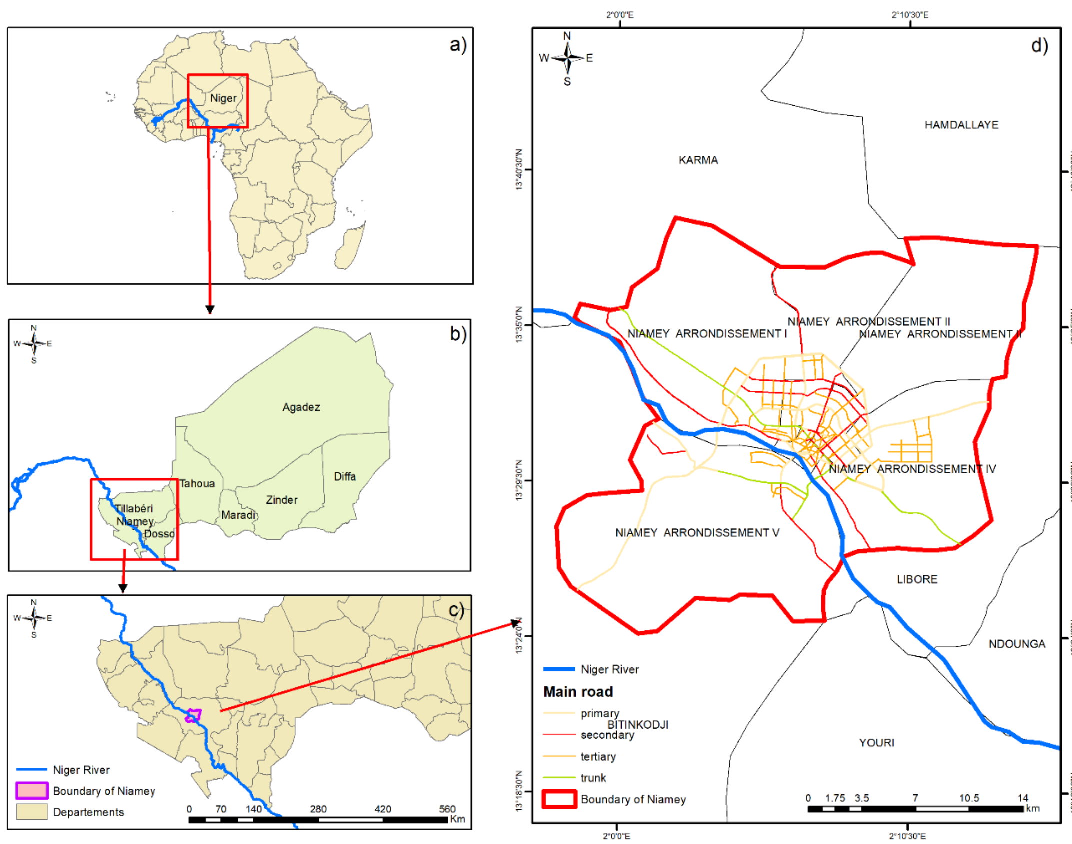

Figure 1.1: a) Localisation of Niger with the river Niger in the whole of Africa, b) Niger with the river Niger flowing through it, c) localisation of Niamey the study area in the western part of Niger, d) situation of Niamey

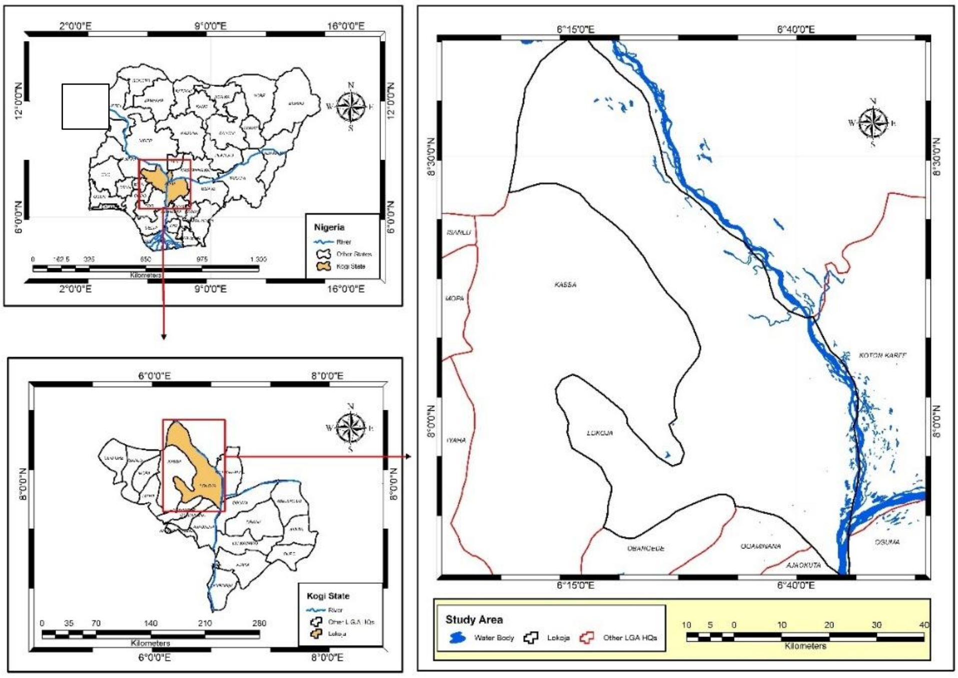

Figure 1.2: Situation of the Lokoja Study area, Localisation of Kogi state in Nigeria with the Niger river (a), Lokoja with the Niger river surrounding with the different Local government (b), location of Niamey the study area (c)

1.6.2 Description of River Niger

The longest river in West Africa, it is located at the heart of the latter and constitutes vital links with its tributaries between the nine riparian countries of its watershed including Benin (2%), Burkina Faso (4%), Cameroon (4%), Côte d'Ivoire (1%), Guinea (6%), Mali (26%), Niger (23%), Nigeria (33%), and Chad (1%) with the Benue River representing one of the most important tributaries of the river and originating in Cameroon on the Adamawa Plateau, joining the main river at Lokoja in Nigeria (ABN, 2020).

Niger River is ranked third on the continent (after the Nile and the Congo) in length (4,200 km), and 14th in the world, with a basin that covers an area of nearly (2,170,500 km2) of which 1,500,000 km2 of the basin is hydrologically active. As the 9th largest river system in the world, its watershed covers more than nine countries, and more than 80% of its surface area is distributed in three countries including Mali, Niger and Nigeria. The River Niger originates in the Guinean backbone in Fouta Djalon, an area of high plateaus with an average altitude of about 1,100 meters, before mixing with the Benue River and flowing into the Atlantic Ocean. From its source, water flows northeast into Mali, forming a vast floodplain in the rainy season, called the Inner Delta or Lake Basin. At the exit of the Inner Delta, the river describes a loop in Mali and Niger; then flows in a south-easterly direction to Nigeria where it meets the ocean (ABN, 2008).

The Niger Basin can be schematically divided into four (4) zones according to the more or less homogeneous physical and geographical characteristics, thus we find the Upper Niger, the Inner Niger Delta, the Middle Niger and the Lower Niger (Bank, 2006)

The climate of the Niger Basin is very heterogeneous and varies according to the ecosystem zones of West and Central Africa, from arid and seasonal climates to humid equatorial climates (FAO and IHE Delft, 2020). Almost the entire basin records between 500 and 1,000 mm/year of precipitation, with average annual precipitation ranging from zero in the Sahara to more than 3,000 mm/year near the coast. Indeed, rainfall in the Niger River basin is highly seasonal with a non-uniform pattern throughout the basin and generally reaches its maximum in August or September (Amogu *et al*., 2010). The hydrological year of the River Niger begins on June 1 of one year and ends on May 31 of the following year. Overall, the regime of the Niger River from one climatic zone to another, but the flows differ from one section of the main course of the Niger during the hydrological year. Thus, two floods are observed in the Middle Niger, the first called "local" beginning in September or October mainly due to the inflow of tributaries from the right bank (Niger, Burkina Faso and Benin) and the second called "Sudanian" appearing in December January or more in February whose maximum largely exceeds that of the previous flood depending on the year.

The flows are largely dependent on the flows coming from the Inner Delta and on the contributions of the various tributaries coming from the right bank, in particular, the Gorouol, the Dargol, the Sirba, the Diamangou, the Tapoa from Burkina Faso and, on the other hand, the Mékrou, the Alibori and the Sota which drain the North of Benin. The average inter-annual flow of the Niger at Niamey between 1971 and 2002 is only 704 m^3/s compared to 1062 m^3/s for the period 1929-1970, i.e. an overall decrease of about 34% (ABN, 2008). In the Lower Niger-Benue, maximum floods are observed thanks to the inflow from the Benue River in early September-October. Indeed, the Niger River receives several inflows from important tributaries in Nigeria, such as the Sokoto, Kaduna and especially the Benue, the main tributary whose watershed covers 450,000 km^2. The input at its confluence with the Niger at Lokoja is at least equivalent to the input of the river itself: at Makurdi before its confluence, its average interannual flow (1955-1995) is 2,920 m^3/s (ABN, 2008). Like the Upper Niger and the Middle Niger, the Lower Niger is experiencing a significant decrease in flow.

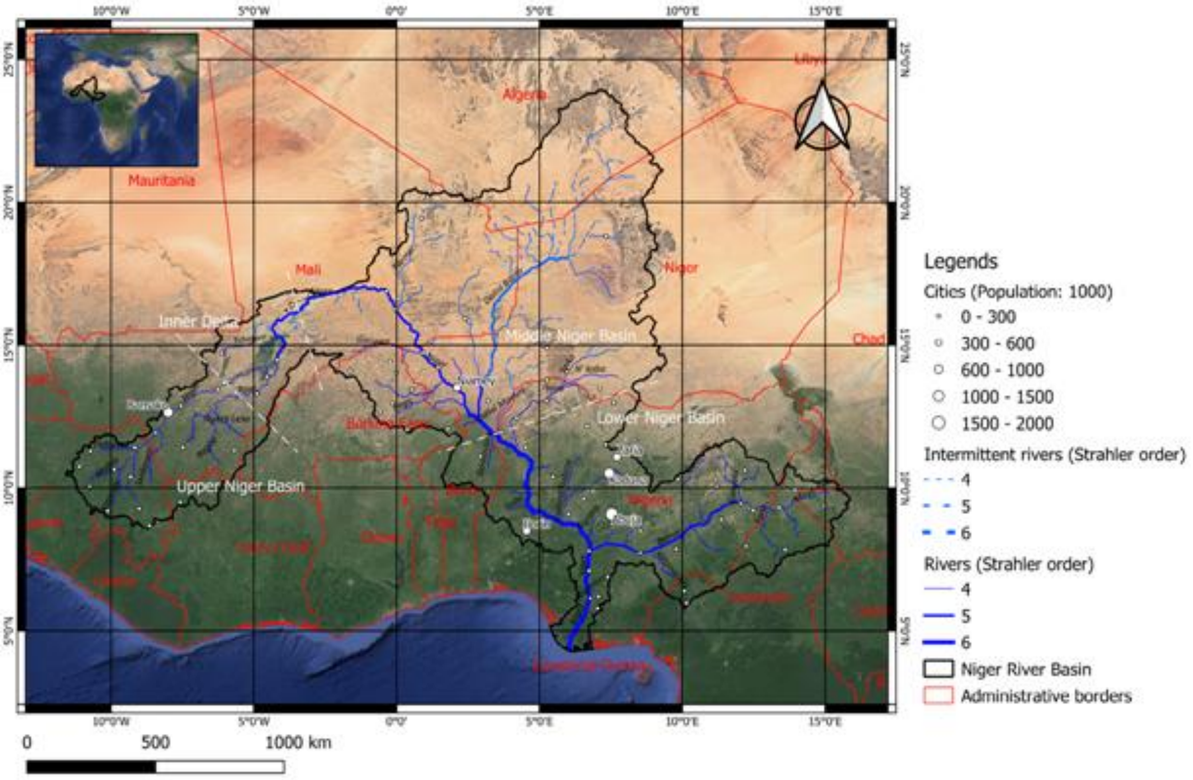

Figure 1.3: The River Niger Basin (Sources: River basin https://www.hydrosheds.org/products/hydrosheds)

1.6.3 Climate of the study area

Lokoja is characterised by a dry humid tropical climate, marked by two seasons, wet and dry. The rainy season starts in May until October, and the dry season starts from November to March (Aderoju *et al*., 2016). The dry season is marked by a dusty and cold environment due to the north-east winds that bring the Harmattan (Ayuba and Tijani, 2021), with average annual temperatures rarely below 30.7 °C and precipitation of about 1000 mm; the maximum temperature is generally observed in February and March (Oloyede, 2012). Niamey on the other hand, has a Sahel-Sudanese climate, which is characterised by high temperatures and low and irregular rainfall, which in most cases occurs as thunderstorms. Two seasons are distinct in the year a long dry season of seven to eight months, where the Harmattan dominates the wind that blows during this period. It experiences hot and dry wind loaded with dust and grain of sand which is directed north-north-east to south-south-west. It is during this period that the maximum temperature is observed; usually between April and May. It represents the hottest period of the year with temperatures above 40 °C. A short rainy season or winter that can last between four and five months, with the monsoon, a humid wind that dominates is characterised by the rainy season with an average of 550 mm of rain (Hamadou, 2010); precisely, strong rainfall with spatio-temporal variability. This period constitutes for the population of Niamey real torment between floods and diseases that follow one another. The city is located in an area with strong radiation; consequently, the temperature always vacillates between 30 and 40 ˚C during the dry season and temperatures below 30˚C during the winter months.

1.6.4 Relief and Soil

Lokoja is a low to moderate relief area characterised by the presence of some hills with an altitude varying between 30 and 400 m (Ayuba and Tijani, 2021) The soils are made up of a sandy texture covered by an accumulation of clay with a weak structure (Ibrahim *et al*., 2015). Alluvial soils are found along the river valleys, sandy, with adjacent lateritic soils that are deeply weathered, grey or reddish, sticky, and permeable (Lanza, 2012). In comparison, Niamey is located in the West African craton and the Ullimenden basin with periods of marine transgressions and continental episodes which shows the difference in geological materials on either side of the river. The region is practically made up of rocks from the Continental Terminal (Yayé Saidou, 2014). The basement rocks are mainly found in the bed of the Niger River where they are locally covered by alluvial deposits from 1 to 7 m thick and on the ledges. The soil of the city of Niamey is built on a lateritic plateau on the left bank with tropical ferruginous soils with little leaching which overhangs the river at an average altitude of 220 m. The right bank is an alluvial plain with an average altitude of 185 m, more vulnerable to flooding than the other bank. The plateau is made up of a series of sandstone banks of the Continental Terminal that rest in the basement (Hassane, 2011).

1.6.5 Water resources of the study area

The study area has both surface and groundwater resources to meet the different needs of the population; the river plays a very important economic and ecological role in the region.

(i) Surface water of the study area

The River Niger and its tributaries represent the main watercourse in the study area, which is permanent throughout the year. In Niamey, the river flows in an NW-SE direction through the city throughout the year, dividing the city in two and providing water for the population and their activities. Recently, silting due to the contribution of sand increased, and the river stopped flowing during the drought of 1985. In the contrary, high water threatens the riverside residents who have occupied its former branches. The average flow at the Niamey station during the 2019-2020 hydrological year was 1060 m^3/s, corresponding to a flow volume of about 33.43 billion m^3. The station recorded a maximum daily flow of 2677 m^3/s on 1st September, 2019 and a minimum daily flow of 62 m^3/s on 30th May, 2020 (ABN, 2020). The minimum flow remained above the low flow alert threshold of 10 m^3/s. During the year, the river flow in Niamey is characterised by two up swells; The first one is during the rainy season in June-July and reaches its maximum in August-September and is called the local flood, coming from the flows of the river tributaries upstream on the right bank whereas the second rise called the Malian flood, reaches its peak in December and January due to the different inflows from the upper basin of the river (Nigerian Hydrological Services Agency, 2024). The different tributaries of the River Niger, ponds, and Doris contribute to the reinforcement of the city's hydrograph during the winter, the Kori that cross the city in its north-western part also remain a scourge for the residents. The population of this place is also prone to flooding due to the rise in the water table.

In like manner, Lokoja is very rich in surface water. Due to its position, it benefits from being at the confluence of the two Rivers Benue and Niger, which are joined in places with which the population uses it for farming and fishing activities. The average flow at the Lokoja station during the 2019-2020 hydrological year was 8751 m^3/s, which corresponds to an average flow of 275.97 billion m3. Lokoja station. Lokoja recorded a maximum daily flow of 24,800 m^3/s on 5 November 2019 and a minimum daily flow of 1,594 m3/s recorded on 7 May 2020.

(ii) Groundwater of the study area

Groundwater in the Lokoja region is located in the altered bedrock and is fed by rainfall and river inflow (Ojoina, 2014). The groundwater of the phreatic aquifer is constituted by the alluvium and is fed by rainfall or flood waters of the Niger-Benue river system (Offodile, 2002), while the deep aquifer waters originate from the basement and constitute a low permeability aquifer due to their porosity resulting from fracturing (Oyinloye and Ademilua, 2005). Due to the presence of river water, the underground resources do not meet the daily needs of the population of Niamey, they are distributed in deep and phreatic aquifers. According to N. Bechler-Carmaux and Mietton, (2000) depending on the topography, two aquifers can be distinguished. On the left bank, there is the water table of the plateau, which is perched about twenty meters above the level of the river and helps to supply the wells on the left bank. The water table located on the plateau of the left bank is fed by the formations of the continental aquifer (CT3) (Hassane, 2011). Nowadays, flooding by rising groundwater is observed in certain neighbourhoods on the left bank of

Niamey, such as the Dar-es-Salam neighbourhood, which causes damage to people and infrastructure (especially in the middle bed of the Kori Gounti Yena).

1.6.6 Vegetation of the study area

Due to its geographical position, Niamey is a city that seems to be an oasis, a space where trees offer the inhabitants a fantastic breezing space in an environment as hot as Niamey. It is common to find houses in Niamey without trees, as the country celebrates the festival of trees on 3 August each year. The city is located in the Sahelian strip, its vegetation is characterised by the tree savannah, of which in the valley of the river species such as acacia nicolittica, sieberiarana, palms, and conifers (Borassus flabellifer) can be found. The herbaceous zone is green belt majorly of Echinochloa stagnima and Aristida mutability. On the plateau, the vegetation is painted by species like Ziziphus jujuba, Combretum micranthum, Balanites aegyptiaca, and Faidherbia albida (Gao) (Hassane, 2011).

The vegetation of the city is mainly green belt majorly of eucalyptus and neem (azadirachta Indica a. juss.) extract, with domestic fruit tree plantations, and gardens along the river (Abdourahamane *et al*., 2016). The most important vegetation in the city is provided by the green belt function initiated in the 1960s on an area of 2500 ha. This belt serves as a screen for the city against the north and northeast winds. Apart from this green belt, which no longer plays its intended role effectively, there are other green spaces located in certain neighbourhoods where the shade of the trees serves as informal workplaces for many city dwellers or also as places for recreation. The vegetation pattern in Lokoja is of Guinea savannah with tall grasses with some trees that can reach up to about six meters. These trees include carob, shea, oilseed, and isoberlinia, with grasses that can reach up to about three meters like Andropogon tectorum, Bambusa vulgarise, Cynodon dactylon (Oloyede, 2012).

1.6.7 Historical of the settlement of the study area

The Sahelian cities are by nature confronted with a climatic weakness, whose availability of water determines in many cases the settlement of populations. One of the most striking features of urbanisation in Africa, particularly in sub-Saharan Africa, is the rapid growth of the population, although the conditions for this growth are necessarily met. The strong growth of these cities is in large part due to the phenomenon of displacement to the cities of poor rural people escaping the misery of their land. On the other hand, once in the city, they often settle in areas that are not very or not at all favourable to urbanisation, which has an impact on all urban management and also because of the numerous risks, including those related to flooding. (World Bank, 2021)

Niamey was chosen by the presence of the River Niger. Among the cities of Niger, Niamey is the only one to have experienced rapid growth since the colonial penetration in the early twentieth century (Nasser and Adam, 2024). From a small village on the river to the country's capital, a third-world city that hosts more than 39% of Niger's urban population (Salamatou *et al*., 2015), the city became the country's capital in 1926. Niamey has developed thanks to the rapid increase in population caused by the rural exodus; indeed, the country has one of the highest growth rates in the world (3.8% per year) and a high fertility rate (including 6 children per woman) (African Development Bank, 2020). However, the proliferation of the city and the basic infrastructure implemented by the government are poorly coordinated, resulting in poor living conditions for the population. Indeed, since independence, the urban planning process has been based on the 1964 and 1967 urban plans, the 1984 urban master plan and the Niamey reference urban plan, which was approved in 2010. On the other hand, Lokoja is one of the cities that is characterised by strong growth, not only because of its geographical position but also advantageous, especially because the populations located around the riverbanks often benefit from the fertility of the soil, contrary to what happens in other regions. Lokoja is a city at the confluence of the Niger and Benue rivers and has left an indisputable mark on the history of colonial and post-colonial Nigeria because of the enviable role it played in the British administration of Nigeria. In addition, Lokoja is known to be an important commercial settlement, remains the capital of the British protectorate of northern Nigeria and a convenient administrative city for the British colonial government after the merger of northern and southern Nigeria in 1914. The city later became a cosmopolitan settlement populated mainly by different ethnic groups from the middle belt and Hausa of northern Nigeria. Lokoja is a multi-ethnic town that owes its development to its role in pre-colonial and colonial trade in Nigeria, and because of its position at the confluence, it was a site used by people as a transit station on the way to the north or south, east or west of Nigeria, some coming to trade, others coming to seek employment opportunities. The city has contributed a lot to the development of the city (Obiahu, 2014)

1.6.8 Socio-economic activities in the study area

The city of Niamey has developed along the Niger River, which is the main source of water supply for the city. The city has grown on the right bank of the river where it has 4 main towns, due to the demographic growth and socio-economic activities, the city has expanded to the other side of the river, an area more vulnerable than the left bank to flooding. The city is a hub of different ethnic groups (eight ethnic groups), Niamey's population has grown significantly over the years, from 242,973 in 1977 to 1,364,268 in 2022 (world population review WPR, 2022), making it the most populous city in the country; it is experiencing accelerated population growth. The city is one of the main economic centres of the country, with agriculture being the most important activity of the population.

Similarly, the main activity of the people in Lokoja is farming with fishing the major activity of the majority of the inhabitants. The town is a producer of cassava, yam, rice, maize, and many other crops. The population of Lokoja was estimated in 1977 to be 37,395 with a projected population of 790,742 in 2022 (world population review WPR, 2022). The town is home to many people from several Nigerian ethnic groups, of which the Igalas, Hausa, Ebira, Yoruba, Igbo, Tiv, and Idoma are the most important. The Yorubas have been the dominant ethnic group since the time the town was part of the ancient Kwara State, while the Igalas have also become a dominant group in the present-day (Olatunde and Adejoh, 2017).

1.7 Scope of the study

This study focuses on the cities of Lokoja and Niamey, two of the largest urban centres located along the River Niger in their respective countries. Niamey, the capital of Niger and Lokoja the federal capital of Kogi state, both cities are located close to the River Niger, making them highly vulnerable to flood-related impacts. The research specifically examines the effects of climate change in the context of extreme events (flooding) in these study areas, in particular their vulnerability to frequent and severe flooding, which has become increasingly frequent in recent years.

The study covers 30 years, from 1991 to 2021, in line with the standard climate study framework recommended by the World Meteorological Organisation (WMO, (2011) and the IPCC (2007). This period allows an in-depth analysis of climate variability, particularly in West Africa, where an increase in rainfall and severe flooding have been observed since the early 1990s, following prolonged droughts. By examining this period, it is possible to identify trends, assess the impacts of flooding and develop informed adaptation strategies.

In terms of the scope of activities, the research is limited to assessing the impact of climate change on urban areas. The research is limited to assessing the impact of climate change on flooding, using future precipitation projections from the IPCC AR6 report (IPCC, 2021). Flood risk modelling was carried out according to differences in precipitation categories. A baseline scenario based on current conditions (2020) will also be included to provide a comparative basis for assessing future flood risk and to inform decision-making processes.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Conceptual Framework

Climate change remains a major issue that transcends disciplines and challenges researchers and decision-makers alike. It is one of the most compelling issues of our time. Described as a lasting and significant change in climatic parameters such as temperature, precipitation and extreme events, it is closely linked to the increase in greenhouse gas (GHG) concentrations in the atmosphere.

According to the Intergovernmental Panel on Climate Change (IPCC), climate refers to the average weather conditions over time, encompassing meteorological parameters such as temperature, precipitation, and wind, which characterise the environment of a specific region during a defined period. The World Meteorological Organisation (WMO) recommends a 30-year timeframe to establish statistical baselines for climatic characteristics. As determined by the IPCC, climate change involves shifts in the climate system driven by alterations in the mean and/or variability of its properties, whether due to natural processes or human activities over extended periods (IPCC, 2007). This broad definition incorporates both natural and anthropogenic factors. However, the United Nations Framework Convention on Climate Change (UNFCCC) explicitly attributes climate change to human activities particularly those altering atmospheric composition thereby framing it as a direct consequence of industrialisation, deforestation, and fossil fuel use (United Nations, 1992). This distinction is critical for policymaking, as it holds human actors accountable for mitigating flood risks through measures like watershed management and sustainable urban planning. Yet, by excluding natural drivers, the UNFCCC's definition risks overlooking localised dynamics, such as seasonal rainfall variability in West Africa, which, though natural, are exacerbated by global warming. Climate change is unequivocal and ranks among the most pressing challenges for scientists and policymakers (Barros *et al*., 2014). In West Africa, its impacts are pronounced. The AGRHYMET Regional Centre 2010) reports that temperatures in the region have risen faster than the global average, with increases of 0.6–0.7°C observed since the mid-20th century. The Sahelian zone of Niger, including Tillabéry, exemplifies this trend: since the 1980s, temperatures have risen sharply and persistently. Studies analysing climatic and hydrological time series (Amogu *et al*., 2010; Sighomnou *et al.*, 2013; Nka *et al*., 2015; Descroix *et al.*, 2018) highlight the consequences, such as extreme rainfall events triggering flash floods in Niamey. West Africa's vulnerability stems from its arid landscapes, reliance on rain-fed agriculture, and exposure to climatic extremes like droughts and storms (AGRHYMET, 2010).

Climate change manifests in West Africa through increased rainfall variability, soil erosion, desertification, and food insecurity. The AGRHYMET (2010) warns that the region could warm by 3–6°C by 2100, intensifying hydrological disruptions. For instance, Sighomnou *et al*. (2013) link extreme rainfall in the Niger River Basin to recurrent flooding. Similarly, Lebel (2020) and Massazza *et al.* (2021) attribute rising flood frequency in Niamey to climate-driven precipitation extremes. In Nigeria, catastrophic floods along the Niger and Benue rivers such as those documented in Lokoja by Buba *et al*., 2021) have devastated communities and ecosystems. (Odiana, 2022) underscores how these events disproportionately affect riverine areas, displacing populations and damaging infrastructure.

The IPCC and UNFCCC definitions diverge in their attribution of climate drivers. While the IPCC acknowledges natural factors like solar activity and volcanic eruptions, the UNFCCC focuses on human-induced atmospheric changes. This dichotomy is pivotal for understanding climate impacts on water resources and extreme events. For example, global warming amplifies the hydrological cycle, altering river flow patterns and exacerbating water scarcity a critical concern for arid regions like the Sahel. By prioritising anthropogenic causes, the UNFCCC framework drives accountability but may underplay synergies between natural variability and human influence, particularly in regions where both forces interact.

Disaster is a brutal and devastating event that causes a significant disruption in the functioning of a society, resulting in loss of life, ecosystems, property and economic assets. According to the United Nations Office for Disaster Risk Reduction (UNDRR), a disaster results from a combination of hazards, vulnerability and insufficient capacity to reduce potential negative consequences (Géoconfluences, 2020). Disasters can be grouped into two main groups: natural disasters, such as earthquakes and floods, storms, and drought, and man-made disasters, such as industrial accidents or those resulting from conflict. These events often exceed the response capacity of the affected community, requiring external assistance to mitigate the effects. For example, the earthquake in Haiti in 2010 highlighted the country's vulnerability to natural disasters and the importance of adequate preparation and rapid response to mitigate the impact (Godin, 2009).

Floods are natural phenomena that occur when normally dry land is temporarily or permanently submerged by water. This phenomenon can result from various hydrometeorological and anthropogenic factors, requiring multidimensional approaches for comprehensive understanding. From a hydrological perspective, Farid *et al.*, (2023) describe floods as the product of extreme rainfall, river overflow, dam breaches, or any situation where land cannot absorb or channel water effectively. While this definition is useful for analysing the physical mechanisms of flooding, it remains limited as it does not account for socio-economic and environmental impacts, nor the spatial and temporal variability of flood events. It fails to address flood impacts, vulnerability, or exposure. Though valuable for understanding causes, it lacks integration of socio-economic and environmental dimensions essential for holistic flood risk analysis.

Expanding this perspective, the environmental approach by Fiorillo *et al.*, (2018) frames floods as disruptions to the water cycle, causing soil erosion, sediment deposition, and biodiversity loss. This view emphasises floodplain dynamics and river morphology but overlooks human activities like urbanisation and deforestation, which exacerbate flood frequency and intensity.

Beyond hydrological and environmental processes, the climate perspective proposed by the Intergovernmental Panel on Climate Change (IPCC, 2014) integrates floods as climate-related risks driven by extreme precipitation, leading to infrastructure damage, loss of life, and socio-economic disruption. This definition incorporates flood impacts, making it relevant for disaster risk management and policy planning. However, while suited for adaptation and emergency response strategies, it focuses primarily on extreme events, neglecting smaller-scale floods that gradually increase territorial vulnerability.

To reconcile these approaches, the European Environment Agency (EEA, 2016) offers an integrated definition, viewing floods as environmental risks shaped by natural and human factors. Here, flooding is seen as water inundating land and affecting populations, ecosystems, and economies. This holistic approach highlights interactions between natural processes and human activities, making it ideal for integrated flood risk management. It is particularly suited for studies examining biophysical and socio-economic aspects of floods.

Thus, considering these dimensions, floods can be defined as hydrometeorological events arising from natural and human causes, resulting in temporary or permanent inundation of dry land. They manifest in various forms (pluvial, fluvial, coastal, and groundwater) and pose significant risks to populations, infrastructure, and ecosystems. Their frequency and intensity are influenced by climate variability, land-use changes, and socio-economic conditions. This comprehensive definition integrates hydrology, geomorphology, disaster management, and socio-environmental dynamics, enabling effective risk assessment and mitigation strategies.

The characterisation of flood typologies and their impacts in the context of climate change is an important step towards a better understanding and management of risk phenomena. Flood events can be classified into various categories based on their causative factors, dynamics and the consequences related. The main flood type and their characteristics in the face of climate change are as follows:

(i) Pluvial or urban flooding: It mostly results from intense rainfall events overwhelming urban drainage. It occurs particularly in urban areas, climate change favorise the increase of the events, increasing the risk of flash floods (Internal Displacement Monitoring Centree IDMC, 2019)

(ii) Fluvial flood event or riverine flooding: Due to the overflowing of rivers after heavy rain. Increased rainfall intensity and higher flow variability raise the probability of riverine flooding, particularly in transboundary rivers like the Niger and Volta

(iii) Groundwater flooding: When the water table rises to the surface due to a prolonged rainfall and raising groundwater levels above the surface

The characterisation of flood of the long-term impacts of flooding under climate change scenarios involves understanding the changing climatic conditions that influence the frequency and intensity of floods, as well as the associated socio-economic consequences. According to the work of Arnell and Gosling, (2016), by

2050, the current 100-year flood could occur at least twice as often over 40% of the entire globe, putting around 450 million people and 430,000 km² of farmland at increased risk of flooding. The relationship between rising temperatures and extreme precipitation is well recognised; for every degree Celsius of warming, atmospheric humidity increases by around 6-7%, leading to more intense precipitation3. This phenomenon is particularly pronounced in regions where flooding is mainly due to intense precipitation rather than snowmelt or other hydrological processes (Maimone et *al*., 2023). The socio-economic consequences of increased flooding under climate change scenarios are significant. The risk of displacement due to flooding is expected to increase considerably; a temperature rise of between 1.5°C and 2°C could lead to a 50% increase in the risks that cause displacement. Urban areas are particularly at risk due to their increased density in flood-prone areas and the alteration of natural water flows by urban development

In addition, the economic costs associated with flooding are also set to rise dramatically. Studies have shown that the global risk of flooding could increase by around 187% by 2050 if no adaptation measures are taken (Arnell and Gosling, 2016). In addition, the uncertainty of climate model projections makes it more difficult to characterise the future impacts of flooding. Different models can produce varying predictions of precipitation patterns and hydrological responses, making it essential to consider a range of scenarios when planning for future flood risk. The different plateaus from I to IV represent the manifestations of different typologies of flooding in various location.

Plate I: The town of Niamey is under water after heavy rain, Niger, 27 August 2020. Source (https://www.rfi.fr/fr/afrique/20200908-niger-niamey-sous-les-eaux-apr%C3%A8s-pluies-diluviennes)

Plate II: Homeless in Niger Floods Source: (https://theglobepost.com/2020/09/10/niger-floods/)

Plate III: Retention wall to prevent the Niger river overflowing its banks at Lokoja, source (field work, August 23, 2023)

Plate IV: Alleyway flooded by overflowing river source (August 23, 2024) (*https://newscentral.africa/severe-flooding-cripples-nigers-capital-niamey/*)

Plate V: A house flooded by the rising water table in the Sonuci district (Niamey, July 3, 2020) source: *https://www.studiokalangou.org/13062-niamey-inondations-quartiers-sonuci*

2.2 Theoretical Framework

2.2.1 The Greenhouse effect theory

The greenhouse effect theory, developed by the IPCC and researchers such as Bast, (2010), posits that human emissions of greenhouse gases (GHGs) such as CO_2, methane, and nitrous oxide amplify global warming by trapping heat in the atmosphere. Since the pre-industrial era, these emissions, stemming from fossil fuel combustion and deforestation, have increased CO_2 concentrations by 50%, leading to a global temperature rise of +1.1°C (Lebel, 2020). This warming disrupts the hydrological cycle: a warmer atmosphere retains more moisture, intensifying rainfall and consequently flood risks. In

West Africa, this manifests as more violent yet erratic rainy seasons, alternating with prolonged droughts, as observed in Niamey (Niger) and Lokoja (Nigeria).

However, the attribution of extreme events (such as floods) to global warming alone is contested because of the decisive influence of local factors. Deforestation in itself reduces the capacity of soils to absorb water, aggravating floods independently of rainfall. This phenomenon illustrates how unplanned urbanisation and poor land management amplify risks, even without climate variation (de la Paix *et al*., 2013; Descroix Luc *et al*., 2020b). Climate models also have difficulty predicting precise regional impacts, as in West Africa, where droughts and floods coexist ('Sahelian paradox'). These uncertainties reflect technical limitations: the interactions between warming, ocean-atmosphere dynamics and vegetation cover are still poorly modelled (IPCC, 2021).

In addition, critics point to neglecting socio-economic inequalities, a key factor in vulnerability to disasters. In the city of Niamey (Niger), informal settlements are located in flood-prone areas, with no adaptation infrastructure. According to Stephane *et al.*,(2017), the poorest populations are likely to die in floods, revealing that disasters are as much the result of structural injustices as of climatic hazards. To add to this, an integrated approach is needed to move beyond this binary debate. Combining climate science and socio-political analysis would make it possible to identify the multiple responsibilities (global warming, local management, colonial legacies) and prioritise appropriate solutions. For example, linking reforestation to inclusive urban reforms, as advocated in the Sendai Framework (Becker *et al.*, 2015), would reduce both risks and inequalities. This interdisciplinary perspective avoids simplifications and strengthens community resilience (Wigley *et al*., 2018)

For this study, the greenhouse effect theory is fundamental to this study, as it provides the scientific basis for understanding how anthropogenic greenhouse gas (GHG) emissions amplify climate extremes, including the intensification of rainfall events observed in West Africa. For example, the theory aligns directly with the study's conclusion that extreme rainfall events such as the 120 mm recorded in Niamey in 2020 are consistent with climate model projections of a warmer atmosphere containing more moisture (IPCC, 2021). This moisture-laden atmosphere increases the likelihood of short, heavy downpours, submerging obsolete drainage systems and triggering flooding. The theory's relevance is further underlined by its ability to explain indirect climatic impacts, such as prolonged droughts in the Sahel, which reduce agricultural yields, displace male populations (in search of livelihoods elsewhere) and increase the risk of flooding.

However, the study also reveals the limitations of the theory when taken in isolation. For example, in Lokoja, the severity of flooding is less related to rainfall intensity than to poor urban planning (e.g. building on flood plains) and the degradation of catchment areas. These results suggest that while the greenhouse effect theory explains climate change (increased GHG emissions, more intense rainfall), it does not fully take into account the local vulnerabilities that determine the outcome of disasters.

The greenhouse effect theory remains of key importance to the study, as it anchors the analysis in a climate mechanism validated on a global scale. For example, while renewable energy (mitigation) addresses GHG-induced trends, dykes and community warning systems (adaptation) address local vulnerabilities; a dual approach is advocated by the Sendai framework (UNDRR, 2015). This research confirms the role of global warming in intensifying West African floods while emphasising the need for a holistic approach. Integrating human and structural factors such as unregulated urbanisation, watershed management, and drainage infrastructure enables a more comprehensive risk assessment. Such a perspective is vital for designing flood management policies that are both resilient and equitable. Thus, the study not only establishes a climate-flood link but offers an in-depth analysis of environmental and socio-economic dynamics, providing recommendations tailored to

2.2.2 Climate Risk Assessment

The concept of climate risk assessment developed by the Intergovernmental Panel on Climate Change (IPCC, 2014) forms the theoretical foundation of this study. This framework, refined by scientists such as Sharma and Ravindranath, (2019), defines climate risk as the product of three interdependent components: climate hazard, exposure of populations and ecosystems, and vulnerability of socio-economic and environmental systems. Widely used in natural disaster research, this approach provides a structured analytical lens to understand how phenomena like floods arise from interactions between physical and human factors.

According to the IPCC, hazard refers to the likelihood and intensity of extreme climate events, such as river floods or exceptional rainfall. Exposure denotes the presence of assets (homes, infrastructure, populations) in geographical areas susceptible to these hazards. Finally, vulnerability encompasses two dimensions: the sensitivity of systems to damage (e.g., fragile construction materials) and their adaptive capacity technical, financial, or institutional resources to mitigate impacts. Risk is thus formulated as an equation 2.1:

$$\text{Risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability} \tag{2.1}$$

This model identifies levers for risk reduction, whether through limiting exposure (via zoning policies) or enhancing resilience (via adapted infrastructure).

However, the theory faces academic criticism. Its static and linear approach overlooks temporal dynamics and feedback loops. For example, urbanisation increases flood exposure but can also intensify hazards by reducing water infiltration zones, an effect rarely integrated into models (Descroix *et al*., 2020a). The IPCC is accused of underestimating political and cultural factors. In West Africa, issues like corruption in infrastructure management or the exclusion of local communities from planning decisions directly shape vulnerability but are not explicitly modelled (Adger *et al*., 2018). The IPCC's climate risk assessment concept is based on an integrated framework that evaluates climate risks by taking into account three interdependent elements: hazards, exposure and vulnerability. Hazards are climate-related physical events, such as extreme precipitation, droughts or sea-level rise. Exposure takes into account the presence of people, infrastructure and ecosystems in areas where hazards occur. Vulnerability reflects the susceptibility of exposed elements to damage, determined by factors such as socio-economic conditions, governance and adaptive capacity. This framework recognises that climate risk is not only caused by natural events but is also shaped by human decisions and policies. In addition, the model incorporates emissions and land-use change as key drivers of climate risk, focusing on how human activities contribute to the severity and frequency of extreme weather events. Socio-economic processes, including governance, adaptation strategies and economic development pathways, further influence risk outcomes by increasing resilience or exacerbating vulnerabilities. Figure 2.1 provides the schematic for analysis the subject within the climate change.

A major critique of the IPCC risk framework is that it artificially separates hazard, exposure, and vulnerability, when in reality, these elements are deeply interconnected. Some scholars argue that vulnerability is not just a passive condition but is actively shaped by historical, economic, and political processes that also determine exposure. For example, marginalised communities are often forced to settle in high-risk areas due to economic constraints, meaning that exposure itself is a function of vulnerability rather than a separate factor O'Brien *et al.*, (2007) highlight that vulnerability is dynamic and continuously shaped by social and political changes, making it difficult to categorise separately from exposure. By treating vulnerability as an independent variable, the framework may overlook the root causes of climate risk, such as unequal land distribution, discriminatory policies, and systemic poverty.

The IPCC's climate risk assessment framework is essential for understanding climate-related risks by integrating hazards, exposure and vulnerability. This holistic approach allows researchers and policymakers to assess how different factors contribute to climate risks, enabling the design of targeted adaptation and mitigation strategies. By identifying vulnerable populations and high-risk regions, the framework promotes efficient allocation of resources and informs climate resilience planning. It also highlights the interaction between natural climate variability and socio-economic processes such as governance, development pathways and land-use change. In this way, climate risk assessments take into account both immediate hazards and long-term vulnerabilities, making them more effective for policy-making.

The framework is widely adopted in scientific research, IPCC reports and climate risk assessments, making it a global standard for climate policy formulation. It plays a key role in disaster risk reduction (DRR), aligning with the Sendai framework by emphasising proactive risk management rather than reactive responses. This is particularly relevant in regions such as Niamey and Lokoja, where extreme rainfall variability influences flood risk. The ability to translate scientific climate data into practical policy measures enables governments and organisations to develop early warning systems, flood zoning strategies and community resilience programmes to effectively mitigate the effects of climate.

Concretely, the study posits those informal settlements in Niamey (e.g., Lamordé) and Lokoja (such as Gadumo) characterised by high exposure (proximity to the river), heightened vulnerability (informal housing, lack of sewers), and increasing hazard (rainfall variability) will face the most severe impacts. However, if analysis reveals exceptions such as high-hazard zones with low damage due to community-led water management practices this would underscore the need to integrate local resilience as a fourth risk dimension, a proposal advocated by researchers like.

This research both validates and enriches the IPCC framework. It confirms its applicability in West African contexts while exposing gaps, particularly the lack of explicit mechanisms to address political inequalities or local knowledge. The findings could inform debates on evolving climate risk models and provide policymakers in Niamey and Lokoja with spatial risk maps and targeted recommendations for example, prioritising drain rehabilitation in neighbourhoods where hazard, exposure, and vulnerability converge.

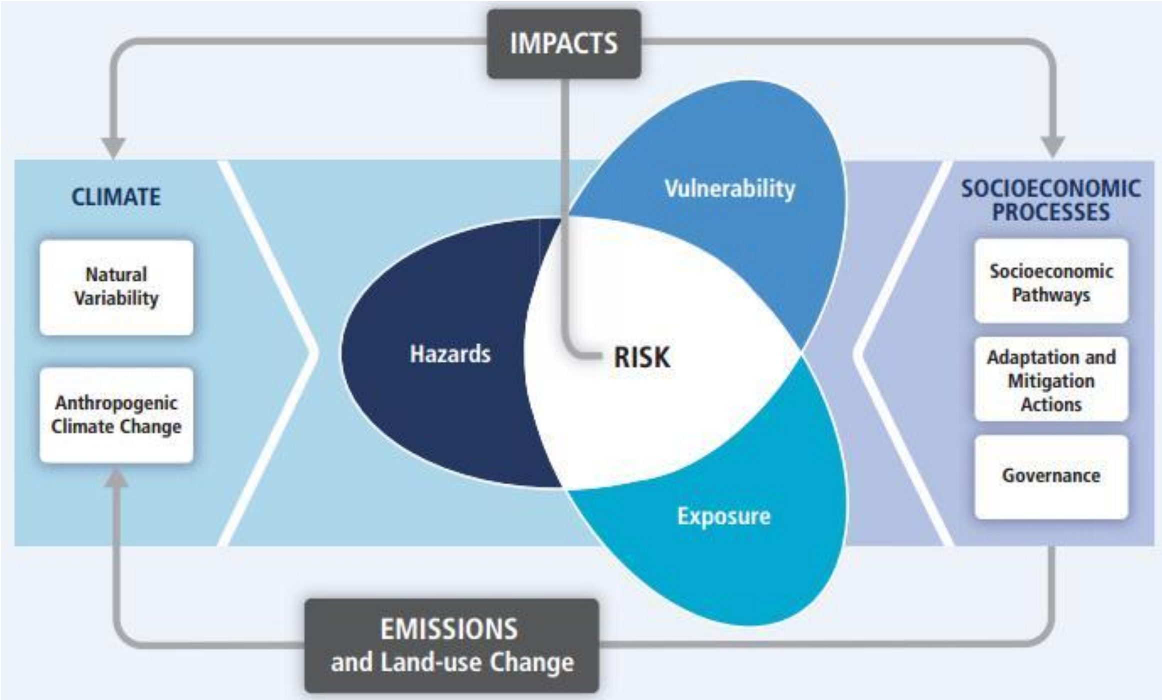

Figure 2.1: Schematic of the interrelationship of components necessary in flood analysis. Source: IPCC, (2014)

2.2.3 Sendai Framework for Action on Disaster Risk Reduction (2015-2030)

The Sendai Framework for Disaster Risk Reduction (2015-2030), adopted by the United Nations in 2015, is a cornerstone for guiding international and local policies to mitigate disaster risks. As the successor to the Hyogo Framework (2005-2015), aims to reduce human, economic, and environmental losses through on four key priorities: understanding disaster risk, strengthening governance, investing in risk reduction and improving disaster preparedness. The framework encourages multi-stakeholder cooperation, linking disaster risk reduction to sustainable development and climate adaptation in order to minimise human and economic losses. it broadens the scope of covered risks, encompassing not only natural hazards (floods, droughts) but also technological, biological, and environmental threats. It explicitly aligns with the Sustainable Development Goals (SDGs) and the African Union's Agenda 2063, emphasising the link between risk reduction, poverty alleviation, and sustainable development.

Despite its strengths, specialists point to a number of limitations. One of the main criticisms is its non-binding nature, which leads to inconsistent implementation, particularly in developing countries (Kelman, 2020). In addition, the framework focuses heavily on risks and technical solutions rather than social vulnerabilities such as poverty and governance failures (Gaillard, 2018). Another concern is its weak integration with climate change adaptation, which lacks clear mechanisms to align disaster risk reduction with changing climate risks (Thomalla *et al.*, 2018). These criticisms suggest that while the Sendai Framework provides a solid foundation, improvements are needed to ensure effective global resilience to disasters.

In West Africa a region highly vulnerable to climate disasters due to its reliance on natural resources and socio-economic challenges the Sendai Framework provides a roadmap for the Regional Flood Risk Management Strategy (2020–2025). For instance, it promotes analysis of vulnerability drivers such as unplanned urbanisation or inadequate resilient infrastructure, alongside integrated solutions like early warning systems and zoning policies. However, academic critiques highlight its limitations: its non-binding nature allows states to neglect commitments, evidenced by insufficient prevention budgets in West Africa. Additionally, implementation faces complex local realities, such as urban informality (unrecognised informal settlements in planning documents) and institutional weaknesses, which hinder multi-stakeholder coordination.

However, The Sendai Framework for Disaster Risk Reduction (2015-2030) is highly relevant to the study of floods as it focuses on risk reduction, governance and building resilience. The framework's emphasis on understanding risk, investing in disaster reduction and strengthening early warning systems matches the need for flood risk assessment and mitigation in the study area. Given the high variability of rainfall and extreme rainfall events observed in the research results, the application of the Sendai principles can help improve preparedness, land-use planning and community resilience to flooding.

The results of the study highlight significant inter-annual variability in rainfall, with stations such as Lokoja experiencing extreme rainfall events leading to flooding. This supports the Sendai Framework's call for climate-sensitive disaster risk planning. However, the research also suggests gaps in governance and adaptation strategies, which aligns with academic criticism that the Sendai Framework lacks robust implementation mechanisms. The study reinforces the idea that without strong governance and socio-economic integration, the framework's objectives remain difficult to implement in regions such as West Africa, where institutional capacity and resources are often limited. This research goes beyond applying the Sendai Framework: it tests its operational scope in high-stakes contexts. While findings validate its utility for prioritising interventions (e.g., targeting neighbourhoods where exposure, vulnerability, and hazards overlap), they could also inform future revisions of the framework. Key recommendations include integrating climate justice indicators (e.g., inclusion of marginalised groups) and establishing predictable funding mechanisms for prevention. Thus, the study strengthens disaster risk policies in West Africa while embedding local challenges within global resilience debates.

2.3 Review of Pertinent Literature and Related Studies

2.3.1 Review of pertinent literature

Climate change has significantly changed flooding dynamics, affecting its frequency, intensity, spatial extent and duration. These changes are mainly due to the intensification of the global hydrological cycle caused by rising global temperatures. Warmer air can hold more moisture, leading to more intense precipitation and more violent storms

(Tabari, 2020). Research has shown that climate change amplifies many of the factors contributing to increased flood risk, including heavier rainfall and storm surges amplified by rising sea levels (Denchak *et al*., 2023). In most regions of the world, an increase in extreme rainfall has been observed, which increases the risk of flash flooding, particularly in urban areas where drainage systems may be submerged. This is particularly the case in sub-Saharan Africa, which is increasingly prey to flash flooding during the rainy season (Amogu *et al*., 2010). In some parts of Europe, Fang *et al*., (2024) demonstrated an average increase of 11.3 % in the extent of flooding over the last 70 years, this pattern is particularly due to increased precipitation and snowmelt. Future projections indicate that the risk of displacement due to flooding could double by the end of the 21st century, even in the most optimistic scenarios. These changes highlight the crucial importance of combining mitigation and adaptation strategies, particularly in the most vulnerable areas (Internal displacement monitoring centre, 2019).

2.3.1.1 Dams and their role in flood management

Dams play a strategic role in water resource management, hydropower generation and flood control. However, their operation can inadvertently exacerbate flooding, particularly in vulnerable areas such as Lokoja, which lies at the confluence of the Niger and Bénoué rivers. The management of dams aims to balance three essential functions, namely in the energy sector (hydroelectric power generation), the agricultural sector and water management. While dams are designed to mitigate flooding, the release of water during periods of intense rainfall can amplify flooding downstream, as was seen at Lokoja during the catastrophic floods of 2022 (OCHA, 2022) . The changes in rainfall patterns brought about by climate change pose major challenges for dam management. The increase in droughts and extreme rainfall makes flow forecasts highly uncertain, complicating efforts to maintain a balance between the competing demands of power generation, irrigation and flood control.

The Lagdo dam in Cameroon is one of the main contributors to flood risk in Nigeria. Originally designed for power generation and flood control, the dam periodically releases large volumes of water during the rainy season, creating cascading effects downstream. The floods of 2022 are a perfect illustration of this problem. The release of water from the Lagdo dam, combined with intense regional rainfall, caused a rapid rise in water levels, flooding infrastructure and affecting millions of people. Reports from Nigeria's National Emergency Management Agency (NEMA) indicate that around 2.4 million people were displaced, highlighting the inadequacy of crisis management mechanisms. More than 660 people have lost their lives. The catastrophic floods have also made 174,000 houses unfit for habitation (United Nations OCHA, 2022).

The recurrent flooding at Lokoja, particularly in recent years, highlights the complex interaction between dam operation and weather conditions. In addition to Lagdo, the Kainji and Shiroro dams in Nigeria also contribute to the risk of downstream flooding. When their water releases coincide with heavy rains, low-lying areas such as Lokoja become particularly vulnerable. Social and economic consequences: The floods of 2022 submerged urban and agricultural areas, causing substantial economic losses, the destruction of homes and a prolonged humanitarian crisis (Olatunde and Adejoh, 2017 ; NIHSA, 2022). The dams along the River Niger, while essential for regional development, present significant challenges in terms of flood management, particularly under the pressure of climate change. A coordinated and proactive approach to dam operation, incorporating advanced hydrological forecasting and cross-border collaboration, is essential to mitigate flood risk and protect vulnerable communities such as those in Lokoja.

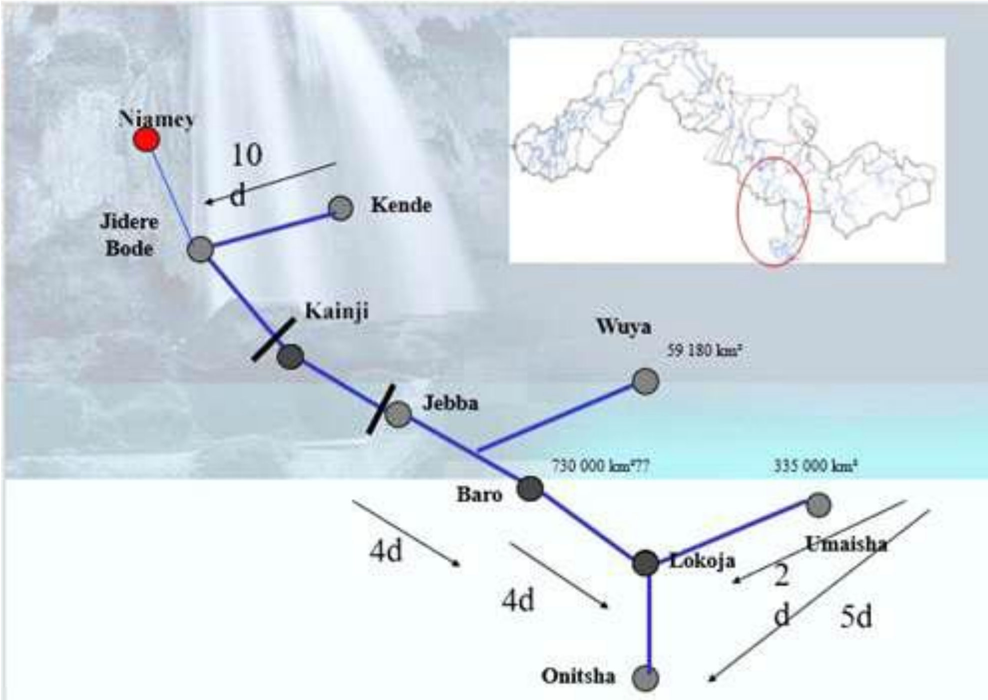

Figure 2.2: Flow chart of Niger River from Niamey into Nigeria (Nigerian Hydrological Services Agency, 2024)

The Kainji and Jebba dams change the hydrological regime of the river by delaying and attenuating certain floods, but they can also intensify flooding downstream if water releases are poorly coordinated. After Baro, river dynamics become more complex with the confluence of the Niger and the Bénoué at Lokoja. This junction increases the risk of flooding, as the two rivers can reach their flood peaks simultaneously. The figure shows flood propagation times of around 4 to 5 days between certain sections, which is crucial for risk planning and management.

2.3.1.2 Hydrologic systems components and temporal response

Hydrological systems comprise various interconnected components that interact to regulate the movement and distribution of water in a given area. Understanding these components and their temporal responses is essential for effective management of water resources, particularly in the context of climate change.

(i) Hydrologic Systems Modelling

Hydrological models simulate flows, discharges or variations in water storage over time in the components of the hydrological cycle. As simplified representations of reality, they rely on simultaneous equations or computer algorithms to predict the behaviour of water. These tools make it possible to understand the impact of human activities and climate on watercourses, while facilitating the design of sustainable water resource management strategies (Dewangan and Vishvakarma, 2020). They play a key role in assessing climate impacts on a regional scale.

In West Africa, these models are essential for anticipating changes in water systems, particularly in basins such as the Volta Blanche. They are used to forecast floods, estimate flows and assess the availability of water resources in the face of future climate change (Kumi *et al*, 2015). For example, regional climate models such as REMO can be combined with hydrological tools to simulate local impacts. However, choosing the right model remains a challenge: experts recommend giving priority to performance, accessibility and efficiency in terms of time and resources (Cunderlik and Simonovic, 2007)

Designed by the US Army Corps of Engineers, the Hydrologic Modelling System (HEC-HMS) is a programme that simulates hydrological processes in watersheds. The successor to the HEC-1 model, it offers advanced features such as continuous simulation of evapotranspiration and soil moisture. Easy to use, it offers great flexibility in modelling basins, canals and water control structures, enabling flows and water levels to be calculated. This model is widely used to analyse urban flooding, design reservoirs or study the impact of climate change on water resources (Brunner, 2021). Climate change has a strong influence on hydrological extremes such as floods and droughts, leading to disruptions in water and food supplies, damage to infrastructure, and degradation of ecosystems and human health (Olajuyigbe *et al.*, 2012). These consequences require decision-makers to integrate these risks into water resource management and adaptation strategies. General Circulation Models (GCMs) are essential for studying climate change. They simulate the effect of greenhouse gases on global climate trends by modelling the interactions between the atmosphere, oceans and land (IPCC, 2007). These projections make it possible to anticipate future changes and plan adaptation and mitigation measures. Climate scenarios, which describe plausible futures based on assumptions such as emissions or land use, help to assess climate-related risks. However, GCMs, designed for global scales, need to be adapted for local studies. Downscaling techniques transform their data into the local meteorological variables, such as daily precipitation, required for accurate hydrological modelling. These adjustments are crucial, as global climate change affects local hydrological regimes, modifying river flows, irrigation systems and the occurrence of floods or droughts.

(ii) Models and Application for Hydrologic System Input Analysis

The Hydrologic Engineering Center's River Analysis System (HEC-RAS) is widely used for simulating river hydraulics (Brunner, 2021). It incorporates mathematical equations to solve open-channel flow dynamics, primarily using:

The Saint-Venant equations, which include:

Continuity equation: $$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \qquad (2.3)$$

Where A is the cross-sectional area, Q is the flow rate, x is the longitudinal distance, t is time, and Q represents lateral inflow.

Momentum equation: $$\frac{\partial Q}{\partial T} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial h}{\partial x} + gQ|Q|C_f = 0 \qquad (2.4)$$

Where h is the water surface elevation, g is gravitational acceleration, and C_f is the friction coefficient.

The frequency and intensity of floods are intrinsically associated with extreme values of meteorological variables, such as precipitation. Climate models, in particular general circulation models (GCMs), predict these extreme values by simulating atmospheric and oceanic dynamics under the effect of increasing greenhouse gas levels (IPCC, 2007). The impact of climate change on flooding was assessed by analysing rainfall and flow variability over different time horizons. The extent of flooding for return periods (e.g. 10, 50 and 100 years) was calculated using the Gumbel distribution:

$$P(T) = 1 - \exp\left(-e^{-\frac{x-\mu}{\sigma}}\right) \qquad (2.5)$$

With P(T)

Refer to the exceedance probability, x as the flood magnitude, μ representer the location parameter, and σ the scale parameter. By comparing these outcomes, the study identified zones with increased flood vulnerability, helping to inform mitigation strategies and resource allocation.

2.3.1.3 Data quality control and analysis

Ensuring the quality of hydrological data begins with an exploratory data analysis. This process uses graphs and charts to visualise the data, allowing for a better understanding of its characteristics and patterns (Kundzewicz and Robson, 2000). Statistical testing involves defining two hypotheses: the null hypothesis (H_0), which assumes no change in the tested properties, and the alternative hypothesis (H_1), which indicates a change. Initially, the null hypothesis is assumed true. Depending on the test results, H_0 is either rejected or accepted. The value used to compare H_0 and H_1 is referred to as the test statistic, and the significance of the result is measured using the significance level (α) or confidence interval.

Kundzewicz and Robson (2000) describe the significance levels as follows:

(i) **Above 10%**: very weak evidence against H_0

(ii) **5% to 10%**: possible evidence against H_0

(iii) **1% to 5%**: strong evidence against H_0

(iv) **Below 1%**: very strong evidence against H_0

For example, a 5% significance level (95% confidence interval) means that, if H_0 is true, one out of 20 tests will yield an incorrect result. Similarly, a 1% significance level (99% confidence interval) implies one incorrect result in 100, and a 10% level (90% confidence interval) equates to one incorrect result in 10. Threshold values for test statistics corresponding to these levels are often tabulated for convenience. The chosen significance level is typically stated when reporting test results.

(i) Homogeneity Tests

Long-term climatological datasets can be affected by human-induced errors that interfere with natural climatic variations and trends. These errors, known as inhomogeneities, often arise from changes in observation methods, schedules, conversion formulas, instruments, or station environments (WMO, (2011). Detecting, correcting, or adjusting these inhomogeneities is a critical step before conducting further climate analyses. Inhomogeneities often manifest as sudden shifts or gradual changes in the statistical properties of time series, corresponding to non-climatic events like station relocations or instrumentation changes. Others, such as urbanisation or vegetation growth, may develop gradually and be harder to detect (al Oumari *et al*., 2003). Homogeneity tests are broadly classified into two types:

(i) **Relative methods**: compare a station's data with that of neighbouring reference stations.

(ii) **Absolute methods**: analyse each station independently.

Detailed metadata is essential for detecting inhomogeneities. This includes information on observation methods, station personnel, location, and history (e.g., relocations, land-use changes, repairs, or upgrades) and any prior quality control procedures applied to the data (Peterson *et al*., 1998 ;Aguilar *et al*., 2003).

Typical steps in a homogenisation process include:

(i) Building a reference time series from neighbouring station data free of inhomogeneities.

(ii) Identifying breakpoints in the series.

(iii) Adjusting the data.

(iv) Evaluating the results.

(v) Documenting the homogenisation procedures and preserving the data.

(ii) Trend Tests

Analysing hydrological data for trends is crucial because statistical tests often assume stationarity (Kundzewicz and Robson, 2000). Parametric methods require assumptions about the data's statistical distribution and independence between data points. These assumptions rarely hold for hydrological data unless transformations are applied or the analysis is restricted to annual series, where independence is more plausible. Non-parametric methods, methods, such as the Mann-Kendall test (Animashaun *et al*., 2020) and Sen's slope estimator (Sen, 1968), are less sensitive to outliers than parametric methods, and are therefore preferred because they do not require assumptions about the distribution of the data and are robust to outliers and non-normal data (Kundzewicz and Robson, 2000).

For robust climate analyses and trend detection, datasets spanning at least 50 years are recommended. Shorter time series may still be useful but are more likely to reflect climate variability or other factors (Kundzewicz and Robson, 2000). Nonetheless, it is essential to test shorter datasets to confirm the absence of trends caused by external influences.

(iii) Standardised Anomaly Index (SAI)

The standardised anomaly index (SAI) is a statistical measure used to analyse variations in rainfall over a given period, making it possible to identify trends in rainfall anomalies. It makes a clear distinction between wet and dry periods, providing a better understanding of climate variability and its link to flooding (Elagib, 2013). By quantifying deviations from the long-term average, the SAI makes it possible to assess whether a given year has experienced excessive or insufficient rainfall, which has a direct influence on the likelihood of pluvial and fluvial flooding.

Table 2.1: Standardised Anomalies Index (SAI)

>2.00	Extremely wet
1.50 to 1.99	Very wet
1.00 to 1.49	Moderately wet
0.01 to 0.99	Mildly wet
-0.99 to 0	Mild dry
-1.0 to -1.49	Moderately dry
-1.50 to -1.99	Severely dry
-2.00 or less	Extremely dry

(Elagib, 2013)

2.3.1.3 Multi-criteria Analysis (MCA) in flood risk assessment

The analytical prioritisation process (AHP) and multi-criteria decision analysis (MCDA) are highly effective tools for addressing complex decision-making problems, such as flood risk management. Flooding is a multi-angled problem involving a variety of criteria, including environmental and hydrological impact, economic costs, social vulnerability and infrastructure resilience. The AHP method can be used to prioritise these criteria according to their relative importance, while the MCDA method can be used to assess and rank potential flood mitigation strategies, such as building dykes, improving drainage systems or setting up early warning systems (Vojtek *et al*., 2021). By decomposing the problem into a hierarchy of criteria and alternatives, decision-makers can systematically evaluate trade-offs and make informed choices that balance competing objectives (De Brito and Evers, 2016). This approach has been successfully applied in numerous flood risk management studies, with papers published focusing on ranking alternatives for flood mitigation, risk assessment, hazard evaluation, and vulnerability assessment (De Brito and Evers, 2016).

Thomas L. Saaty developed the Analytic Hierarchy Process (AHP) in the 1970s. AHP helps decision-makers prioritise and make the best decision when both qualitative and quantitative aspects of a decision need to be taken into account. The process involves breaking down a complex problem into a hierarchy of more easily understood sub-problems, each of which can be analysed independently. The elements of the hierarchy can relate to any aspect of the decision problem - tangible or intangible, carefully measured or crudely estimated, well or poorly understood - whatever is relevant to the decision in question (Canco *et al*., 2021).

The Analytical Hierarchy Process (AHP), involves the following steps:

(i) Pairwise comparison: Criteria are compared in pairs to determine their relative importance. This is done using a scale from 1 (equal importance) to 9 (extreme importance) (table 2.1). The pair-wise comparison matrix is constructed as follows:

$$S = \begin{bmatrix} a_{10} & a_{11} & \cdots & a1_n \\ a_{21} & a_{22} & \cdots & a2_n \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \tag{2.2}$$

Where a_{ij} reprensents the relative importance of factor i compared to factor j.

(ii) **Weight Calculation:** decision-makers can assign weights to different criteria according to their relative importance, and then use these weights to evaluate and rank alternatives.

(iii) **Consistency Check:** The consistency ratio (CR) is calculated to ensure the reliability of the pairwise comparisons.

Table 2.2: Saaty scale on relative importance

1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very to extremely strong importance
9	Extreme importance

Source: Saaty (1990**)**

2.3.2 Review of related studies

Recently, the overall of population has increased considerably, the villages of yesterday have developed to become large cities. Most of the world's population is concentrated in urban areas. By 2021, cities will account for around 70% of global greenhouse gas emissions, despite occupying just 2% of the Earth's surface (IPCC, 2014). Rapid population growth is accelerating urbanisation, leading to soil impermeability, deforestation, environmental degradation and overexploitation of groundwater (IPCC, 2022). In another hand, the galloping development of cities is exposed to the effect of climate change to which they have been vulnerable as well as being plagued by extreme temperature and precipitation events with rising sea levels. This exponential rise in water levels confronts the populations with floods that are often devastating. Numerous studies have shown that in order to cope with the consequences of climate change, especially natural disasters such as floods, it is more appropriate to develop warning system tools to prevent their occurrence.

Mahe *et al* (2011) argues that the evolution of the Niger River regime in its last decades is directly associated with the effect of climate change. The decline in rainfall in the region in the 1970s led to changes in the river regime throughout the Niger Basin. However, although the document refers to the evolution of river flows the impact of such a change on the environment and the life of habitats has not been demonstrated extensively. However, several research (Saley *et al*., 2005; Amogu *et al*., 2010; Nka *et al*., 2015; Sighomnou *et al*., 2013) have analysed climatic and hydrological time series, reporting an increasing in the number of floods and flood-related consequences in West Africa. Nka *et al*. (2015) through an empirical method analysed the dynamics of maximum flows in West African rivers in multiple watersheds and found a strong growth in the frequency and intensity of the phenomenon attributed to the increase in annual runoff coefficients using the AM (annual maximum) method and the peak over threshold (POT) method are the two methods for sampling flood events included in the methodology. Additionally, two perspectives of analysis are presented: a long-term analysis based on two long flood time series and a regional perspective involving 11 catchments with shorter series. Nonstationarities in the time series were found using the Mann-Kendall trend test and the Pettitt break test. To determine the primary cause of change in flood magnitude and frequency, the trends in the flood time series were compared to the trends in the rainfall index and vegetation indices using contingency tables. The relationship between the flood index and the physiographic index was assessed using a success criterion and the Cramer criterion calculated from the flood index.

This study explores whether floods are becoming more frequent or severe, as well as how much these changes have been influenced by climatic patterns. Authors examined the patterns of the floods that occurred in 11 catchments within the main climate zones of West Africa. The outcomes of the study demonstrate the existence of trends in flood frequency and magnitude time series, with two key themes. While the trends in normalised difference vegetation indices (NDVIs) do not show a significant agreement with flood trends for the entire catchment under study, the trends in the maximum 5-day consecutive rainfall index (R5d) do show good coherence with trends in flood, suggesting that this index may not have any bearing on the behavior of floods in the area. The detection of trends in flood time series is of scientific importance and also of economic benefit. It is essential for the planning of flood protection systems. However, the study did not explore the use of hydrological models, which have the advantage of providing a more accurate account of certain hydrological processes, allowing better anticipation of future changes in climate parameters.

Similarly, Kumi *et al*, (2015) assessed the hydrological consequences of potential future climate change in the White Volta catchment (West Africa). The research study of the sensitivity of climate change particularly in the rainfall and air temperature changes. To achieve these goals of the study, their methodology involved the use of a set of regional climate models (REMO) to simulate and project climate at the basin scale. Results from the REMO climate model were compared with rainfall and temperature data for the period 1995-2008. The study found an increase in precipitation and temperature of 8 % and 1.7 % respectively in the future climate scenario. This will result in a 26 % and 24 % increase in surface runoff and base flow respectively at the catchment level. Thus, the projected meteorological data from the model was used as input data for the SWAT hydrological model.

This study therefore demonstrated the effectiveness of applying such a model in a data-poor rural West African catchment with variable land cover, soils and topography can provide reliable results for estimating the impact of climate change on the region's surface and groundwater resources, suggesting that the catchment is likely to experience an increase in rainfall, and thus become even more flood-prone. The study contributes to the body of knowledge and helps planners to better anticipate the future hydrological process of climate change. However, the authors have not shown the manners of how the study can benefit to the country and also the consequences of the trend of rainfall in the parts of the basin.

Gebre and Getahum, (2015) also analyses the flood risk and flood zone mapping of the Awash River basin. The study determines the river basin's inundated area with a certain return period of 5, 10, 25, 50, and 100 years, as well as the locations most vulnerable to flooding in the basin... The methodology involves the use of flood-generating factors (including slope, elevation, rainfall, drainage density, land use and soil type) which were evaluated and combined to define flood risk areas using the multi-criteria evaluation technique in a GIS environment. The weight of each flooding factor was calculated by pair-wise comparison of the final weighted analysis by overlaying all factors to generate the flood risk map. The flood risk analysis showed that the low-lying areas near the Awash River, especially in the downstream part, are in the high to very high flood hazard zone. Similarly, the one-dimensional numerical software HEC-RAS was used to map the flood-prone areas along the Awash River based on the highest flows exceeding 5% at different return periods of 5, 10, 25, 50 and 100 years. The study's key findings revealed that the amount of inundation in the upper and intermediate reaches of the Awash River Basin is lower than in the lower reaches. The findings will assist the relevant organisations in developing plans in response to the area's current flood hazard. The study contributes to the body of knowledge and helps planners to better anticipate the future hydrological process of climate change. The result of this report is very important as a preliminary information guide for land use planning, policy-making, and investment decisions as well as for security reasons. However, this study lacks historical flood map data and river flow data also this study did not include the dynamics of land use land cover.

Several studies have been published worldwide on the impacts of climate change and the consequences of flooding on cities. For example, Wang *et al*., (2021), have conducted work to analyse future flood patterns and evaluate the impact of changing precipitation on flooding under climate change in the Lancang-Mekong River Basin (LMRB), in the light of flood control, disaster reduction and water resources cooperation policy development in LMRB, the study employed the use of four global climate models to project future precipitation that influences the hydrological modelling of future daily runoff over 30 years in the basin. The study found that the area is likely to be vulnerable, the greater the return period, the greater the flood risk and the greater the impact of climate change. the change in average basin precipitation in the future is likely to increase the peak flooding at the paksé station. Li *et al*., (2013) conducted a study to analyse the assessment of the impact of urbanisation on flood risk in the Yangtze River delta, considering six urbanisation areas in the valley. the Yangtze River delta area is considered to be the region with the highest urbanisation growth in China. the study pointed out that due to the urbanisation process, which further exposes the area to disasters, the overall flood risk in the selected areas has gradually increased, posing a serious threat to sustainable urban development. Nevertheless, effective means of flood risk management in the urbanisation areas of the Yangtze River Delta have been proposed based on the assessment results. Fasona *et al*, (2002) employ remote sensing data and GIS to delineate and classify the susceptibly of the western Niger Delta area to flood risk. The results show that a total land surface of about 3183.45 km^2 lies below 5 m and 1407 km^2 of this lies below 1m. 88 built-up areas (30% of the total) with a total area of about 9.69 km^2, and 78.1 km^2 of cultivated lands are always at the risk of serious impact by seasonal flooding.

In light of knowing the influence of climate change on the water resources of the transboundary Jhelum River basin of Pakistan and India, Mahmood and Jia, (2016) conducted a work to analyse the impact of climate change on the water resource availability in the valley area using the hydrologic HEC-HMS model to simulate over different future period. Thus, the results confirm an increase in flows of 10% - !5% of the annual mean flow compared to the baseline.

2.4 Examples from Other Regions/Countries

Flooding is a growing global challenge, exacerbated by climate change, and is often seen as a key factor in the increasing frequency and magnitude of extreme events. This dynamic has encouraged a large number of research projects aimed at analysing the complex interactions between global warming, hydrological regimes and the increased vulnerability of urban ecosystems, where populations, infrastructures and critical socio-economic issues are now concentrated. For instance Wang *et al.*, (2021), have conducted work to analyse future flood patterns and evaluate the impact of changing precipitation on flooding under climate change in the Lancang-Mekong River Basin (LMRB), in the light of flood control, disaster reduction and water resources cooperation policy development in LMRB, the study employed the use of four global climate models to project future precipitation that influence the hydrological modelling of future daily runoff over a 30-year period in the basin. The study found that the area is likely to be vulnerable, the greater the return period, the greater the flood risk and the greater the impact of climate change. the change in average basin precipitation in the future is likely to increase the peak flooding at the Paksé station.

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2.5 The Overview and Key Issues of the Study

The climate in West Africa has been characterised by low rainfall since the late 1960s, particularly in Sahelian countries such as Niger (Luc Descroix *et al*., 2013) . Paradoxically, despite this persistent aridity, run-off and river flow increased, leading to recurrent flooding. This phenomenon, observed particularly between 1970 and 1980, intensified at the start of the 21st century, affecting agricultural production and people's living conditions (Tarhule, 2005). This trend is often attributed to two main factors: changes in land use, marked by deforestation and urbanisation, and the effects of climate change, which are amplifying extreme weather events.

Historically, climatic aberrations have had devastating consequences on a global scale, providing a broader context for the West African situation. The floods in China in 1931 (3.7 million victims), the cyclone in Bangladesh in 1970 (300,000 deaths) and the drought in Sudan in 1983 (150,000 deaths) illustrate the human impact of climatic disasters. In response, the United Nations Environment Programme (UNEP) and the World Meteorological Organisation (WMO) set up the Intergovernmental Panel on Climate Change (IPCC) in 1988. The purpose of this initiative was to assess knowledge about climate change and promote scientific solutions to improve environmental conditions, an issue that has become central to the well-being of the world's populations.

In Niger, the prolonged drought of the 1970-1980s exacerbated vulnerability, particularly in terms of food production and access to drinking water. In response to this crisis, on 29 December 1998 the Nigerien government adopted law no. 98-56 on environmental management. This framework law, which states that ‘Everyone has the right to a healthy environment’ (article 4), reflects the political will to protect natural resources and meet the challenges of climate change. It lays the foundations for proactive environmental management, linking the historical issues of drought to the contemporary problems of flooding. Today, flooding is a major obstacle to development in Sahelian countries, requiring modern approaches to identifying flood-prone areas and mitigating their effects.

Like Niger, Nigeria is also committed to addressing the effects of climate change. Indeed, the second part of the federal environmental protection agency act provides the standards for national environmental protection. The section of this act is based on a set of parameters that aim to limit environmental contamination in order to promote national welfare. Also, a set of measures have been taken to address flood damage by the Federal Ministry of Environment in Nigeria, including "Flood plain management through good practices that will reduce flood runoffs". These timely decisions confirm the willingness of the Nigerian government to align itself with the rest of the world in the fight against climate change. It also confirms the signature of the different international treaties of fight against climate change of the country such as its contribution determine, kyoto protocol. This is undoubtedly what the work of (Adebayo, 2014) which presented the efforts of the Nigerian government in the regulation of floods has tried to show. Thus, due to their different political wills, Niger and Nigeria are converging together, like the rest of the world, to an environment less vulnerable to the effects of climate change. Indeed, these two nations, like the rest of the world, have realised that the fight against flooding caused by climate change can only be achieved through close collaboration between policy, science and the population.

Disaster management in Niger depends on several institutional structures responsible for preventing and responding to floods. The Early Warning System (SAP), set up in 1989, monitors climatic risks, while the National Food Crisis Prevention and Management System (DNPGCCA), established in 1998, coordinates responses to crises (Ministre). The Ministry of Humanitarian Action and Disaster Management also plays a key role in organising relief efforts (Cabinet Du premier Ministre, 2021). However, these institutions face major challenges: a lack of funding limits their capacity for action, while coordination problems hamper the effectiveness of interventions. The need for human, logistical and material resources remain insufficiently covered, compromising preparedness and response to recurring floods. Strengthening these institutional capacities is essential if the regulatory framework is to be translated into concrete action.

In the face of extreme flooding, specific initiatives have been launched to support the populations affected. The CERF (Central Emergency Response Fund) project, for example, provided emergency aid to victims of the 2020 floods in the regions. This programme illustrates an immediate response to disasters, aimed at mitigating their impact on vulnerable communities. In the longer term, the use of modern techniques, such as flood zone mapping, is advocated to anticipate risks and strengthen resilience. These activities, while promising, depend on stable funding and greater coordination between local, national and international players to maximise their impact.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of Materials

This chapter outlines the scientific approach used to collect and process the data required to achieve the various objectives assigned in this research. It describes the overall methodological framework, justifies the choice of approaches used, and presents the technical tools employed to carry out this study. The research adopts a mixed-methods approach combining quantitative and qualitative techniques. This strategy integrates spatial analyses and physical modelling to quantify flooding processes, as well as socio-economic assessments to understand human impacts and local adaptation strategies.

This approach enables the addressing of the multidimensional complexity of flooding's effects in the Niger Basin, where hydrological, climatic, and anthropogenic factors interact. It allows for the triangulation of data, which is essential for cross-referencing satellite observations, model outputs and field reports, thereby strengthening the robustness of the results. This approach is particularly suited to the Nigerien context, which is characterised by significant spatial heterogeneity (from the arid Sahel to wetlands) and social vulnerabilities requiring detailed investigation of local realities.

Last of all, technical implementation relies on a suite of specialised tools, notably geographic information systems (QGIS and ArcGIS) for spatial analysis and satellite image processing. Modelling uses HEC-RAS (hydraulics). Statistical analyses were conducted using R (tests and time series, and survey processing), while data collection and qualitative analysis were carried out using the KoboToolbox tool (digitised field surveys). This combination of tools makes it possible to meet the various objectives and effectively understand the impacts of flooding in the context of the Niger River Basin.

3.1.1 Data Types and Sources

3.1.1.1 Types of Data

The type of data used in this study is a combination of field data and archive data. The field data (primary data) was collected using a survey method involving a questionnaire to obtain information on the type, frequent causes and effects of flood risks in the study area. The questionnaire consists of questions carefully designed to suit the research topic.

Archival data (secondary data), including historical data on precipitation, temperatures, and stream flow, were also collected from reports made available by hydrometeorological agencies available; other data sources used for the study include satellite images of the affected areas (for the study period: 1990-2020) and Digital Elevation Model (DEM),

The stations were selected on specific criteria to cover different parts of the region, enabling a representative analysis of rainfall in the study area, thus capturing the spatial variability of rainfall patterns. This distribution enables an exhaustive analysis of local climatic conditions. In addition, these stations have reliable and sufficiently long rainfall time series, which are essential for a robust statistical study. To illustrate this geographical diversity.

3.1.1.2 Source of data

This study is based on primary data collected directly in the field. Surveys were administered to households in flood-prone areas, gathering socio-economic data and local perceptions (Appendix A). Figure 3.1 and 3.2 provides the location of the rainfall stations on a map of the study area, as well as the location of the different sites where the questionnaires were administered, both for Niamey and lokoja, respectively. Secondary data comes from various institutional sources:

(i) Climate data (1991–2021): Niger National Meteorological Service (DMN) for Niamey, AMMA CATCH collection and Nigerian Meteorological Agency (NIMET) for Lokoja.

(ii) Hydrological data: Niger Basin Authority (ABN) and Nigerian Inland Waterways Authority (NIWA), Nigeria Hydrological Services Agency (NIHSA);

(iii) Landsat satellite images (USGS) covering 1990-2021; Digital Elevation Model (USGS);

(iv) Soil data (ISRIC Data Hub) and demographic data (Copernicus).

Primary and secondary sources of data are summary in Tables 3.1 and 3.2.

3.1.1.3 Ethical Considerations

This study strictly adhered to academic ethical principles through key measures: informed consent was obtained from all participants, clearly explaining the research objectives, data use, and participant rights. Verbal agreements were also obtained, particularly with female respondents. Confidentiality was ensured through rigorous anonymisation of personal data and secure storage. The privacy and anonymity of respondents remained a central concern, with all responses being treated as strictly confidential. In addition, the researcher demonstrated consistent professionalism by transparently explaining his role throughout the process, particularly during interviews.

3.1.1.4 Study Area Selection

Flooding in the Niger Basin has intensified significantly in recent decades, exacerbated by climate change, rapid urbanisation and shortcomings in water resource management. Extreme events, such as the floods of 2010, 2012, 2017, 2020 and 2022, have revealed the vulnerability of populations and infrastructure in urban and peri-urban areas (Ocha, 2012). These floods have caused loss of life, mass displacement, destruction of crops and homes, and significant economic disruption. For example, the 2020 floods affected more than 2 million people in the Sahel region, with particularly severe impacts in Niamey and Lokoja, where flood management systems proved inadequate in the face of the scale of the events. The criteria for selecting the study areas are based on their vulnerability to flooding, their demographic and economic importance, and their representativeness of the hydrological and social dynamics of the Niger Basin. Niamey and Lokoja were selected because of their complementary characteristics, their recurrent exposure to flooding, and the specific challenges they face in terms of risk management.

Niamey, the capital of Niger, is one of the most densely populated areas in the upper Niger River basin. Located on the banks of the river, it is particularly vulnerable to seasonal flooding, exacerbated by extreme rainfall and poor stormwater management. The major floods of 2010, 2017 and 2020 caused considerable damage, with economic losses and thousands of people displaced (Massazza *et al*., 2021).

The rapid urbanisation of Niamey has exacerbated the risk of flooding. The uncontrolled occupation of floodplains, where informal settlements have developed without adequate planning, has reduced the soil's capacity to absorb water. In addition, urban drainage systems, which are often obsolete or poorly maintained, are unable to cope with the volume of water during floods. These factors, combined with the growing dependence of populations on risk areas for their housing and economic activities, make Niamey a critical case study for analysing the interactions between urbanisation, climate change and flood management.

The Lokoja area, located at the confluence of the Niger and Benoué rivers, is a key point in the Niger basin. With a population of over 500,000, it is exposed to recurrent flooding, amplified by its unique geographical position. The floods of 2012 and 2022 were particularly devastating, submerging entire neighbourhoods, destroying vital infrastructure (roads, bridges, schools) and affecting the livelihoods of thousands of people, particularly in the agriculture and fishing sectors. In Nigeria, Lokoja is one of the most affected areas. The failure of early warning and flood management systems in Lokoja exacerbates the impacts of flooding. Despite efforts to improve infrastructure, warning mechanisms remain limited, often due to technical constraints. The Niger-Benue confluence, due to its role in regional hydrological dynamics, makes Lokoja an ideal site for studying the combined impacts of river flooding and risk governance challenges.

Niamey and Lokoja offer valuable complementarity for the study of flooding in the Niger basin. Niamey represents the challenges of an upstream metropolis facing rapid urbanisation and planning constraints. Lokoja, downstream, illustrates the amplified impacts of the convergence of two major rivers and gaps in warning and response systems. Together, these sites allow for the exploration of a range of aggravating factors (urbanisation, climate change, governance) and the proposal of solutions adapted to the varied contexts of the basin.

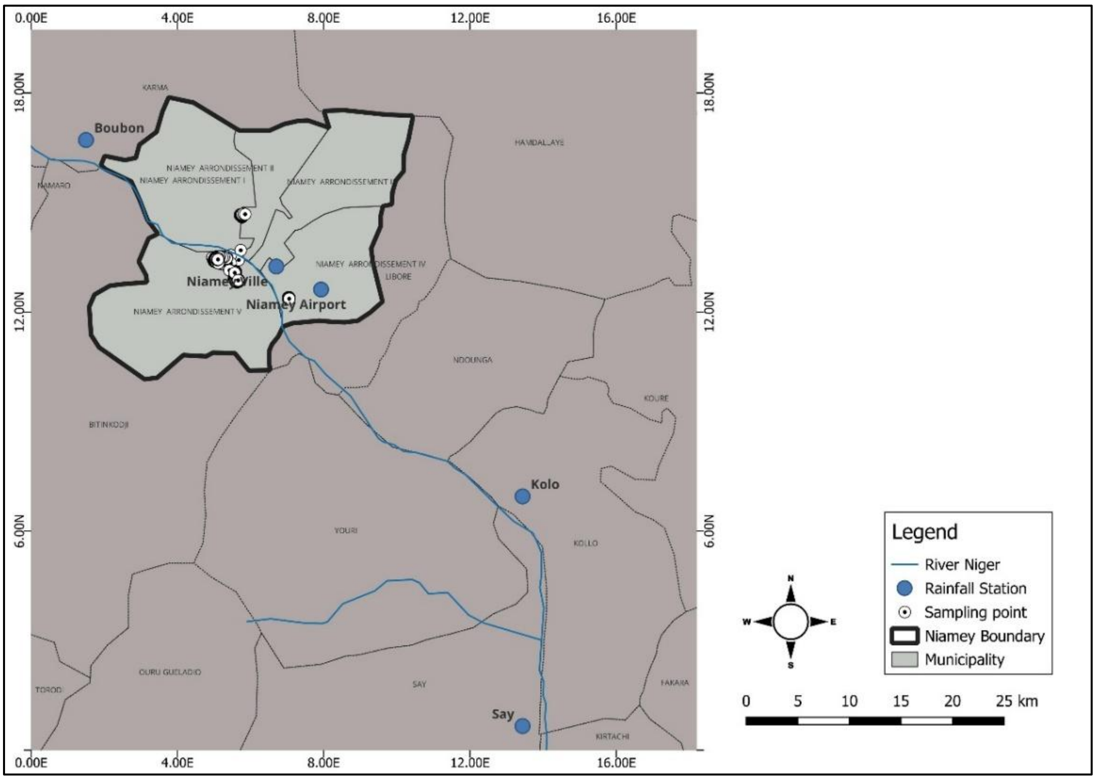

Figure 3.1: Map of rainfall stations and administrative boundaries of the Niamey region (including the River Niger)

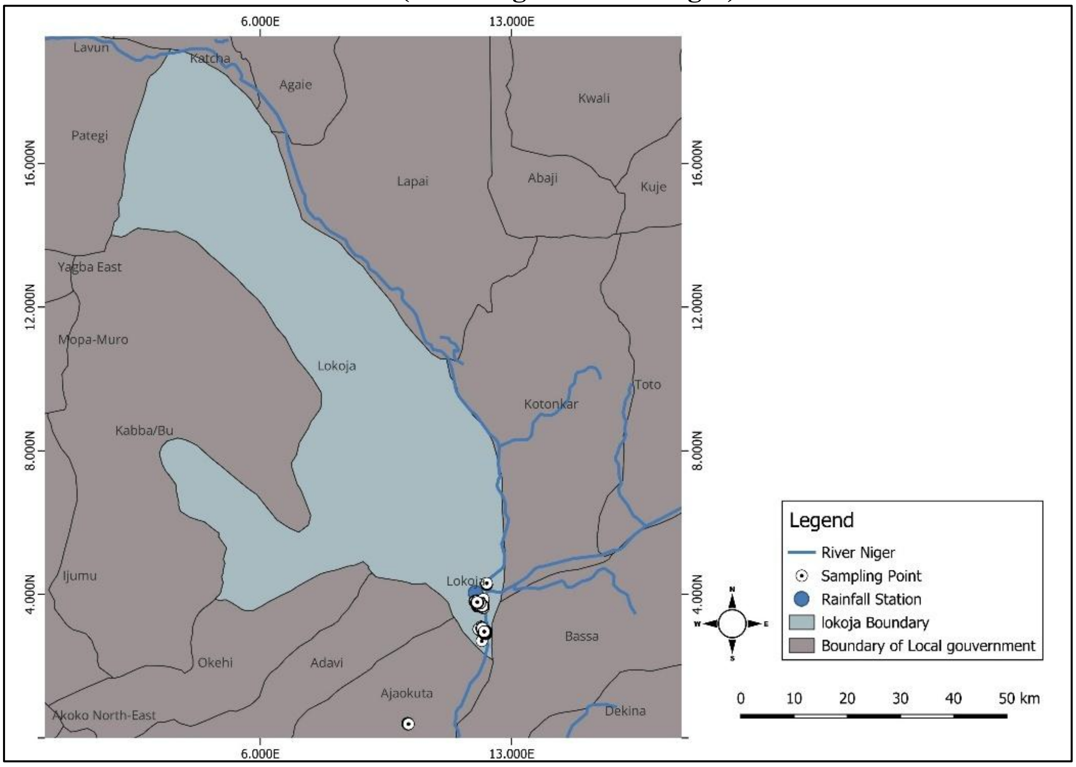

Figure 3.2: Map of rainfall stations and administrative boundaries of the Lokoja region (including the River Niger

Table 3.1: Summary of data source used to achieve the various objectives

Type of data	Extent (Period)	Source (Niamey)	Source (Lokoja)
		Primary Data	
Structured questionnaires	400 households	Flood-prone communities	Flood-prone communities
		Secondary Data	
Rainfall data	30 years (1991–2021)	Direction Nationale de la Météorologie du Niger (DMN) and AMMA CATCH collection	Nigerian Meteorological Agency (NIMET)
Temperature data	30 years (1991–2022)	Direction Nationale de la Météorologie du Niger (DMN)	Nigerian Meteorological Agency (NIMET)
Streamflow	30 years (1990–2022)	Niger Basin Authority (ABN)	NIWA, NIHSA
River stage/level	30 years (1990–2021)	Niger Basin Authority (ABN)	NIWA, NIHSA
Digital Elevation Model (DEM)		United States Geological Survey (USGS) from: https://earthexplorer.usgs.gov	
Soil Texture	Digital soil texture data from ISRIC Data Hub	https://data.isric.org/geonetwork/srv/eng/catalog.search#/metadata/2a7d2fb8-e0db-4a4b-9661-4809865aaccfwms (accessed on 19 October 2024)	
Population data	Spatial distribution of population	https://human-settlement.emergency.copernicus.eu/download.php?ds=pop (15 October 2024)	
Satellite image	Landsat	United States Geological Survey (USGS)	

Source: Author (2025)

Table 3.2: Details of the satellite image that were utilised in this research

Zone	Satellite Image	Acquisition date	Resolution	Path/row
Lokoja	Landsat 4	2/12/1990	30 m	189/054 ; 189/055
	Landsat 7	12/9/2006	30 m	189/054 ; 189/055
	Landsat 7	12/25/2012	30 m	189/054 ; 189/055
	Landsat 8	12/28/2016	30 m	189/054 ; 189/055
	Landsat 8	12/18/2021	30 m	189/054 ; 189/055
Niamey	Landsat 4	1/10/1990	30 m	193/051
	Landsat 7	1/12/2006	30 m	193/051
	Landsat 7	1/25/2011	30 m	193/051
	Landsat 8	11/22/2016	30 m	193/051
	Landsat 8	12/6/2021	30 m	193/051

Source: Author (2025)

3.2 Methods of Data Analysis

3.2.1 Quality Control and Preliminary Data Processing

3.2.1.1 Data quality test for rainfall data

The collected data were quality-controlled using a combination of quantitative and visual methods to ensure consistency and suitability for the planned analyses. This involved:

(i) Time series graphs were generated to visualise the variability and distribution of the data. For example, time series plots helped to detect long-term trends in rainfall and temperature data over 30 years.

(ii) The double mass curves method was applied to the annual data to assess their coherence and detect any inconsistencies or breaks in the time series. This method is particularly useful for identifying periods when changes in collection practices or environmental conditions could have affected data quality. The curve is obtained by accumulating a rainfall series for the rainfall station whose consistency must be checked with the sum of the other rainfall stations considered (Khalil, 2021)

3.2.1.2 Trend, cycles and statistical change point detection (Mutation)

This study used a quantitative approach to analyse trends, cycles and points of change (mutations) in rainfall data from Niamey and Lokoja, two key stations in the Niger River basin. The primary objective was to evaluate the consistency of rainfall datasets and identify significant changes in rainfall patterns, which are crucial for understanding climate risks in the context of climate variability and urbanisation in the region (Caloiero *et al*., 2020). The research specifically aimed to answer specific questions, in particular to determine the uniformity of the rainfall data sets for Niamey and Lokoja over time, thereby ensuring the reliability of flood risk analysis, and to identify significant points of change in the data series.

To this end, a series of statistical homogeneity tests, notably those of SNHT, Pettit, Buishand and von Neumann, were applied. These tests were chosen for their complementary strengths in detecting breaks, changes and non-homogeneities in time series data, identifying sudden changes or anomalies that could signal breakpoints (Conte *et al*., 2019). In addition, trend detection tests, namely the Mann-Kendall test, Sen's slope and Sequential Mann-Kendall, were used to assess long-term changes, capturing both gradual and dynamic changes in rainfall patterns over time.

The analysis was performed using R software, which provided a robust platform for performing reliable calculations and visualising the results. This quantitative approach, incorporating tests for abrupt changes and long-term trends, allowed for a comprehensive assessment of rainfall variability. By verifying data consistency and identifying significant changes, the study provides valuable insights into the evolution of rainfall dynamics in Niamey and Lokoja, thereby enhancing flood risk management in the Niger River basin.

I. Homogeneity test for Rainfall data

Four tests were employed for homogeneity analyses in the rainfall dataset. These include the Standard Normal Homogeneity Test (SNHT), von Neumann test, Pettitt, and Buishand, which were applied to study homogeneity on an annual and monthly basis (Wijngaard *et al*., 2003). The various tests were carried out with the R software. The homogeneity test results obtained in this study are classified into three categories. According to the number of homogeneity tests that rejected the null hypothesis with a p-value of 0.05, the results are classified as "useful", "doubtful" and "suspect". The result of the homogeneity was interpreted according to the suggestion by Wijngaard *et al*. (2003). Based on the result, the rainfall stations were divided into the following classes:

Class U: 'Useful' One or none of the tests rejects the null hypothesis at the 5 % significance level

Claas D: 'Doubtful' Two of the tests reject the null hypothesis at the 5 % significance level

Claas S: 'Suspect' Tree or more of the tests reject the null hypothesis at the 5 % significance level

The stations classified as Class S were excluded from the analysis.

a) Standard Normal Homogeneity Test (SNHT) for Rainfall series:

The standard normal homogeneity test developed by Alexandersson, (1986) was used based on the following steps (Pohlert, 2020):

For a data series Xi (i is the year from 1 to n) with for mean "X" and standard deviation " ", T(k) is used for comparing the mean of the first "k" years of the record with that of the last "n - k", or σ

$$T_{(K)} = k\bar{z}_1^2 + (n-k)\bar{z}_2^2 \qquad (1 \le k < n) \tag{3.1}$$

With $\bar{z}_1$ *and* $\bar{z}_2$ defined by the equation 3.2:

$$\bar{z}_1 = \frac{1}{k}\sum_{i=1}^{k}\frac{(X_i - \overline{X})}{\sigma} \qquad and\ \bar{z}_2 = \frac{1}{(n-k)}\sum_{i=k+1}^{n}\frac{(X_i - \bar{X})}{\sigma} \tag{3.2}$$

Or the statistical test T_0 is defined by the equation 3.3:

$$T_0 = maxT(k) \tag{3.3}$$

b) Buishand's Range Test for Rainfall series:

The Buishand's Range test was modified, adjusted partial sums are calculated according to the following equations 3.4 (Pohlert, 2020):

With Xi (and i is the year from 1 to n) and is the mean and the standard deviation of "$\bar{X}\sigma$

$$S_k = \sum_{i=1}^{k}(X_i - \overline{X}) \qquad ou\ k = 1, 2, \dots .n \tag{3.4}$$

The statistical value of the test is calculated as described by the Equation 3.5:

$$Rb = \frac{(maxS_k + minS_k)}{\sigma} \tag{3.5}$$

$Rb/\sqrt{n}$ represents the critical value of Buishand, (1982) to test the relevance

c) **Pettitt's Test for Rainfall series**

Developed by (Pettitt, 1979), The Pettitt test is a non-parametric test for detecting change points (Otache *et al*,.2018) was implemented by following these steps:

The ranks r1, r2, . . . , rn of the data series X1, X2, . . . Xn in the series are arranged in ascending order and were used to calculate (equation 3.6) the statistics of the test (Patakamuri *et al.*, 2020) **:**

$$U(k) = 2\sum_{i=1}^{k} rj - k(n + 1) \tag{3.6}$$

With:

k= 1, 2...,n

The test statistic is the maximum of the absolute value of the vector using the equations 3.7:

$$K = max|U(k)| \tag{3.7}$$

When Uk determines the maximum value of K in a series, then a point of change was occur in the data series (Otache *et al,*.2018)

The approximate probability of a two-sided test was calculated using the following formula in equation 3.8:

$$p = 2\exp\left(\frac{-6k^2}{N^2 + N^3}\right) \tag{3.8}$$

If the p-value < ∝, then the null hypothesis is rejected. The time t where K occurs is the point of change.

d) Von Neumann ratio test for Rainfall series

It is defined as the ratio between the mean square of the successive difference and the variance, given as follows by equation 3.9 (Patakamuri *et al*., 2020) **:**

$$VN = \frac{\sum_{i=1}^{n-1}(X_i - X_{i+1})^2}{\sum_{i=1}^{n}(X_i - \bar{X})^2} \tag{3.9}$$

II. Trend Test

The two trend tests employed for the trend analysis were the non-parametric test namely: Mann-Kendall (Mann, 1945) and the Sen's slope (Sen, 1968). The trend analysis was performed for the monthly and the annual daily rainfall data for all the selected stations.

The Mann-Kendall test is based on Mann's work and Kendall's work is related to the Kendall correlation coefficient. This is a nonparametric test for determining the monotonic variation of a time series (increasing or decreasing). The Mann-Kendall test is arguably one of the most widely used nonparametric tests for detecting trends in hydrometeorological and environmental data (Gedefaw *et al*., 2018, Ali *et al*., 2019)**.** For this purpose, the test was used to determine changes in temporal data both at the annual and monthly level of precipitation, temperature and flow of the river. The S statistic of the MK test is determined by equation 3.10 (Gedefaw *et al.*, 2018) :

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\ (xj - xk) \tag{3.10}$$

With: n, which corresponds to the number in the data series, xi and xj represent the values of the time series i and j (j > i) respectively, and sgn(xj-xi) is the sign function given below by the formulas 3.11 to 3.12:

$$sgn(x_j - x_i) = \begin{cases} +1\ if\ (xj - xk)\ >\ 0; \\ 0\ if\ (xj - xk)\ =\ 0\ ; \\ -1, if\ (xj - xk)\ <\ 0; \end{cases} \tag{3.11}$$

Where j>k and k=1, 2... ..., n-1

J=2, 3...., n, and n is the number of the data.

$$Sgn(xj - xk) = \begin{cases} +1\ if\ (xj - xk)\ >\ 0; \\ 0\ if\ (xj - xk)\ =\ 0\ ; \\ -1, if\ (xj - xk)\ <\ 0; \end{cases} \tag{3.12}$$

the variance of (S) is determined by the following equation 3.13:

$$Var(S) = \frac{(n(n-1)(2n+5)) - \sum_{k=1}^{m} t_k(t_k-1)(2t_k+5)}{n} \tag{3.13}$$

Where n = Number of data values and S = The Mann-Kendall test statistic

The standardised test statistic Z is obtained by the following (3.14) calculation:

$$Z = \begin{cases} \frac{S\ -\ 1}{\sqrt{VAR(S)}} \quad If\ S > 0 \\ 0\ if\ S = 0 \\ \frac{S+1}{\sqrt{VAR(s)}} \quad If\ S < 0 \end{cases} \tag{3.14}$$

The variation of z indicates the trend, if Z is positive, it indicates an increasing trend, while a negative value of Z indicates a downward trend.

For the Sen slope test was used method for determining the magnitude of changes in data time series. The Sen slope is estimated as the median of all slopes per pair between each pair of points. It was estimated according to the following formula 3.15 (Sen, 1968 ; Patakamuri *et al*., 2020):

$$m = \frac{x_j - x_i}{j - i} \tag{3.15}$$

With: X_j and y_i to the values of the data at time j and i (j>i)." If there are n values of xj in the time series, there was N= n(n-2)/2 slope estimates. The Sen's slope corresponds to the median slope of these N values of slopes. A positive value of the Sen slope corresponds to an upward or upward evolution and a negative value indicates a downward or downward trend of the time series.

In addition, the Sequential Mann-Kendall Test (SQ-Mk) developed by (Sneyers, 1991), was applied to the level of annual precipitation for selected stations. The test can detect the point of change in a time data series (Tiwari and Pandey, 2019). The progressive u(t) values of the Mann-Kendall test were calculated in order to see the change in trend over time. The test was used based on the following equation (3.16 to 3.19), namely:

Time series data xj (with j = 1.2...., n), are compared with xi (or i = 1,..., d-1), From each point of comparison, the number of cases where xj > xi is counted and designated by nj is calculated.

The t of the test was calculated as follows:

$$t_j = \sum_i^j nj \quad (3.16)$$

The mean (E) and variance (var) of the statistical test:

$$E(t_j) = \frac{j(j-1)}{4} \quad (3.17)$$

And with variance (Var)

$$Var(t_j) = \frac{j(j-1)(2j+5)}{72} \quad (3.18)$$

The sequential or partial values of the statistics U(t) are then calculated as follows:

$$U(t) = \frac{t_j - E(t_j)}{\sqrt{var(t_j)}} \quad (3.19)$$

The values of the u'(t) of the series were obtained starting from the end of the series

3.2.1.3 Determination of flood signatures or point

I. Coefficients of variation (CV) for rainfall

The coefficient of Variation (CV), which is the percentage fraction of the standard deviation from the long-term annual average precipitation, was calculated by using the following equation 3.20:

$$CV = \frac{\sigma}{\mu} \times 100 \quad (3.20)$$

where CV is the coefficient of variation σ is the standard deviation μ is the mean precipitation. The CV was used to classify the degree of the variability of rainfall events. The table 3.3 allows the interpretation of the values obtained.

Table 3.3: The coefficient of variation (CV)

Categories	Interval of the coefficient of variation (CV)
Less	< 20
Moderate	20 < CV <30
High	30 < CV < 40,
Very High	40 < CV < 70
Extreme high	CV > 70

Source: Asfaw *et al*., (2018)

II. **Standardised anomaly index (SAI)**

The Standardised Anomaly Index (SAI) was used to define the recurrent nature of the hazard. This index makes it possible to characterise the deficit or excess amount of rainfall during the years more precisely and to deduce the main trends that have evolved during the period considered (Elagib, 2013).

The following expression was used to calculate the Standardised anomaly index (SAI) (Das and Bhattacharya, 2018)

$$Z = \frac{X_i - \bar{X}_i}{\sigma} \quad (3.21)$$

With: Z corresponds to the standardised rainfall anomaly; Xi is the annual rainfall of a particular year; Xi is the long-term average annual rainfall over an observation period and ' σ ' is the standard deviation of the annual rainfall over the observation period. This is to establish the temporal change regime concerning changing precipitation vis a vis pluvial and fluvial flood occurrence.

3.2.2 Detailed Study

3.2.2.1 Analysis of Land Use and Land Cover (LULC) Pattern

The determination of land use and land cover (LULC) trends in the two study areas between 1991 and 2021 was based on remote sensing and GIS techniques. The 30-year study period was divided into approximately equal 5-year intervals, resulting in the selection of satellite images for the years 1991, 2006, 2011, 2016, and 2021. This choice of intervals was motivated by the need to capture significant long-term changes for robust comparative analysis, while also corresponding to the availability of Landsat data, the requirement for images without major obstacles (such as heavy cloud cover), and the study's objectives of detecting dynamics in specific areas. It represents a balance between the desired level of detail and practical feasibility, and is within the range of intervals used in similar studies (Dammag *et al*., 2023). The images were obtained from the United States Geological Survey (USGS) website (see Table 3.2 for more details), with preference given to those with cloud cover of 10% or less.

The selected images underwent a series of pre-processing operations in the ArcGIS environment. All images were first projected into the same coordinate system to ensure accurate distance and area measurements within the study area. Geometric and atmospheric corrections were then applied to eliminate distortions caused by the sensor's shooting geometry and atmospheric conditions. Finally, a stack of relevant spectral bands was created to produce composite images optimised for determining land cover changes. Different combinations of bands (assigned to the Red, Green and Blue channels) were explored to improve the discrimination of different surface characteristics.

The classification of composite images was performed using spectral information to assign each pixel to a predefined land cover and land use (LULC) class. The classification scheme used included the main classes, namely Vegetation (including different types of forest and shrubland), Habitable/Urban Areas (including residential areas and road networks), Cultivated Land, Water Bodies and all Bare Land.

To improve the spatial consistency of the classification results, a standard 5x5 pixel majority filter was applied after classification. This filter is based on the principle that land cover tends to be spatially contiguous; a pixel is therefore more likely to belong to the dominant class in its immediate vicinity (Islam and Ahmed, 2011 ; Mandal, 2014).

The accuracy of the final classified LULC maps was rigorously evaluated. This evaluation was carried out using standard statistical metrics: Overall Accuracy (percentage of validation pixels correctly classified for all classes combined) and Kappa Coefficient (a robust measure of agreement between the classified map and reference data, taking into account the agreement expected by chance). The Kappa test was specifically used to validate the results of the land use maps.

3.2.2.2 Determination of flood vulnerability and risk patterns

The hierarchical analytical process (AHP), a multi-criteria decision-making approach, has been integrated with geographic information system (GIS) techniques to delineate areas susceptible to flooding and vulnerable to flooding in the study areas. This combined methodology systematically assesses flood risks by evaluating multiple environmental and socio-economic factors, assigning weights based on their relative importance, and spatially mapping the results to produce flood risk maps (Samanta *et al.*, 2018).

The selection of factors for assessing flood susceptibility and vulnerability was based on their ability to capture the main environmental and socio-economic aspects that influence flood processes, such as water flow, vegetation health and land use. Nine critical factors were chosen to derive the susceptibility map and three for the vulnerability map, each justified by its relevance in hydrological, ecological, and land management studies (Mitra *et al.*, 2022): elevation, slope, drainage density, topographic moisture index (TWI), distance from water courts, rainfall, soil type, normalised difference water index (NDWI) and normalised difference vegetation index (NDVI). Elevation and slope data were derived from digital elevation models (DEM) obtained from the USGS database. Elevation influences water flow and accumulation, with low-elevation areas being more prone to flooding; slope influences flow velocity and water retention. Steeper slopes reduce the risk of flooding due to faster runoff. Drainage network density measures the density of drainage networks, indicating areas where water flow is more concentrated and the risk of flooding is higher. The normalised difference water index (NDWI) and the normalised difference vegetation index (NDVI) were derived from satellite images. Factors such as land use and land cover (LuLc), population distribution, and proximity to roads were incorporated into the GIS analysis to assess vulnerability. These factors were processed to create a vulnerability map, reflecting the socio-economic exposure and susceptibility of the study areas to flooding. Each variable provides unique information about the environment, such as topography (elevation, slope), water distribution (TWI, drainage density, distance to rivers, NDWI), climate (precipitation), soil (soil type) and vegetation health (NDVI). These data are commonly used in hydrology, ecology or land management studies to understand how these factors interact (Mitra *et al.*, 2022).

The TWI thematic layer is prepared from the SRTM using equation 3.14

$$TWI = Ln\left\{\frac{a}{\tan B}\right\} \tag{3.14}$$

With A and B representing the specific characteristic area and slope of the region, respectively.

NDWI and NDVI are both extracted from the satellite image using the following equation 3.15 and 3.16 respectively:

$$NDWI = \frac{Green - SWIR}{Green + SWIR} \tag{3.15}$$

$$NDVI = \frac{NIR - Red}{NIR + Red} \tag{3.16}$$

With NIR represented the near-infrared band, green to the green band, SWIR presents the shorts-wave infrared bands (Choudhury *et al*., 2022).

The workflow consists of three main steps (Boultif *et al*., 2024) :

(i) Pair-wise comparison matrix: Factors were compared in pairs, with scores ranging from 1 (equal importance) to 9 (extreme importance), generating a matrix of relative priorities.

(ii) Assignment of Weights: Weights were assigned to each factor according to their contribution to flooding, and the consistency of the matrix was validated to ensure its reliability.

(iii) Flood risk mapping: The weighted factors were combined and a classification was applied to rank the susceptibility, vulnerability and risk to flooding in the study areas, categorising areas from very low to very high risk. This integrated approach enabled a systematic assessment of flood-risk areas, ensuring that each factor's contribution was correctly represented. The weighting allows the values to be judged against each other on a scale of 1 to 9 based on the indices proposed by Saaty (1990). When comparing one criterion with the other, each factor was assigned a score, with the lower figures representing non-essential factors and the higher values indicating much more important factors. Between the two indices, all gradations are possible, depending on the relationship of importance between the criteria, from the most important to the least important. So, if the relative importance of n has been assigned to the comparison is compared here in the table coincides with the diagonal elements it is scored with the value. two criteria A and B, then the ratio between B and ratio between is evaluated by the fraction of 1/n. When the element A. the figure 3.3 describes the methodology used for this objective.

Risk is commonly expressed using the following equation 3.17:

$$\text{Risk} = \text{Hazards} \times \text{Vulnerability} \quad (3.17)$$

It is often described as the product of three main factors, including exposure, which specifically refers to the physical aspects of vulnerability. In this study, specific weights were assigned to the different classes and thematic indicator layers based on their respective characteristics. The following equation demonstrates the formula used to calculate the eigenvector (Vp) and the weighting coefficient (Cp):

$$\text{Vp} = \sqrt[n]{\text{C1} \times \text{C2} \ldots . \times \text{Cn}} \quad (3.18)$$

With n being the number of factors used (nine factors in this study), the consistency ratio (CR) is derived using the following formula of 3.19:

$$\text{Cp} = \frac{\text{Vp}}{\text{Vp1} + \text{Vp2} + \cdots .. + \text{Vn}} \quad (3.19)$$

The pairwise comparison tables were ranked with nine factors in the field of natural disasters. Their results were standardised and examined using the consistency ratio (CR) test where CI is obtains by the equations 3.20

$$\text{CI} = \frac{(\lambda\text{max} - \text{n})}{(\text{n} - 1)} \quad (3.20)$$

The matrix was coherent if the ratio is < 0.1. the consistency ratio was calculated using the following equation 3.21:

$$\text{CR} = \frac{\text{CI}}{\text{RCI}} \quad (3.21)$$

Where CI is the coherence index, RCI is the random coherence index whose value depends on the number n, and n is the number of factors as shown in the table 3.4 (this study used nine factors which gave and RCI value of 1.45). Where CI: coherence index; n: number of factors evaluated (n=9 for the case of this study); λmax: eigenvalue calculated from the comparison matrix.

The pairwise comparison matrix is consistent if λMax ≥ n

The maximum eigenvalue, λmax, is determined using the following equation 3.22:

$$\lambda Max = \frac{[E]}{n} \tag{3.22}$$

Table 3.4:Consistency ratio table

n	1	2	3	4	5	6	7	8	**9**	10	11	12	13	14	15
RCI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	**1.45**	1.49	1.51	1.48	1.56	1.57	1.59

Source: (Hussain *et al*., 2014)

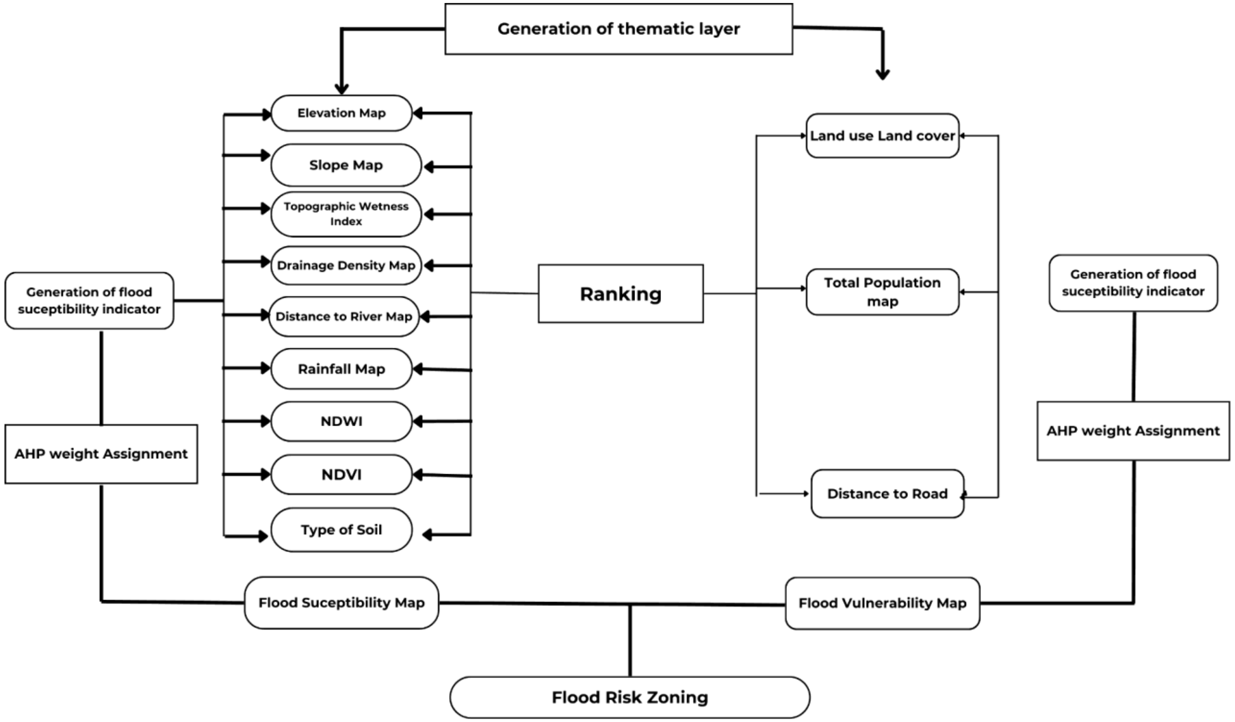

Figure 3.3: Flow chart used for objective two

3.2.2.3 Evaluation of flood risk based on extreme rainfall or heavy rainfall

This study employed a structured methodological approach to examine the relationship between extreme precipitation events and flooding in the study area. The analysis involved calculating a series of rainfall indices for frequency, intensity, and duration using daily rainfall time series data. These indices were selected based on the guidelines provided by the Expert Team on Climate Change Detection and Indices (ETCCDMI) (Fofana *et al.*, 2022). A detailed summary of the selected indices is provided in Table 3.5. The analysis of these indices was performed with the software R Studio, leveraging the RClimDex package, which is specifically designed for analysing climate extremes. This tool facilitated the accurate calculation and visualisation of trends in extreme rainfall, providing a comprehensive understanding of their temporal patterns. In parallel, in addition to rainfall indices, the study employed statistical methods to determine return periods associated with extreme precipitation events, which are critical for understanding the risk of floods. Two widely used statistical distributions in hydrology; the Generalised Extreme Value (GEV) distribution and the Gumbel distribution were applied to adjust extreme values from the daily rainfall series. These models allow for the estimation of probabilities and magnitudes of extreme rainfall events under varying return periods. The HYFRAN software (El Adlouni and Bobée, 2015), was used to estimate the different return periods of extreme rainfall (Bologo *et al*., 2019). A return period is the average interval between two events of a given intensity, and is defined by the following formula 3.23:

$$T = \frac{1}{1 - F(x)} \tag{3.23}$$

With F represents the probability of non-exceedance associated with the best-fit distribution.

Given the current context of climate change, understand the change in the frequency and intensity of extreme events are changing, as this amplifies the risks associated with phenomena such as floods, droughts and other disasters (Tazen *et al*., 2019; Avila-Diaz *et al.*, 2020).

Table 3.5: Extreme precipitation Indices applied in this study

Indices	Index description	Units
RX1DAY	Annual maximum amount of precipitation on 1 day	mm
RX5DAY	Annual maximum amount of precipitation on five consecutive days	mm
R95p	Total annual extreme daily precipitation above the 95th percentile	mm

3.2.2.4 Development of flood scenario for varying climate change

The methodological approach was applied to characterise flooding in the study area and develop comprehensive flood scenarios under different climate change conditions. This approach integrated hydrological, topographical and climatic data into a hydraulic modelling framework, using HEC-RAS 6.0 software in a 2D environment.

The main datasets used in the modelling process were as follows:

(i) Digital Elevation Model (DEM): provides detailed topographic information, essential for accurately defining the geometry of the riverbed and identifying flood-prone riparian areas (valleys). The 30m resolution DEM has been used to capture the subtle variations in terrain that influence the flow of water and the extent of flooding.

(ii) Land use data: land use and land cover maps were incorporated to assess surface characteristics and their impact on infiltration and runoff. These data were used to differentiate between areas of natural vegetation, urban (impermeable) areas and flood zones.

(iii) Soil data: soil types have been mapped to create an infiltration map, which shows the capacity of the soil to absorb or repel water during extreme rainfall events.

(iv) Precipitation data: Precipitation projections from CO_2 emission scenarios (SSP585) were used to estimate future hydrological conditions. These scenarios simulated peak flows and flood dynamics under different climatic conditions.

The integration of these datasets into HEC-RAS 6.0 in 2D was chosen because of its ability to simulate detailed flood dynamics. The 2D modelling capability provides more accurate results than 1D models, as it allows the lateral movement of water over complex terrain to be simulated. This makes it particularly useful in areas with varying topography and land use. The intensity of flooding was grouped into four categories based on precipitation levels:

(i) Low Precipitation: 0–20 mm

(ii) Moderate Precipitation: 20–50 mm

(iii) High Precipitation: 50–100 mm

(iv) Very High Precipitation: Greater than 100 mm

This categorisation enabled a clearer understanding of the relationship between rainfall intensity and flood dynamics. Each category was analysed to assess its corresponding flood extent and depth within the study area. The hydraulic model was built and calibrated using historical flood data in HEC-RAS 6.0 to simulate flood propagation (Figure 3.4). The key stages were as follows:

(i) Model set-up: The DEM was used to define the river geometry, including cross-sections, floodplains and riparian zones.

(ii) Hydrological data: Rainfall data from the SSP585 scenarios was processed in R Studio to extract the relevant rainfall patterns, which were then converted into hydrological input conditions for the HEC-RAS model.

(iii) Integration of soils and land use: Manning's roughness coefficients were assigned according to land use and soil type to account for variations in resistance to water flow.

After calibration, the model was validated using an independent set of historical flood data. This step confirmed the predictive accuracy of the model for different conditions, thereby strengthening confidence in its ability to simulate future flood scenarios in the context of climate change.

The 2D modelling approach was essential to visualise the spatial distribution of water depth for flood events. The model simulated the propagation of floods under different rainfall intensities and return periods. The simulations focused on:

Extent of flooding: Mapping of the geographical boundaries of areas subject to flooding.

Flood depth: Estimation of the water depth in the study area, a key parameter for assessing damage and potential risks.

The results of the HEC-RAS simulations were exported and analysed in ArcGIS to create flood maps. These maps highlighted the area most vulnerable to flooding under different climate scenarios. The spatial extent and depth of flooding. The expected results of this methodology: Detailed maps showing the extent and depth of flooding under different climatic conditions and rainfall intensities. Understanding climate impacts: Information on how increased rainfall under different climate scenarios will influence flooding dynamics in the study area.

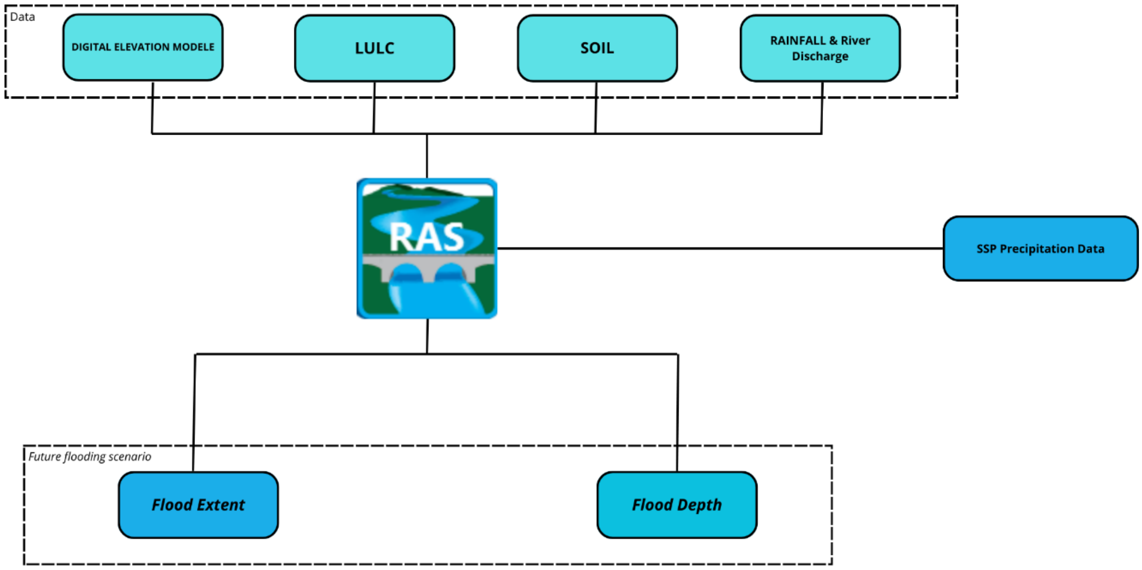

Figure 3.4: Flow chart of the third objective

3.2.2.5 Development of Flood Risk Management / Adaptation Strategies

(i) Sampling Technique and Sample Size

The study population did not encompass the entire town; only individuals residing within a specified radius of the river were considered. Consequently, the study does not cover the entire floodplain, but focuses on samples taken from specific spatial areas, and the results are generalised accordingly. At the beginning of the data collection process, the researcher informed all participants of the ethical and confidentiality considerations of the study. The researcher applied specific inclusion criteria when selecting the population sample. People affected by the flooding and associated factors were included in the study. The age of the participants was a key factor, with the researcher only including people aged 18 and over. People who were not directly or partially affected by the flooding or its after-effects were excluded from the study. A sample size indicates the proportion of a research population adequately selected to represent.

The study population, characteristically, the sample size of this study was determined using the Sample Size Calculator. Thus, the representation of households was surveyed in both Lokoja and Niamey. The sampling technique was based on the following classical formula 3.24:

$$n = \left[z^2 \times \frac{p \times q}{e^2}\right] \qquad (3.24)$$

Where:

n = sample size

z = linked to 95% confidence interval (use 1.96), The level of confidence used in ENA is always 95%.

p = is a proportion of people (head of household) with the behaviour estimated to be accurate ($p = \frac{n}{N} i$). with N corresponding to the size of the study population. The maximum proportion of 50% was chosen for the study. expected prevalence (as a fraction of 1)

q = 1- p (expected non-prevalence)

e = relative desired precision, corresponding to the margin of error that one is prepared to accept (e.g. if precision is 5%, e= 0.05), and for the study, the n by using the following formula in determining the sample size.

$$n = \left[1{,}96^2 \times \frac{0.5\ (1 - 0.5)}{0.05^2}\right] = 384{,}16 \sim 384$$

The sample per study area was 384 heads of household. So, in total, considering both cities for the study, this corresponded to 768 households were surveyed for the study

This study employs a mixed-methods approach integrating both qualitative and quantitative techniques to assess and prioritise flood mitigation strategies. The analysis of perceptions of flood risk management employs a structured approach using a 4-point Likert rating scale to quantify respondent's perceptions of flood risk management practices, with ratings defined with the following ratings:

1 : Strongly Disagree

2 : Disagree

3 : Agree

4 : Highly Agree

The methodological approach can be refined for greater clarity and depth by improving the explanation of the Likert scale, the development of the SWOT and the strategic implications derived from the results. The perception of flood risk management was assessed using a four-point Thus, the reference mean for the scale was obtained as:

Reference Mean $=\frac{4+3+2+1}{4} = 2.5$ in this context, a mean score of $\geq 2.5 \geq 2.5$ indicates agreement with effective flood risk management practices, while a $< 2.5 < 2.5$ score suggests disagreement. This threshold is crucial for interpreting survey results and understanding community perceptions.

To complement the perception analysis, the SWOT matrix was employed to expand the traditional SWOT framework. The SWOT matrix is an extension of the SWOT analysis framework, providing a strategic tool to identify how internal strengths and weaknesses interact with external opportunities and threats. The data for this analysis were obtained from survey results that evaluated perceptions of flood risk management and adaptation strategies.

(i) Strengths (S): Survey statements with mean scores above 2.5, reflecting strong community agreement.

(ii) Weaknesses (W): statement with mean scores below 2,5, Internal limitations or constraints to be taken into account.

(iii) Opportunities (O): External influences that can have a positive impact on management strategies, such as a technological advancement or an aid

(iv) Threats (T): External risks or challenges that need to be attenuated**.**

In this study, the strengths and weaknesses were identified with statements with the highest and lowest mean, respectively. The opportunities and threats were derived from external factors that influence flood risk management.

Development of the strategic pairings of SWOT as shown in equation 3.22 :

$$SWOT = \begin{cases} SO: (w_s S_i + w_o O_j) \\ ST(w_s S_i - w_t T_k) \\ WO - (w_w W_m + w_s O_j) \\ WT\ (w_w W_m - w_t T_k) \end{cases} \quad (3.22)$$

With:

(i) S_i: Score of the i-th strength from survey results

(ii) O_j: Weight of the j-th opportunity derived from contextual analysis

(iii) W_m: Score of the m-th weakness

(iv) T_k: Weight of the k-th threat

(v) w_s, w_o, w_w, w_t : Weights indicating the relative importance of strengths, opportunities, weaknesses, and threats, respectively.

In this study, Strengths and Weaknesses were identified as the statements with the highest and lowest mean scores, respectively, from the survey data.

Based on contextual and environmental analyses, opportunities and Threats were derived from external factors influencing flood risk management.

The SO, ST, WO, and WT strategies offered actionable insights:

SO, strategies: Combine strengths and opportunities to exploit external benefits (such as using established community networks to access international funding).

ST strategies: Mitigate threats by applying strengths (e.g., leveraging technical expertise to counteract resource mismanagement).

WO strategies: Address weaknesses by utilising opportunities (e.g., addressing low technical capacity through training initiatives funded by international partners).

WT strategies: Reduce weaknesses to counter threats (e.g., improving early warning systems to reduce the impact of misinformation).

This combined approach of Likert-scale perception analysis and SWOT strategic pairing ensures a comprehensive evaluation of flood risk management for the study area. It identifies priority areas for intervention and aligns internal strengths and weaknesses with external opportunities and threats to craft actionable, sustainable strategies.

3.3 Limitation of the Methodology

This study offers an in-depth analysis of climatic, environmental and socio-economic dynamics, integrating geographical, human and climatological perspectives. A rigorous approach combining field surveys, documentary analysis and remote sensing was adopted. This methodology focuses on documentary research, the collection and analysis of quantitative data (meteorological records) and qualitative data (population surveys), and the interpretation of results. Fieldwork gathered crucial information on this variability, public perceptions and local adaptation strategies. This methodological approach has made it possible to identify critical areas and local adaptation strategies, providing a systemic and nuanced understanding of the complex interactions between environmental and human factors, as well as the associated risks.

However, several limitations affect the scope of the results and must be acknowledged. At the level of data collection, there are gaps, including potential inaccuracies in survey data due to incomplete records, inconsistencies or logistical constraints, affecting overall reliability.

The sampling methods used may limit the representativeness of the diversity of the populations studied. Issues such as small sample sizes may affect the reliability of the data, particularly concerning public perceptions and adaptation strategies. The complexity of climate systems and the difficulty of anticipating future human actions make these projections inherently uncertain. The results are based on current knowledge and may evolve.

In terms of resolution, the use of DEM limited to a resolution of 30 metres has restricted the accuracy of the topographical analysis, which is crucial for modelling flows in micro-watersheds. Although this resolution allows for a general identification of potentially vulnerable areas, it is insufficient to capture the details necessary for accurate mapping of risk areas, particularly in urban areas or areas with complex topography. Higher-resolution DEM (e.g., 10 m or 1 m) would allow for a more detailed analysis but are often costly and less available, especially in developing regions. In addition, the resolution of the satellite images used in certain periods has proven inadequate for accurately mapping informal infrastructure or precarious habitats. Finally, a notable limitation concerns precipitation data, particularly for the Lokoja area. Unlike Niamey, which has several stations allowing for robust interpolation, Lokoja has only one meteorological station. This limited coverage does not adequately reflect the spatial variability of local precipitation, creating an asymmetry in the quality and reliability of climate data between the two study areas. A higher density of stations would significantly improve the accuracy of analyses for Lokoja.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Results

4.1.1 Preliminary analysis

Table 4.1 presents the descriptive statistics of annual rainfall data across the study stations. The highest variability was found at the Niamey Ville climate station, with a CV of 24.98, while the lowest was at the Niamey airport station, with a CV of 20.72. All the other stations showed moderate variability, with CV values between 20 and 30 %. According to the CV results, the study area is characterised by intermediate rainfall variability, which has implications for flood risk and water resource planning. The characteristics of the data of annual precipitation collected are presented in the following table 4.1. Furthermore, the descriptive statistical analysis of the annual precipitation data collected from different stations provides valuable insights into the characteristics of rainfall in the study area. The mean annual rainfall values range from 500.18 mm at Boubon to 590.12 mm at Say station, while in Lokoja, the mean reaches 1248.00 mm, reflecting the spatial variability in precipitation across the region. The minimum and maximum values highlight the range of annual rainfall experienced in the region, with the highest maximum value of 2517.00 mm recorded at Lokoja. The temporal plot of the distribution of total annual precipitation around the long-term mean for the stations is illustrated in Figure 4.1

Table 4.1: Statistical description of the annual rainfall (mm)

	Statistics						
Stations	Mean (mm)	Standard Deviation	coefficient of variation (%)	Skewness	Minimum (mm)	Maximum (mm)	Kurtosis
Niamey Ville	584.16	145.93	24.98	2.09	386	1161.3	5.41
Niamey Airport	550.45	115.96	20.72	0.73	359.8	833.2	-0.06
Say	590.12	138.79	23.52	0.63	376.9	927.9	-0.37
Boubon	500.18	118.13	23.35	-0.1	274.96	737.95	-0.12
Kollo	502.13	114.94	22.89	0.63	261.7	848.5	1.17
Lokoja	1248	326	21.1	2	772	2517	3.53

As shown in Figure 4.2, graphs of standardised precipitation anomalies, the years show significant fluctuations in precipitation compared with the long-term average, the alternating periods of surplus and deficit precipitation. This section presents precipitation anomaly analyses for the stations selected for this study. The standardised anomalies reveal significant changes in rainfall over the years compared with the long-term average. These results highlight an alternation between periods of surplus and deficit in rainfall, demonstrating strong regional climatic variability. The Niamey Ville and Niamey Airport stations, as well as the Kollo station, show striking similarities in their respective wet and dry seasons occurring in the same geographical region. In particular, excessive rainfall in 1998 stands out, with notable differences of + 3.95 for Niamey Ville, + 2.30 for Niamey airport and + 3.01 for Kollo. Moreover, in 2017 Niamey airport recorded another wet period (+ 2.43), highlighting a new phase of exceptionally wet weather. Nevertheless, despite these wet periods, the Niamey Ville and Kollo stations show a decrease in annual precipitation, with declines of -03.07 % and -03.56 % respectively, highlighting an overall downward trend in precipitation in these regions.

In contrast to the trends observed in Niamey and Kollo, the stations in Say and Lokoja show an increase in rainfall over the period studied. These increases, of 3.50 % 3.00 %

respectively, illustrate a marked rainfall trend in these regions. In addition, some years stand out for their extreme humidity. For example, the Say station recorded anomalies of +2.43 in 1994 and +2.14 in 2020, highlighting peaks in humidity in both periods. The Lokoja station showed significant increases in 2015 (+2.53) and 2016 (+3.98), the latter being an exceptionally wet year.

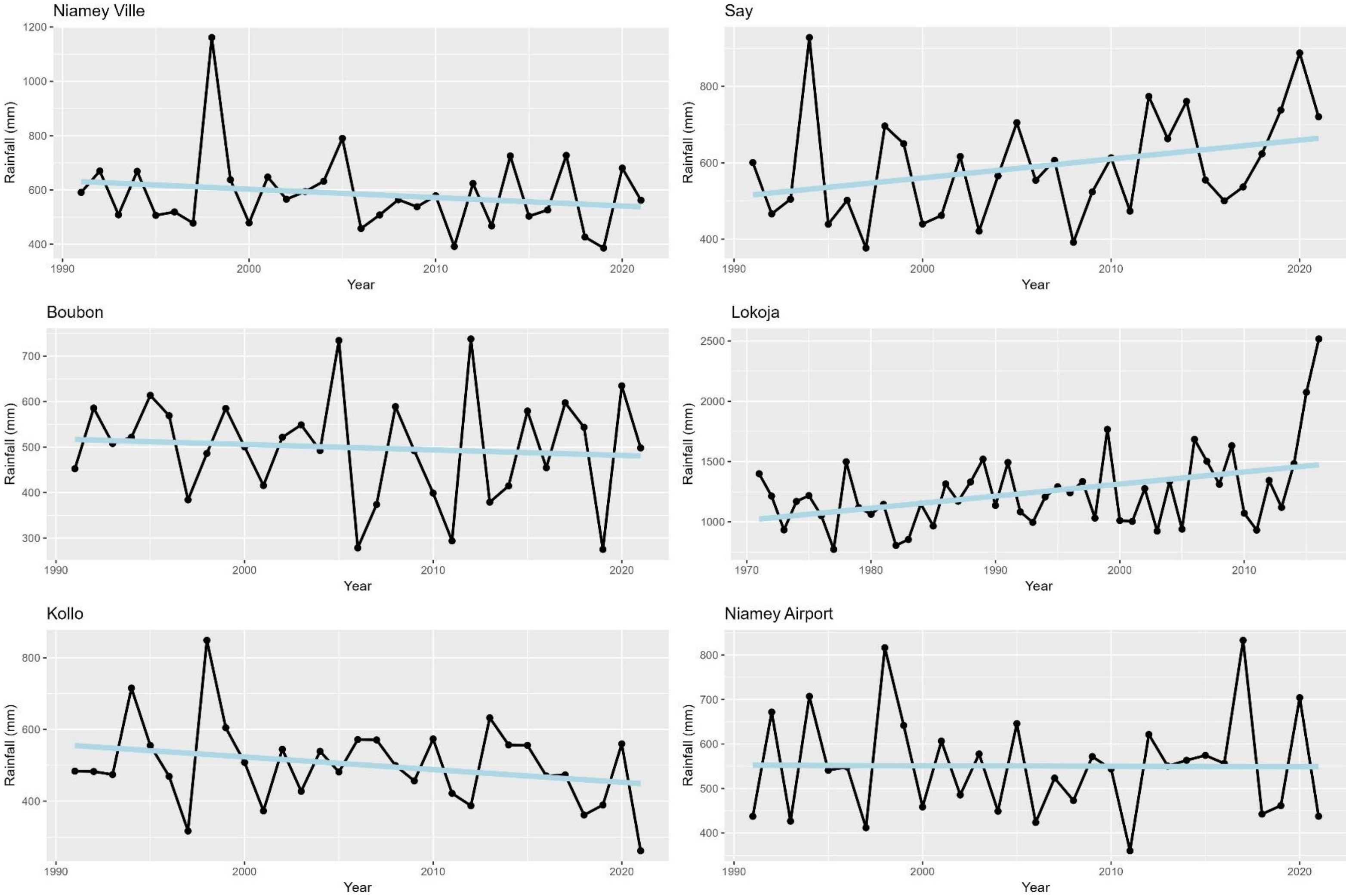

Figure 4.1: Annual rainfall partner for the specific stations

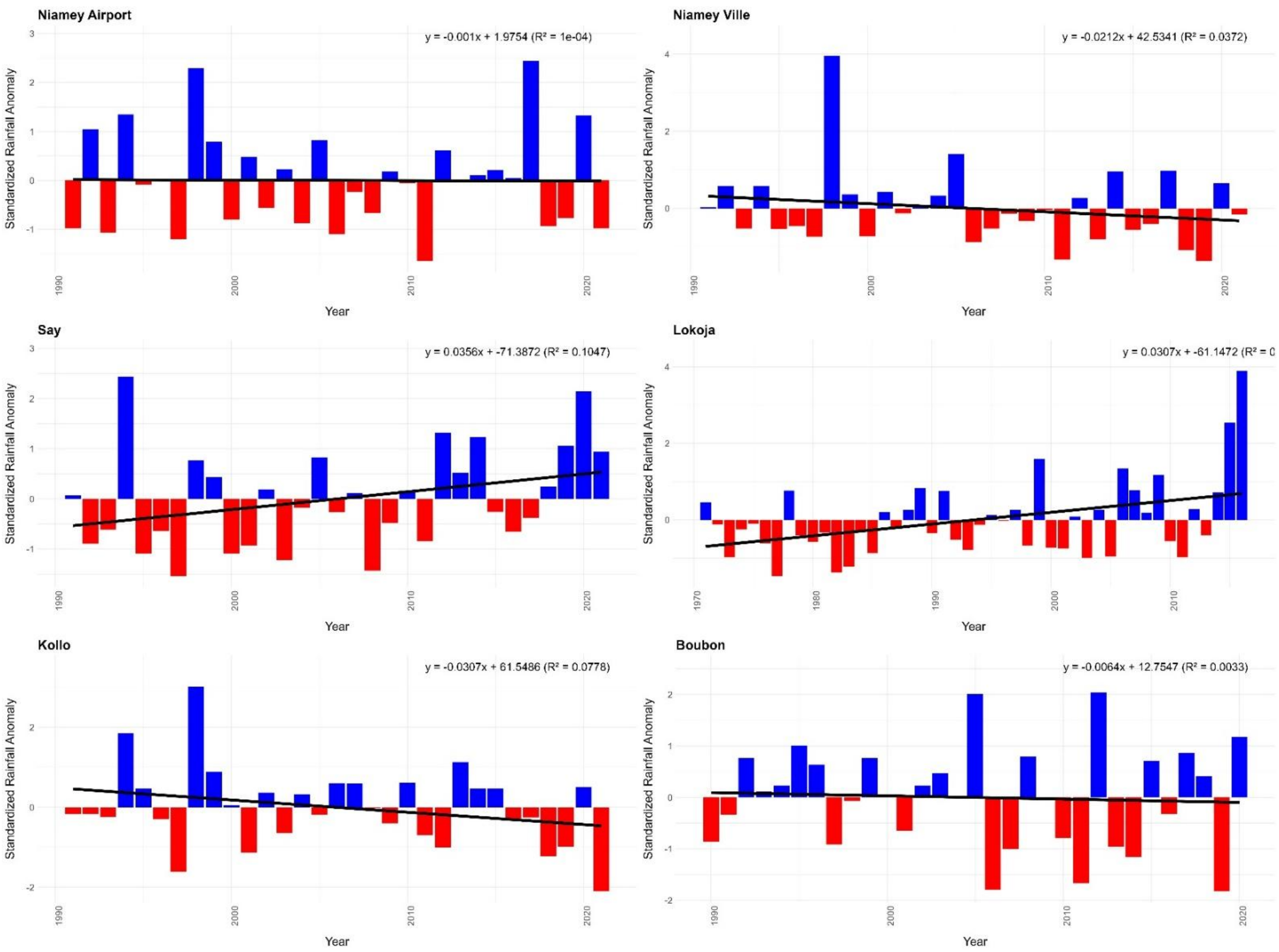

Figure 4.2: The standardised precipitation anomaly (SPA) of the selected raining gauging

4.1.2 Consistency and Homogeneity Analysis

4.1.2.1 Consistency analysis

The double mass curve method was employed to assess the consistency of the precipitation data before applying statistical analyses. Figure 4.3 presents the double mass curves for the observations from the precipitation records from the analysed stations. The cumulative precipitation for each station was compared with the average cumulative precipitation for the other stations. The resulting graphs show well-defined slopes and straight lines for all stations, indicating a high degree of consistency in the precipitation measurements. This consistency suggests that the data from all the stations are reliable and do not require adjustment, which reinforces the robustness of the dataset for further analysis.

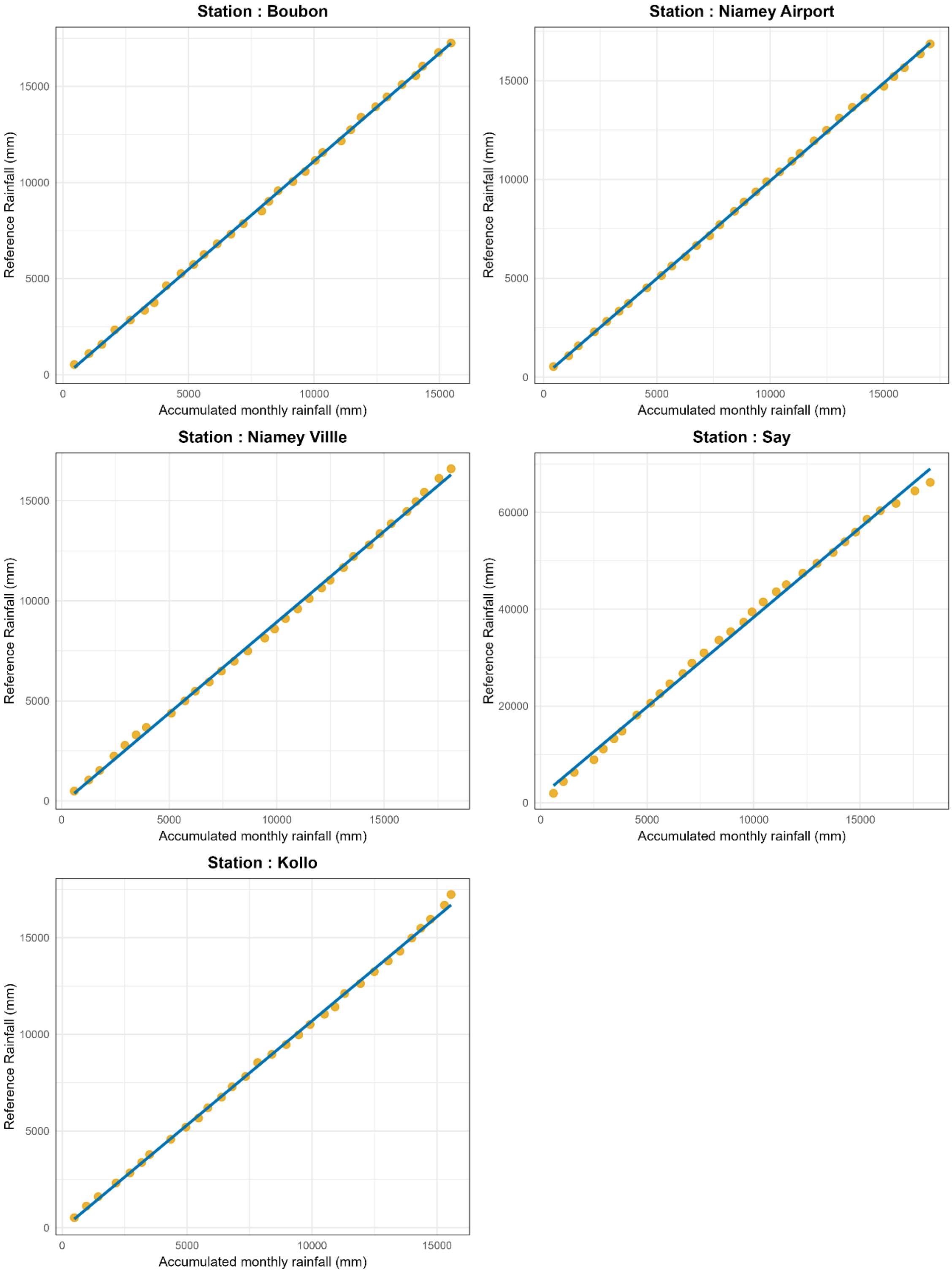

Figure 4.3: Consistency testing of rainfall data for each station

4.1.2.2 Homogeneity analysis

The monthly temporal data from the Ten rainfall stations for each station were subjected to four homogeneity tests (Pettitt test, Standard Normal Homogeneity Test (SNHT), Buishand test (BRT) and von Neumann test (VNR). The results of the homogeneity tests were used to detect non-homogeneous periods according to the number of tests rejecting the null hypothesis. This study accepted the null hypothesis for data with a calculated p-value above the significance threshold (0.05).

(i) Rainfall monthly homogeneity test

The results of the monthly precipitation homogeneity tests for the various stations are presented in Table 4.2. The stations are classified as 'useful' (U), 'doubtful' (D) or 'suspect' (S) according to the number of homogeneity tests that rejected the null hypothesis of homogeneity. The analysis indicates that most stations have homogeneous and useful monthly rainfall data series (U). However, some inhomogeneities were detected at certain stations: Kollo stations was classified as having inhomogeneous data for June. The Say station was classified as doubtful (D) for the month of March. The Lokoja station presented inhomogeneous data, classified as doubtful (D) for the months of March and July, and as suspect (S) for the month of May. For the rest of the stations, the monthly rainfall data were classified as homogeneous, and the climatic trends and analysis results for these stations can therefore be considered reliable. The identification of inhomogeneous data series at certain stations is an important finding, as it suggests that analysis results for these specific months and stations should be interpreted with caution. The classification of stations as useful, doubtful or suspect, based on the homogeneity tests, provides an indication of the level of confidence that can be placed in the data and the conclusions drawn from it.

Table 4.2: Results of a homogeneity test for monthly rainfall data

Stations \ Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Niamey Ville	Na	U	U	U	U	U	U	U	U	U	U	U
Niamey Airport	U	U	U	U	U	U	U	U	U	U	Na	U
Kollo	Na	Na	U	U	U	S	U	U	U	U	Na	Na
Boubon	Na	Na	Na	U	U	U	U	D	U	U	Na	Na
Say	Na	Na	D	U	U	U	U	U	U	U	Na	Na
Lokoja	U	U	D	U	S	U	D	U	U	U	U	U

Na= "Missing Values" U = "Useful" ; D= "doubtful" ; S= "Suspect"

On the basis of the results in Table 4.3, these reveal significant disparities between stations: Boubon and Kollo are the stations with the most missing values ("NA"), respectively five and four over the 12 months. They also have isolated occurrences of "D" (once at Boubon) and "S" (once at Kollo). The Lokoja station stands out for the total absence of "NA", but with two occurrences of "D" (July and March) and one of "S" in May, suggesting greater homogeneity in its data. The stations at Niamey (Ville and Airport) show a dominance of "U" (in November and December, respectively), with only one "NA" each, indicating a relative homogeneity of observations. The Say station has a similar profile to Boubon and Kollo, with four "NA" and one "D", but no "S".

For the monthly variability highlights seasonal trends: January and November are the months with the most missing data (four "NA" each), probably linked to logistical or climatic constraints. "D" are concentrated in March (two cases), July (one case), and August (one case). The "S" only appeared in June (one case in Kollo) and May (one case in Lokoja), suggesting exceptional rainfall events. The months of April, October and September are the most complete, with zero "NA" and a total dominance of "U", indicating reliable collection and stable conditions. Overall, Lokoja emerges as the most homogeneous station (with a total of zero "NA"), while Boubon and Janvier represent the critical points of missing data. The occurrences of "D" and "S", although rare, underline the importance of studying anomalies to understand climate extremes.

To assess the homogeneity of the rainfall data series, the monthly data were aggregated to obtain the total annual precipitation for each station. The four homogeneity tests were then applied to the annual precipitation data for each station. The results show that all the selected stations were classified as belonging to the "Useful" class. This indicates that the annual rainfall data (Table 4.3) series at these stations do not exhibit significant inhomogeneities or changes over the study period.

The classification of all stations as "Useful" suggests that the annual precipitation data series can be considered homogeneous and reliable for further analysis and interpretation of long-term climatic trends and patterns. The lack of detected inhomogeneities in the annual data provides confidence that the observed variations and changes in precipitation are reflective of actual climatic conditions rather than being influenced by non-climatic factors or data quality issues. This finding on the homogeneity of the annual rainfall data series is an important validation of the data quality and reliability, which underpins the subsequent analyses and conclusions drawn from the precipitation records at the selected stations.

Table 4.3: The p-values obtained from the four homogeneity tests for annual rainfall

Stations	Statistics P-Value				Results
	Pettitt Test	Standard Normal Homogeneity Test (SNHT)	von Neumann's test/	Buishand review	
Niamey City	0.5048	0.6715	0.9601	0.5379	Useful
Niamey Airport	1	0.9917	0.9954	0.9158	Useful
Kollo	0.6102	0.3381	0.487	0.7665	Useful
Boubon	0.9447	0.887	0.94	0.76	Useful
Say	0.1096	0.1356	0.2757	0.18	Useful
Lokoja	0.1834	5.00E-05	0.3599	0.1218	Useful

(ii) Temperature homogeneity test

The temperature data for the available station (Niamey Airport) were subjected to homogeneity tests at both the monthly and annual time scales. The results of these tests are presented in Table 4.4. The analysis of the monthly temperature data shows that most months had homogeneous data for maximum and minimum temperatures at the station. This indicates that the monthly temperature records can be considered reliable for further analysis.

However, the results of the annual temperature homogeneity tests present a different picture. At the annual time scale, the Niamey Airport station was classified as "suspect" for maximum, minimum, and mean temperatures, indicating the presence of potential inhomogeneities in the long-term annual temperature data series. Further examination of the monthly results reveals some specific issues. The Niamey Airport station showed inhomogeneities in minimum temperatures during several months (March, June, July, August, September, and November). The mean temperatures at this station were also classified as inhomogeneous in March and November.

Table 4.4: Results of homogeneity tests for temperature on a monthly and annual

Stations \ Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Niamey Airport Tmax	U	U	U	D	U	U	U	U	U	U	U	U	S
Niamey Airport Tmin	U	U	D	U	U	S	D	D	S	U	S	U	S

(iii) Discharge homogeneity tests

Homogeneity tests were conducted on the river discharge data for the available gauging stations, including Niamey, Kandadji, and Lokoja. For the Niamey station (table 4.5), the results of the monthly discharge homogeneity tests indicated that the p-values for four months were classified as inhomogeneous: January, July, August, and September. At the Lokoja station, the majority of the months were classified as "Useful", indicating homogeneous data. However, January and October were classified as "Suspect", and November was classified as "Doubtful". When considering the annual discharge data, the Niamey station was classified as inhomogeneous, while the Kandadji and Lokoja stations were classified as "Useful", indicating homogeneous annual discharge records.

Table 4.5: Results of homogeneity tests for discharge on a monthly and annual

Stations \ **Months**	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Niamey	D	U	U	U	U	U	S	S	D	U	U	U	S
Kandadji	S	D	U	U	U	U	U	U	U	U	U	D	D
Lokoja	S	U	U	U	U	U	U	U	U	S	D	U	U

4.1.3 Trend, Cycle, Mutation and Flood Point

4.1.3.1 Annual rainfall trends

The annual rainfall curves revealed various trends depending on the sites studied, with increases in some cases and decreases in others. These variations reflect the potential effects of climate change, which is altering rainfall patterns on different geographical and temporal scales.

(i) Increasing precipitation trends

Sites such as Lokoja show positive slopes in annual rainfall trends. These increases could be attributed to phenomena such as the strengthening of monsoons in West Africa. Climate change could also intensify hydrological cycles, leading to increased rainfall in some areas. However, this increase is not necessarily positive. In Lokoja, for example, increased rainfall amplifies the risk of flooding, particularly in low-lying areas and along rivers. This highlights the need to improve drainage infrastructure and implement adaptation strategies, such as climate-sensitive urban planning and the installation of retention basins.

(ii) Precipitation declines trends

Some sites, such as Niamey Ville, Say, Kollo and Niamey Airport, show negative slopes, indicating a gradual decrease in rainfall. This trend is consistent with climate projections for parts of West Africa (Tarif, 2023), where aridification and increased rainfall variability disproportionately affect certain regions. Reduced rainfall in these areas may exacerbate drought conditions, compromising rain-fed agriculture, which is crucial to local food security, and reducing the availability of drinking water.

(iii) High inter-annual variability

The low R^2 values observed for all sites indicate high inter-annual variability in rainfall. This reflects the complexity of climate impacts in the region and highlights the challenges for climate models, which often struggle to capture these small-scale fluctuations. This variability also complicates water resource planning and increases uncertainty for farmers and local decision-makers. In sites where rainfall is increasing, policies need to be put in place to manage the risk of flooding. In Lokoja, this includes the construction of effective drainage systems, the reforestation of catchment areas and the identification of areas vulnerable to flooding. For sites with reduced rainfall, strategies such as sustainable irrigation, rainwater harvesting and the adoption of drought-resistant crops are essential to mitigate impacts.

The results highlight contrasting climate dynamics in the region studied. Increases in rainfall in some areas increase the risk of flooding, while decreases in others accentuate the problems of drought and water security. These trends, linked to climate change, require targeted responses to reduce vulnerability and strengthen the resilience of local populations. A better understanding of climate variability and trends will help to effectively guide policies for managing water resources and adapting to climate risks.

(iv) Annual Rainy Days trends

Based on the results, its reveal that's divergent trends in the annual rainy days (Figure 4.4) across the study sites, reflecting the localised effects of climate change and regional climate variability. These observations are consistent with the complexity of climatic responses in West Africa. Niamey Ville, Boubon, and Kollo show negative slopes. This suggests a decrease in rainy days at these stations over the years. show marked decreases, compatible with the progressive aridification observed in many regions of the Sahel

(Lebel *et al*., 2003), where rainfall patterns are increasingly sporadic (Nicholson, 2017). A reduction in groundwater recharge, limiting access to drinking water and affecting rain-fed crops that depend on regular rainfall. A shorter and more intense rainy season is a phenomenon often associated with climate change, where the frequency of rainfall decreases but its intensity increases. Lokoja's rainy day patterns show a significant positive slope (y = 0.72x - 1344.652), indicating a slight increase in rainy days. However, the R^2 value of 0.0679 (6.79%) shows a low correlation, indicating insignificant variability. In the context of climate-related studies, this low explanatory capacity may reflect the complexity of climate variability, which is influenced by multiple interacting factors, such as localised weather patterns, regional weather patterns and global climate factors such as ocean-atmosphere interactions. In regions such as West Africa, increases in rainfall variability and the frequency of rainy days are often associated with increased monsoon activity or changes in atmospheric circulation (Todzo *et al.*, 2020). The risk of flooding due to a combination of more frequent rainfall and low altitude in the region is already identified as vulnerable (Descroix *et al*., 2012).

Natural climate variability, including cycles such as ENSO (El Niño-Southern Oscillation) and NAO (North Atlantic Oscillation), influence rainfall in This region. These observations show significant spatial variability in rainy days. While some regions are showing signs of aridification, others, such as Lokoja, are experiencing an intensification of rainfall. These trends, although moderated by high inter-annual variability, reflect the impacts of climate change and underline the urgent need to adapt water resource management and agricultural policies.

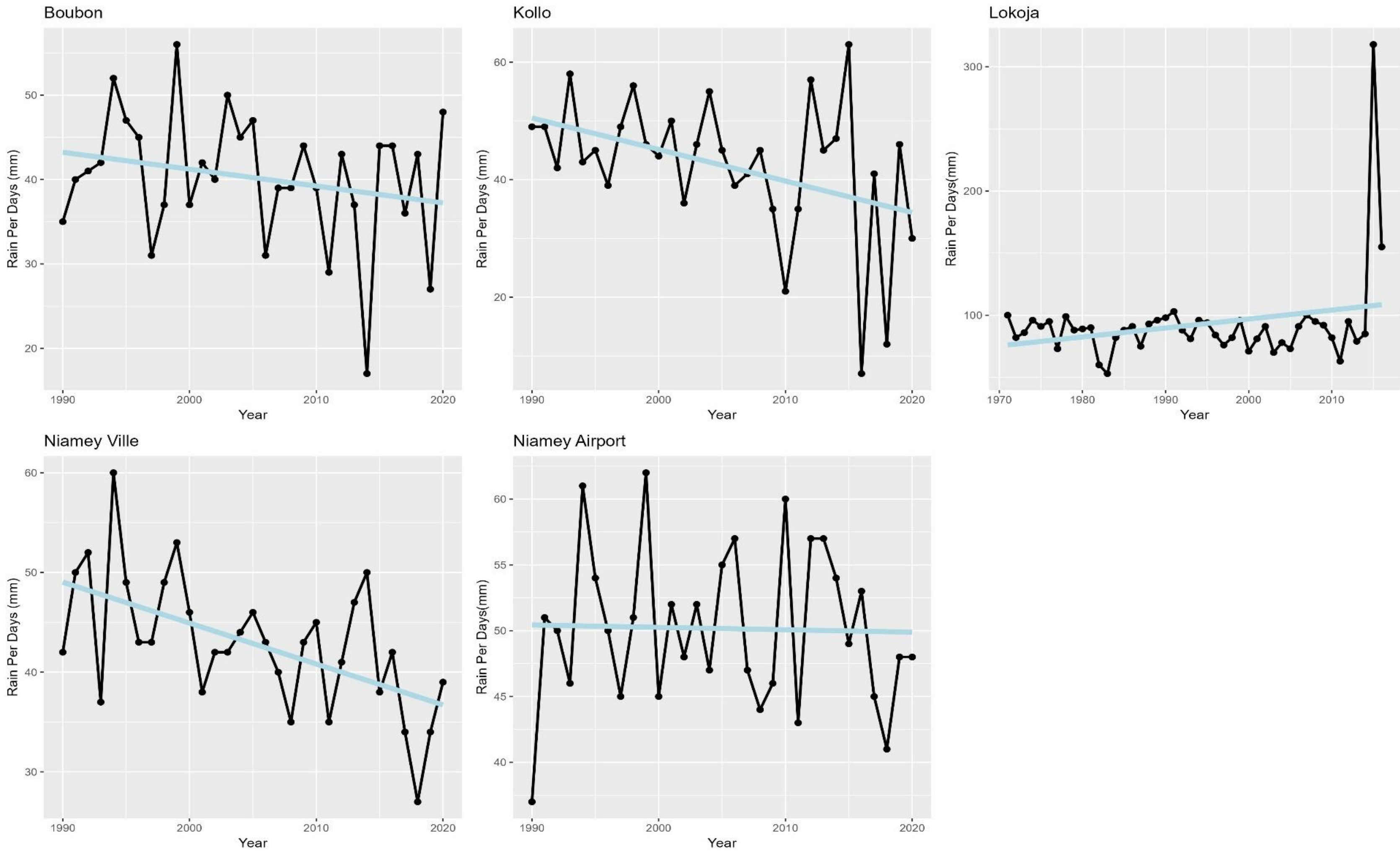

Figure 4.4: Number of rainy days in the selected station

4.1.3.2 Annual and seasonal trends in rainfall

The results of Mann-Kendall and Sen's slope trend analysis on an annual basis are presented in the tables 4.6. The Mann-Kendall test revealed a significant upward trend in annual rainfall at the Niamey Ville station (Z = -1.01, p= 3.11E-15), say (Z = 2.00, p = 0.04) and Lokoja station (Z = 2.13, P=0.032371). In contrast, the Kollo station showed a significant downward trend (Z= -1.22, p < 0.05), while other stations exhibited non-significant trends. However, the Niamey Airport station has a slight increase in rainfall although it is still positive, unlike the Kollo station which has a negative S which indicates a downward trend. On the other hand, in the estimation of the slope of Sen, there is an increase in annual rainfall for the majority of the different stations, with a tendency to increase rainfall the most important at the station of lokoja (6.8mm), Say (6.05 mm), In revenge, the station of Kollo show a decrease in the trend of precipitation at (-2.86).

Table 4.6: Annual rainfall trend analysis results

Station	Z	P-Value	Nature of trend	Sens's slope
Niamey Ville	-1.01	3.10E-15	No Trend	-2.44
Niamey Airport	0	1	No Trend	0.01
Say	2	0.04	Trend	6.05
Kollo	-1.22	0.22	No Trend	-2.86
Boubon	0	0.658	No Trend	-0.94
Lokoja	2.13	0.03237	Trend	6.8

According to the monthly test results, significant downward trends have been observed at the Niamey Ville, Kollo stations. Conversely at Say and Lokoja, statistically significant upward trends have been noted, as shown in Table 4.8. Interestingly, these significant trends were only detected during the rainy seasons, indicating a change in precipitation patterns within the study area. However, the downward trend in precipitation during the rainy months could lead to agricultural production deficits and adversely affect crop yields (table 4.7).

Table 4.7: Seasonal precipitation Mann Kendall trends test

Station	Season	Statistic Value			
		Z	P-Value	Nature of trend	Sens's slope
Niamey Ville	Dry	-2.493	0.013	Trend	-0.14
	Wet	-1.122	0.262	No Trend	-2.58
Niamey Airport	Dry	-1.329	0.184	No Trend	-0.13
	Wet	-0.034	0.973	No Trend	-0.21
Boubon	Dry	-1.33	0.18	No Trend	0
	Wet	-0.47	0.63	No Trend	-1.04
Say	Dry	-0.69	0.49	No Trend	0
	Wet	2.108	0.035	Trend	6
Kollo	Dry	-1.322	0.186	No Trend	0
	Wet	0.68	0.497	No Trend	1.5
Lokoja	Dry	1.439	0.15	No Trend	1.47
	Wet	2.102	0.036	Trend	5.53

Table 4.8: Monthly precipitation Mann-Kendall trends test

Station	Statistic Value	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Niamey Ville	P-value	1	0.26	0.34	0.01	0.93	0.13	0.92	0.79	0.66	0.69	1	0.4
	Z	0.61	1.76	-0.73	-1.66	0.48	-1.6	-0.14	0.37	0.44	1.02	0	0.06
Niamey Airport	P-value	0.54	0.08	0.46	0.1	0.63	0.11	0.89	0.71	0.66	0.31	1	0.96
	Z	0	1.12	-0.96	-2.55	0.08	-1.53	-0.1	0.44	0.44	-0.4	0	0.8
Kollo	P-value	1	1	0.04	0.21	0.04	0.01	0.89	0.25	0.95	0.75	1	1
	Z	0	0	-2.07	-1.26	-2.08	-2.6	0.14	-1.16	0.07	-0.32	0	0
Boubon	P-value	1	1	1	0.18	0.4	1	0.22	0.22	0.29	0.52	1	1
	Z	0	0	0	-1.33	-0.83	0	1.22	-0.3	-1.05	-0.64	0	0
Say	P-value	1	1	0.11	0.54	0.13	1	0.04	0.08	0.41	0.81	1	1
	Z	0	0	-1.62	-0.62	-1.51	0	2.09	1.73	0.82	0.25	0	0
Lokoja	P-value	0.99	0.56	0.36	0.04	0.36	0.17	0.02	0.13	0.81	0.01	0.3	0.59
	Z	-0.01	0.58	0.9	2.07	0.9	1.38	2.42	1.53	0.24	2.49	1.03	0.53

(i) Trend detection in temperature

Based on the results of the analysis, Table 4.9 shows the results of the monthly Mann-Kendall tests. At all treated stations, monthly temperatures were dominated by positive (upward) trends, except certain months where downward trends were present. This was particularly true of the Lokoja station (January to April). In addition, the monthly data series revealed statistically significant upward trends, with only one statistically significant downward trend observed at the Lokoja station in February. In Niamey, the minimum temperature was preferred, as it showed statistically significant upward trends, except for January, February, May and October. In Niamey, maximum temperatures showed an upward trend throughout the period but were particularly significant.

Table 4.9: Mann-Kendall for monthly maximum and minimum temperatures

Station	Statistic Value	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Niamey Tmax	P-value	0.5	0.48	0.13	0.01	0.24	0.13	0.1	0.21	0.54	0.34	0.01	0.48
	Z	0.68	0.71	1.51	2.62	1.17	1.53	1.63	1.26	0.61	0.95	2.58	0.71
Niamey Tmin	P-value	0.84	0.16	0.04	0.04	0.08	0.01	0.02	0.02	0.01	0.21	0	0.01
	Z	0.2	1.41	2.07	2.11	1.77	2.75	2.35	2.38	2.65	1.26	2.86	2.62
Lokoja Tmax	P-value	0.32	0.8	0.17	0.3	0.77	0.92	0.66	0.2	0.77	0.11	0.07	0.62
	Z	0.98	-0.24	-1.38	-1.04	0.29	-0.09	0.44	1.28	0.29	1.58	1.78	-0.49
Lokoja Tmin	P-value	0.2	0.02	0.49	0.55	0.37	0.14	0.32	0.2	0.77	0.28	0.2	0.43
	Z	-1.28	-2.27	-0.69	-0.59	0.37	1.48	0.98	1.28	0.29	1.08	1.28	0.79

The results of the seasonal and annual Mann Kendall and Sen's slope tests for maximum and minimum temperatures are shown in Table 4.10. the table shows that the minimum temperatures in dry and wet periods for the Niamey stations show statistically significant trends, while the lokoja station shows no significant trend.

Table 4.10: Mann-Kendall and Sen's slope for seasonal temperatures

Stations	Season	Statistics			
		Z	P-Value	Nature of trend	Sens's slope
Niamey Airport Tmin	Dry	3.70	0	Trend	0.053
	Wet	3.22	0.001	Trend	0.024
Niamey Airport Tmax	Dry	3.09	0.002	Trend	0.038
	Wet	1.90	0.057	No Trend	0.02
Lokoja Tmax	Dry	0.09	0.92	No Trend	0.005
	Wet	0.89	0.37	No Trend	0.012
Lokoja Tmin	Dry	-0.76	0.77	No Trend	-0.007
	Wet	0.55	0.55	No Trend	0.011

(i) Spectral analyses for rainfall

Spectral analysis of the time series data from the various rainfall stations has revealed dominant cycles and periods that vary according to time intervals. According to the results of this analysis, the data reveal significant variations in rainfall over periods of several years. Long cycles such as the 31-year cycle at the Tera station show very high spectral energy, suggesting large-scale climatic cycles that significantly influence precipitation. Similarly, intermediate cycles (15.5 to 7.75 years) have been observed at various stations, indicating moderate variations associated with seasonal events (Niamey town = 22014.98; Lokoja = 1170; Niamey airport = 22014.98; Ouallam= 32691.47; Tera = 32465.47; Say= 7148.613, Tillabéry = 24088.06). In addition, short cycles of 2 to 6.2 years are characterised by very large peaks, indicating rapid and intense rainfall fluctuations (Kollo = 55675.59, Ouallam = 35525.116, Torodi = 8985.449, Tillabéry = 72921.32, Niamey Ville = 124245.43). The results show that for certain periods, the cycles are particularly critical, with rainfall variations that can have a major impact on the environment and human activities. By identifying these dominant cycles, it was possible to better anticipate extreme weather events and manage water resources more effectively.

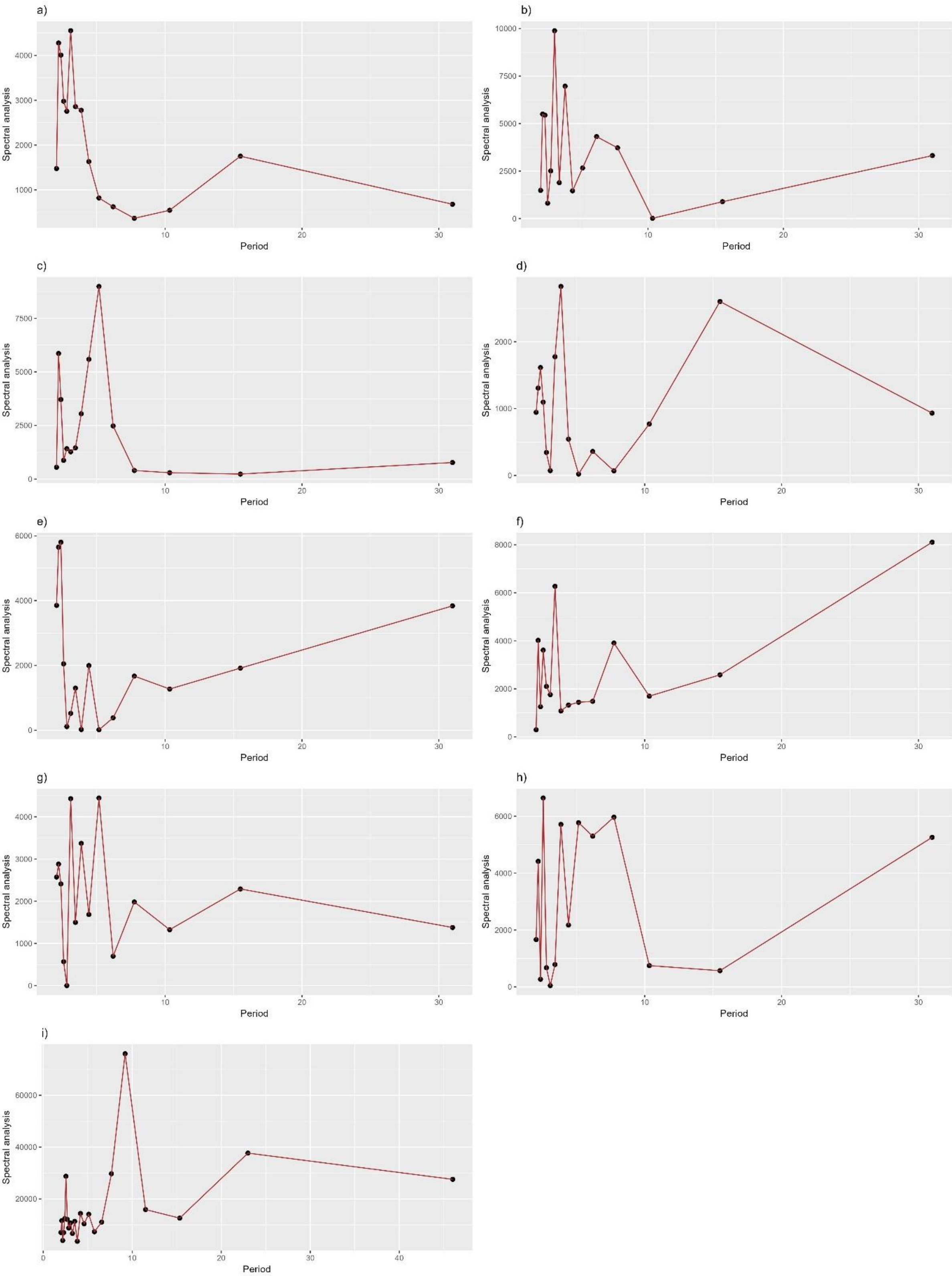

Figure 4.5: Spectral analyses of the Station

(ii) Sequential Mann–Kendall

(a) Sequential Mann–Kendall for Precipitation

The curves of the Mann-Kendall sequence test presented in Figure 4.6 are based on the interactions between the prograde U and retrograded V data. The method makes it possible to deduce the year in which there was a change in the trend, particularly when a significant intersection between the two curves is observed in the graph. The SQMK tests were conducted only on annual precipitation and minimum and maximum temperature data. The SQMK values of the pluviometry stations are presented as a line graph of two curves of progressive and retrograde; these results are illustrated in Figure 4.6. The graph for Niamey city shows a combination of upward and downward trends, particularly in 2000, when rainfall was characterised by an upward trend, and in 2006, when a downward trend, albeit insignificant, was identified. Kollo figure shows a slight but insignificant upward trend in precipitation until a new encounter in 2017, characterised by a downward trend. The figure for Say, shows similar non-significant increasing trends around 2012, 2010 and 2016 respectively until it becomes significant in 2020, 2019, and 2020 for the different stations. The curves U and V for the Niamey Airport station intersected from the beginning of the series and several times during the time series; nevertheless, among these points of change, there is no significant inflexion point compared to the confidence limit considered ($p \leq 0.05$). At Boubon, several change points, namely 1997, 1998, 2000, 2020 and 2021. They do not represent a significant turning point, based on the results from the Boubon station, which show regression in annual precipitation. The station of Lokoja presents several points of change, namely, 2006, 2007 and 2014. They are not a significant turning point for the series because the calculated SQMK values are below the normal standard value of 1.96.

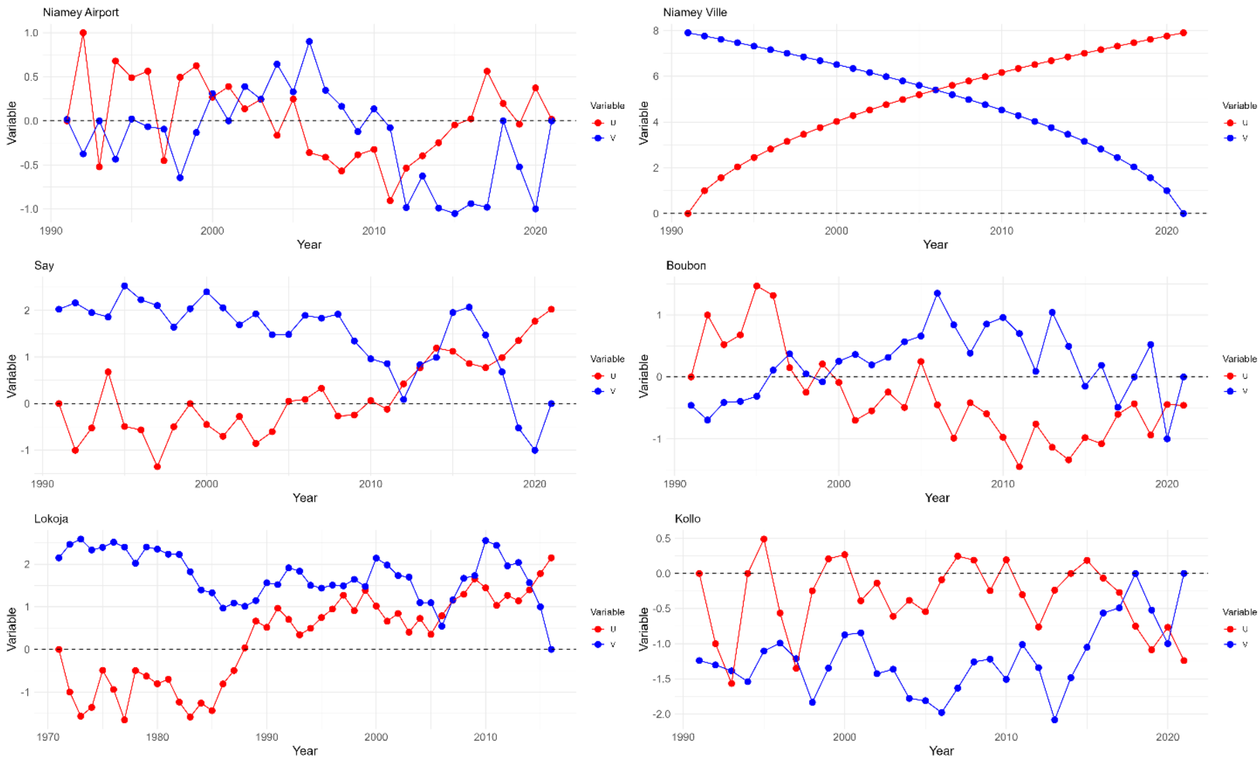

Figure 4.6: Sequential Mann-Kendal test for each rainfall Station

4.1.4 Dynamics and Implications of River Niger in Niamey and Lokoja

The River Niger plays a crucial role in the economic and social life of the cities of Niamey and Lokoja. In Niamey, the river is a major source of water for local agriculture and drinking water supply. However, it is also responsible for the frequent flooding that seriously affects the city. In 2020, for example, the level of the river reached an all-time high following a particularly heavy rainy season (NIHSA, 2024). These floods not only caused significant material damage but also endangered the daily lives of many residents. At Lokoja, the River Niger merges with the Benue, almost doubling its annual flow. This confluence creates a lacustrine landscape with several islands and sandbanks. The average flow of the Niger at Lokoja varies considerably from year to year. Although less frequently affected by catastrophic flooding than Niamey, Lokoja remains vulnerable to seasonal flooding, which can disrupt local agriculture. The hydrological implications of the River Niger are crucial for these two towns, directly influencing their economic development and environmental security

4.1.4.1 River Niger flow at Niamey

At the Niamey station, the River Niger regime is characterised by two flood periods (Figure 4.9), the White flood and the Black flood, due to a heavy load of suspended matter. The white flood occurs from June to September during the rainy season, largely due to contributions from its right bank tributaries, notably the Sirba and Dargol rivers (Descroix Luc , 2013). The black flood, on the other hand, comes from the upper reaches of the River Niger coming from Guinea, and starts between December and February, reflecting upstream contributions and delayed hydrological processes. The maximum flow of the white flood at Niamey in 2023 corresponds to 1,773 m^3/s on the first of September 2023, while the maximum flow of the black flood is 1,588 m^3/s on 14 January 2024 (NIHSA, 2024).

These figures illustrate the seasonal variability of flood flows, with white floods generally having slightly higher peak flows due to their dependence on intense rainfall. A historical comparison of hydrographs shows that the 2023 flood flows at Niamey were lower than those recorded in 2012/2013 and 2020/2021, but exceeded the lower levels observed in 2021/2022. This trend may indicate a change in flood dynamics influenced by changes in climate or land use.

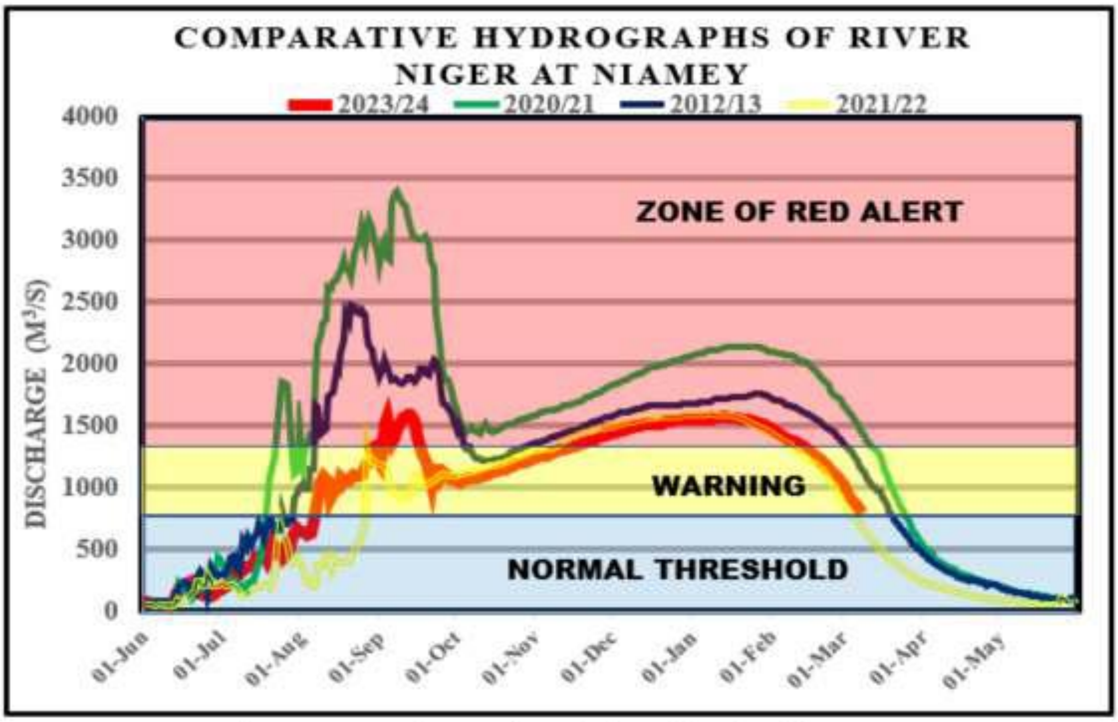

Figure 4.7:Flow hydrographs of River Niger at Niamey station with the warming level (NIHSA, 2024).

4.1.4.2 River Niger flow at Lokoja

At Lokoja, located at the confluence of the Niger and Bénoué rivers, hydrological patterns show more significant variability. In 2023, the maximum flow reached 20,578 m^3/s on 16 September, reflecting the contributions of both rivers, while the minimum flow was recorded at 3,056 m^3/s on 1 June, with an annual average of 10,986 m^3/s. Analysis of hydrographs from 2020 to 2023 reveals that flood flows in 2023 exceeded 2021/2022 levels but remained below those of 2020/2021, suggesting variations in upstream runoff and local contributions (NIHSA, 2024). The frequency of exceedances of the red alert threshold reflects Lokoja's increased vulnerability to flooding. The maximum flows observed during the rainy season, generally between August and September, coincide with periods of soil saturation and floodplain overflow, exacerbating the impact of flooding. The convergence of the two rivers amplifies the risks, as the combined inflows increase the hydrological load in the region.

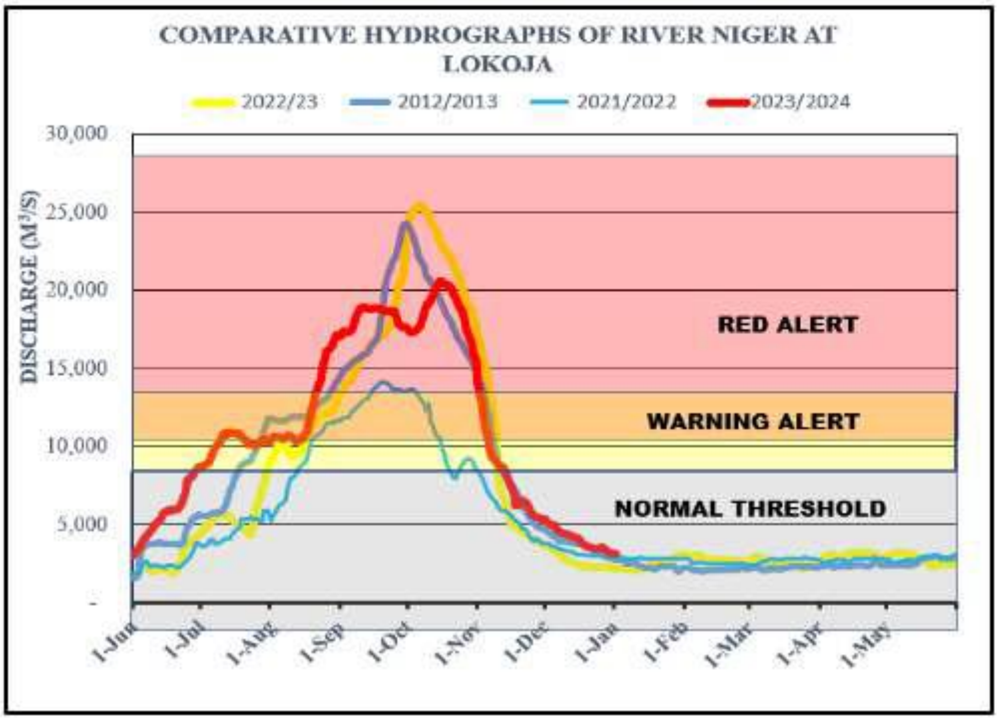

Figure 4.8: Flow hydrographs of River Niger at Lokoja station with the warming level (NIHSA, 2024)

4.1.5 Assessment of Land Use and Land Cover Pattern (LULC) and its implication

Land use and land cover are crucial factors in determining the various modifications within a given landscape, reflecting the types of land use and their distribution within the area. Similarly, improved land use management can mitigate flood risks and address climate events, as land developments such as infrastructure and canals can influence runoff rates due to their impermeability. Consequently, land use and land cover types have a resistance effect and contribute to increased runoff, often resulting in flooding. The study area was classified into major land use zones, including water bodies, vegetation, bare land, and agricultural and residential areas, Overall, this classification provides a clear framework for representing the environmental zone. Over three decades (1991-2021), Niamey and Lokoja experienced major transformations in land use and land cover, driven by urbanisation, demographic pressures and environmental change. Satellite-derived LULC maps and GIS analysis revealed marked contrasts in landscape dynamics between the two regions.

In Niamey, rapid urban expansion dominated the landscape, with built-up areas increasing by 312.88 % (from 5,023.6 ha to 20,741.5 ha) illustrated in Table 4.11. This growth has occurred in two phases: 47.06% (1991 to 2006) and 54.25% (2006 to 2021), reflecting the escalating demand for housing due to population growth (Table 4.13). At the same time, critical natural and agricultural areas have shrunk: green belts (- 45.60 %), riparian formations (-58.55 %), and rain-fed agriculture (- 40.18 %) have been lost to urbanisation. Hydrological changes include a 14.66 % expansion of water pools, probably linked to groundwater fluctuations, while the River Niger area contracted by 16.87 %, signalling a reduction in floodplain capacity. Bare soil increased by 175.39 %, highlighting the exposure and impermeability of the soil. By 2021, urban areas will cover 39% of Niamey, displacing rain-fed agriculture (24%) and vegetation. By the year 2021, urban zones covered 39% of Niamey, displacing rainfed agriculture (24%) and natural vegetation. Bare ground, a marker of soil exposure and impermeability, surged by 175.39%, exacerbating runoff risks during a rainfall event. The land use maps of Niamey (Figure 4.9) from 1991 and 2006 reveal a significant transformation in land use. In 1991, natural areas dominated, with a strong presence of rain-fed crops (21 750 ha) and the green belt (1 911.29 ha), reflecting a predominance of relatively preserved ecosystems. The built-up area was still modest (5 024 ha), concentrated around historic urban centres. However, in 2006, artificial areas were markedly expanded (5 889.33 ha for built-up areas) and the beginnings of urban spread.

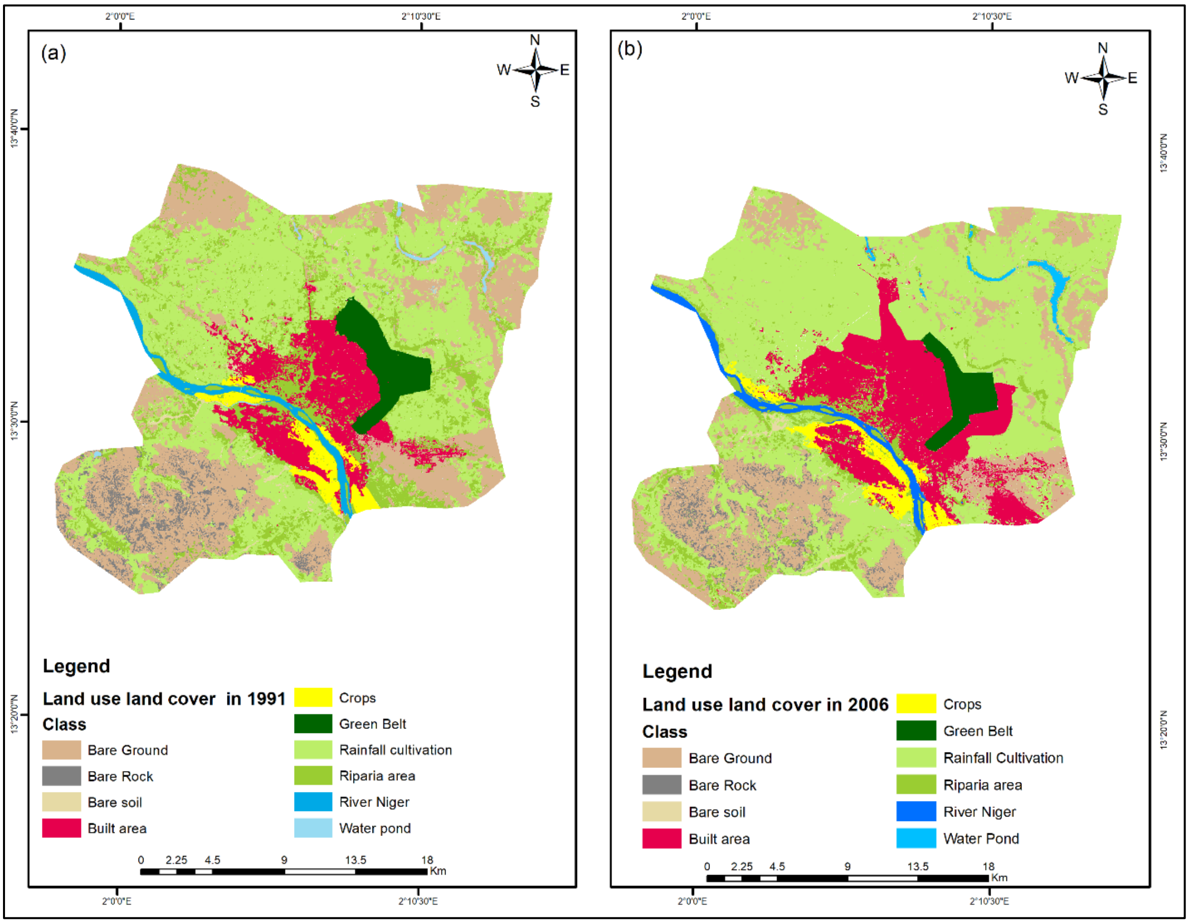

Figure 4.9: Spatial analysis of Land use and land cover pattern in Niamey: a) Niamey In 1991 and in b) Niamey in 2006

Table 4.11: Land use and Land cover change in Niamey between 1991 and 2021

Class types	Changes in land cover between 1991 and 2021			
	Area 1991 (ha)	Area 2021 (ha)	Change (ha)	Change (%)
Bare ground	516.04	1421.12	905.08	175.39
Bare rock	12740.30	10969.30	-1771.00	-13.90
Bare soil	1585.97	572.97	-1013.00	-63.87
Built aera	5023.60	20741.50	15717.90	312.88
Crops	1274.20	1506.12	231.92	18.20
Green belt	1911.29	1039.69	-871.60	-45.60
Rainfall cultivation	21750.30	13012.00	-8738.30	-40.18
Riparia area	7445.43	3086.23	-4359.20	-58.55
Niger river	1015.18	868.42	-146.76	-14.46
Water Pond	258.98	296.95	37.96	14.66

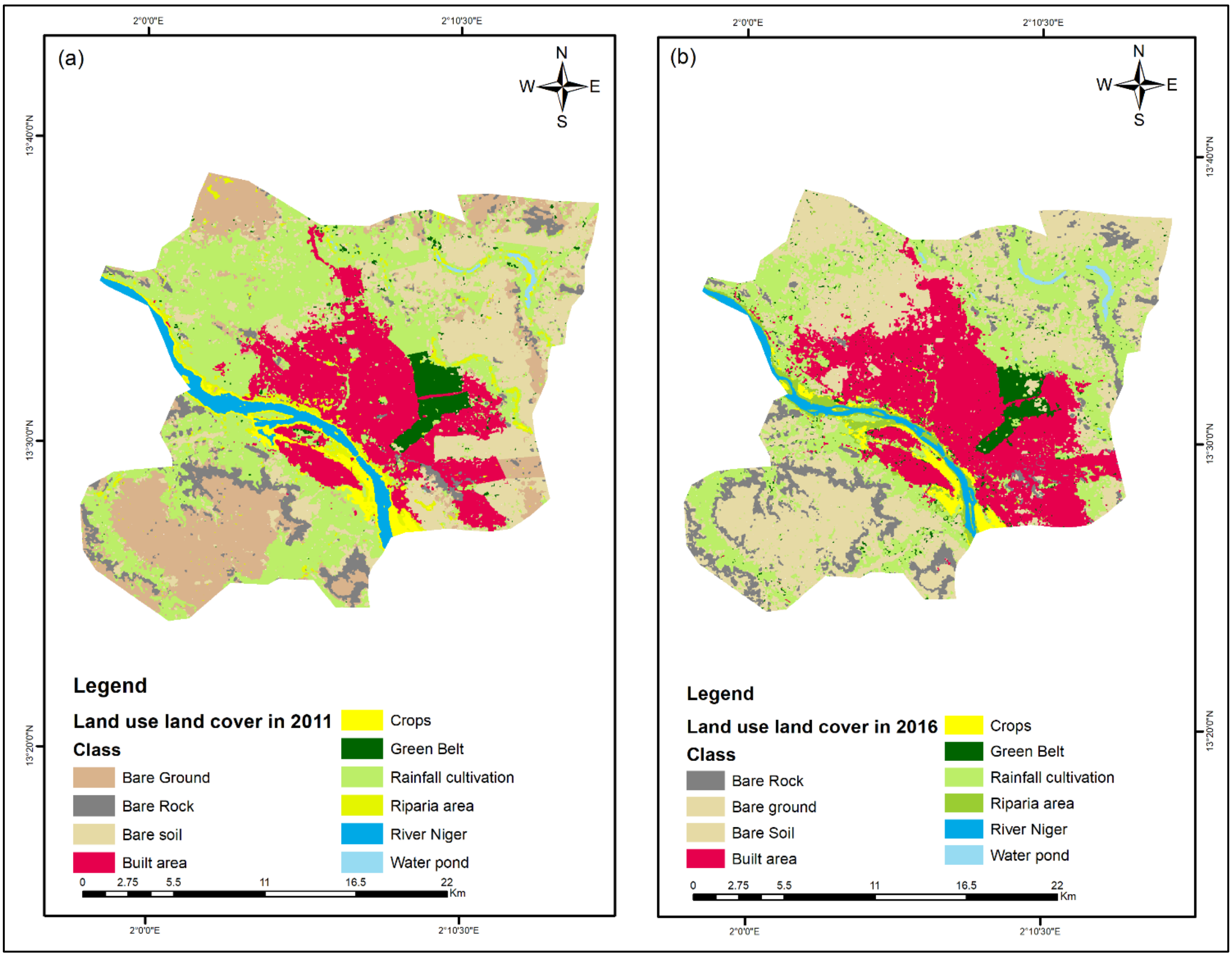

Figure 4.10: Spatial analysis of Land use and land cover pattern in Niamey: a) Niamey In 2011 and in b) Niamey in 2016

The period 2011–2016 saw an acceleration in anthropisation. In 2011, the map (Figure 4.10) highlights the continuing importance of rain-fed crops (still 13,012 ha in 2021) with the reduction of the green belt (1,496.53 ha), but the 'Built area' class is gaining ground, foreshadowing the urban growth of the following years. The 2016 map confirms this trend.

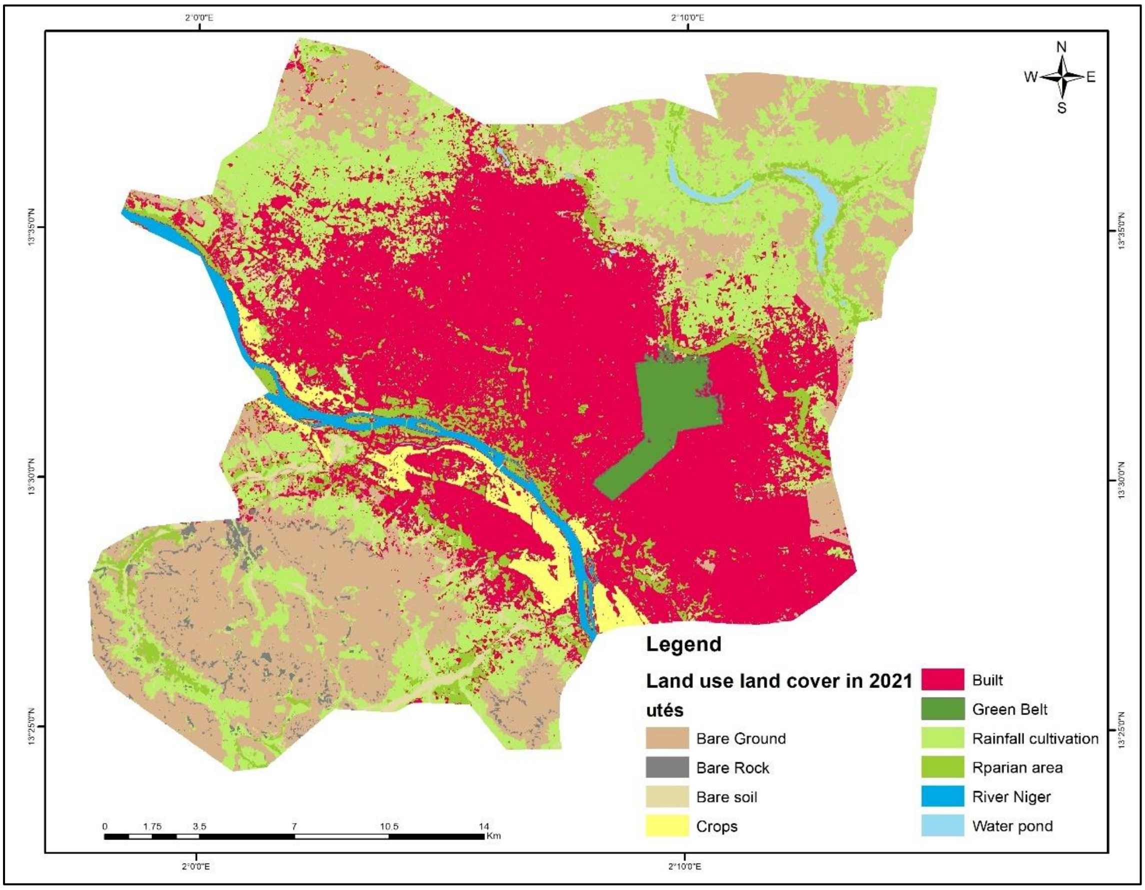

Figure 4.11: Spatial analysis of Land use and land cover pattern in Niamey in 2021

Figure 4.11 from 2021 reveals the outcome of a radical transformation of the territory, with built-up areas becoming dominant (20,742 ha) table 4.11, tripling in size in 30 years at the expense of natural ecosystems and becoming the most extensive class. The alarming decline of the green belt (-46%) combined with the explosion of degraded soils paints a picture of a landscape where urban pressure and environmental degradation prevail. Only water bodies are still holding out. This map summarises three decades of change between development and sustainability, highlighting the urgent need to preserve the last remaining ecological corridors in the face of urban sprawl. Figure 4.12 shows the spatial evolution of the different land use classes in the Niamey study area over a 30-year observation period. In this image, it is remarkable to note the dominance of built-up areas over other classes, thus becoming the most important class, reflecting rapid acceleration in the area.

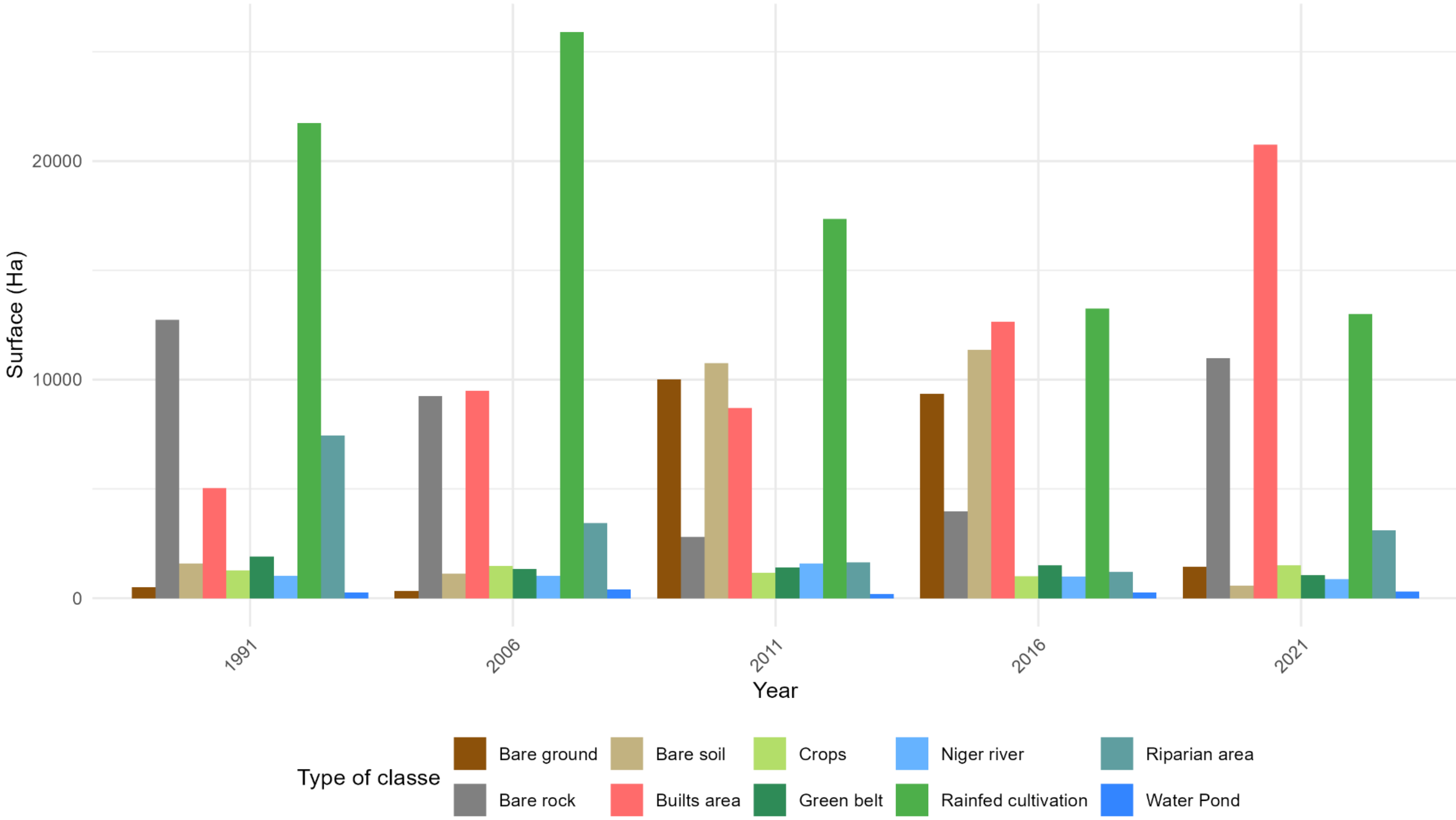

Figure 4.12: Comparison of land use and land cover change in Niamey from 1991 to 2021

In Lokoja, the land use map reveals a diverse landscape dominated by natural and agricultural areas. Agricultural land is a major component, indicating significant agricultural activity. Human activities (built-up area) are visible but appear to be limited in extent, suggesting that urbanisation is still moderate. Vegetation cover is polarised between dense vegetation (probably mature forests or wooded areas) and more open areas of shrub and grassland, reflecting varied ecosystems. The presence of bare land and outcropping rocks indicates relatively unaltered areas or low ecological potential, while water bodies structure the local hydrology. The 2006 map reveals apparent stability in the major land use categories compared with 1990 (Figure 4.13). Agricultural land retains its footprint, highlighting the persistence of agricultural activities. Built-up areas are still identifiable with no obvious expansion, suggesting controlled urban development.

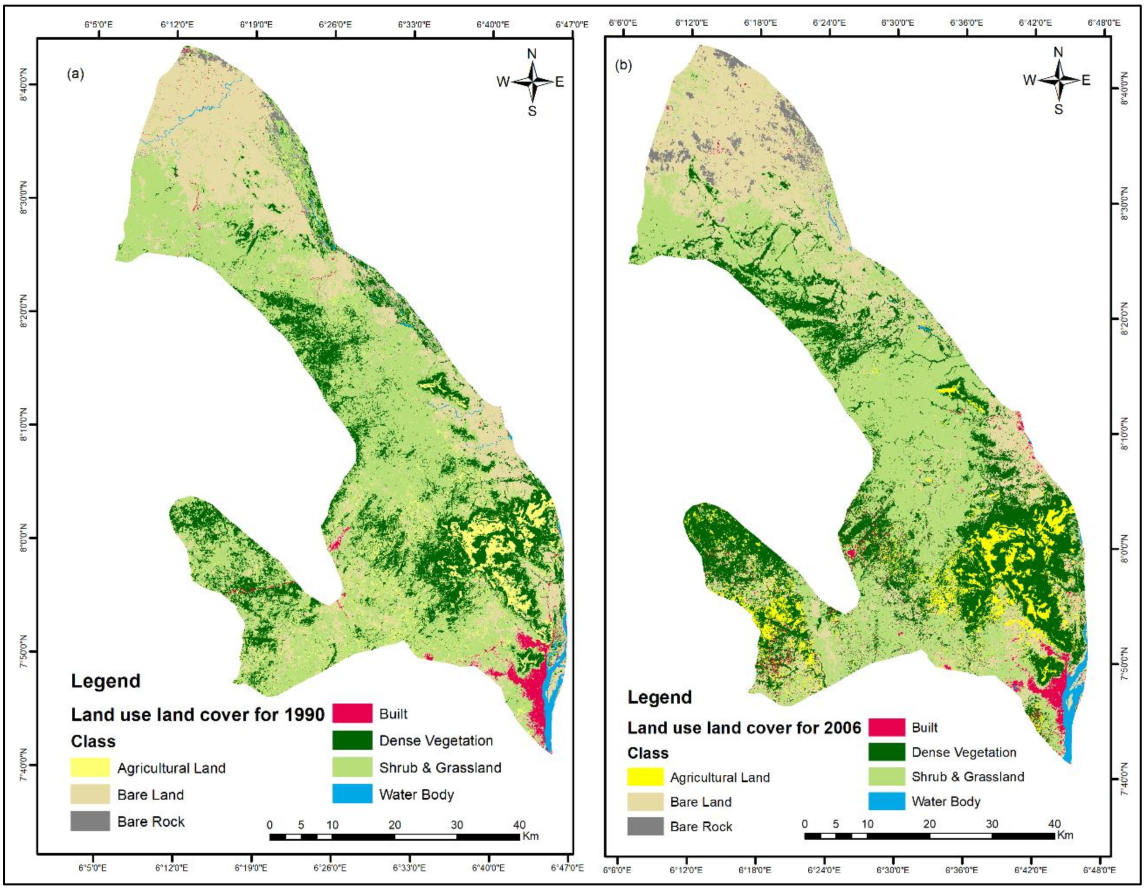

Figure 4.13: Spatial analysis of Land use and land cover pattern in Lokoja: a) Lokoja In 1991, b) lokoja in 2006

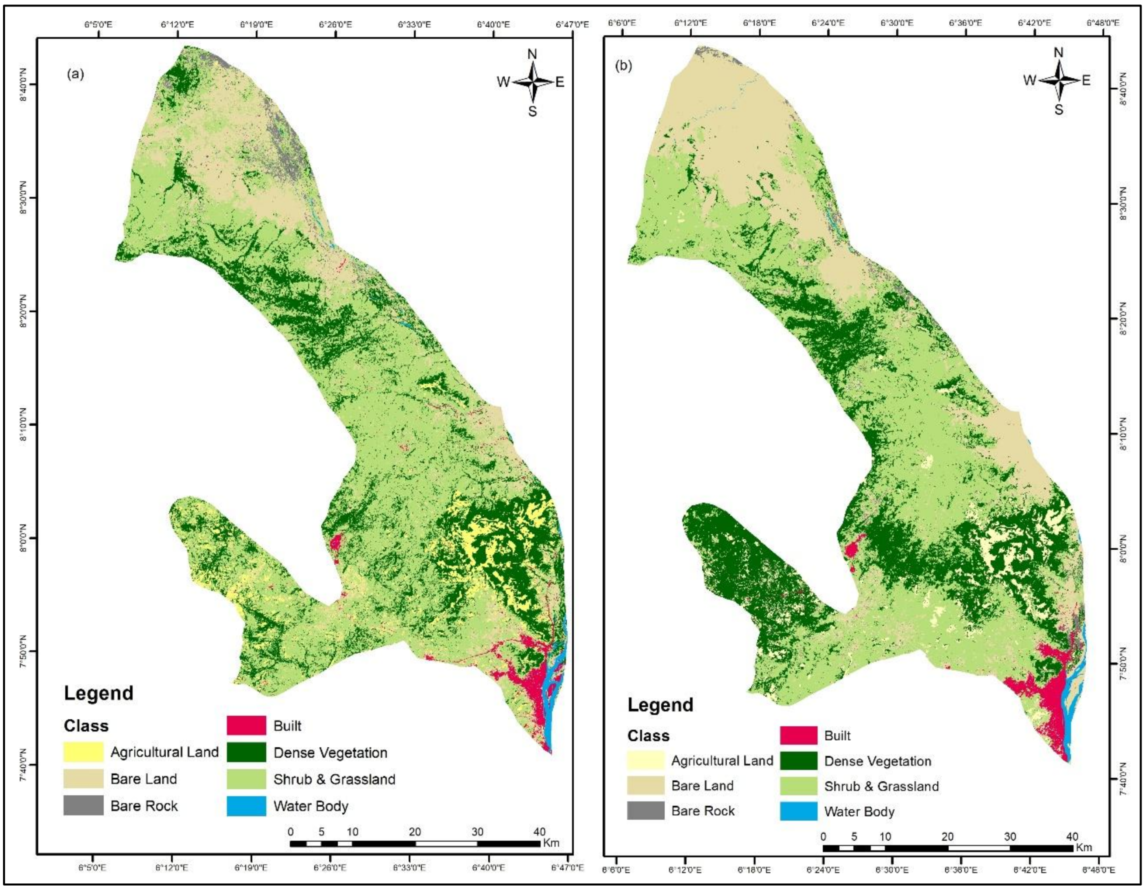

Figure 4.14: Spatial analysis of Land use and land cover pattern in Lokoja: a) Lokoja in 2012, b) Lokoja in 2016

The map from 2012 to 2016 (Figure 4.14) shows significant urban expansion. Built-up areas are gaining ground, especially along the river in the south-east. This growth increases the risk of flooding in the plains. Dense vegetation has spread to the west and centre (figure 4.15). Fallow land and savannahs have been transformed directly into closed forests. Agricultural land is decreasing in the north. However, water bodies remain stable.

The urbanisation and territorial transformation dynamics from 1991 to 2021, in table 4.12 and figure 4.16, reveal urban expansion with significant growth in built-up areas (+21%, +1,209 ha). Agriculture is intensifying its hold (+8%, +1,673 ha), often in connection with peri-urbanisation. This expansion suggests joint land consumption between cities and cultivated land, a phenomenon typical of urban fringes.

Conversely, natural environments (dense vegetation and shrubland and grassland) are holding up remarkably well (-0.3% to -0.6%), with their slight contraction demonstrating ecological resilience in the face of urban expansion (Table 4.12).

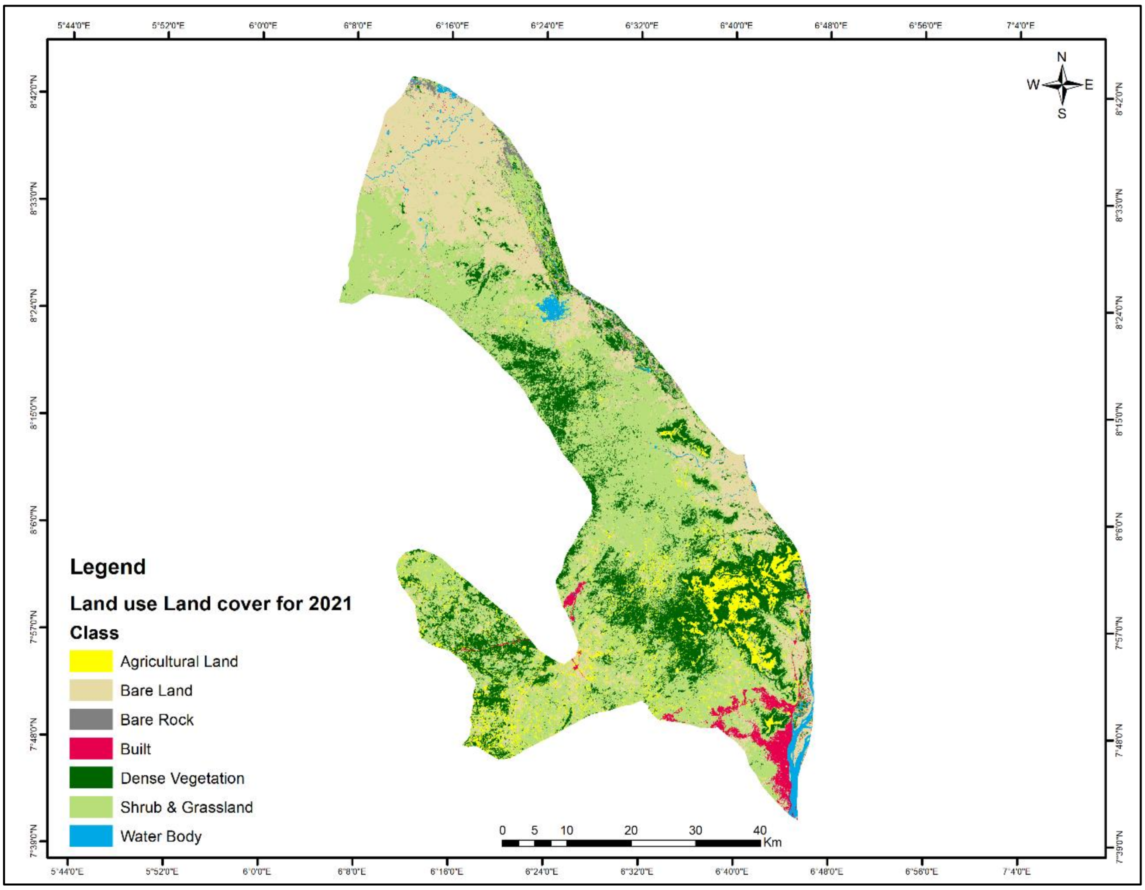

Figure 4.15: Spatial analysis of Land use and land cover pattern in Lokoja in 2021

Table 4.12: Land use and Land cover change in Lokoja between 1991 and 2021

Class type	**Changes in land cover between 1991 and 2021**			
	Area 1991 (ha)	Area 2021 (ha)	Change (ha)	Change (%)
Agricultural Land	20937.2	22610.0	1672.8	8.0
Bare Land	81957.0	77068.6	-4888.4	-6.0
Bare Rock	4689.4	5829.5	1140.2	24.3
Built	5767.1	6976.0	1208.9	21.0
Dense Vegetation	64380.4	64017.2	-363.2	-0.6
Shrub & Grassland	158581.0	158120.0	-461.0	-0.3
Water Body	3292.8	4983.9	1691.2	51.4

Spatially, Niamey's LULC maps revealed urban zones tripling in extent, encroaching on riparian corridors (e.g., the Green Belt) and agricultural land. The decline of green belts to 2% by 2021 and the expansion of bare ground to 20% underscored unsustainable land management practices. Critical observations link these changes to heightened flood vulnerability. Both cities' urbanisation increased impermeable surfaces (Niamey: +312.88 %; Lokoja: +21 %), reducing rainwater infiltration and elevating runoff. The loss of green belts, riparian zones, and forests weakened natural flood buffers, exacerbating sedimentation and flash floods.

The land use and land cover change maps highlight key areas requiring action to mitigate the risk of flooding:

(i) Protection of riparian formations and vegetated areas as natural buffers against flooding. Urban planning incorporates permeable infrastructure and retention basins to manage increased runoff.

(ii) Promotion of sustainable agriculture to limit deforestation and maintain stable soils.

Changes in land use and land cover in Niamey and Lokoja over the last three decades reflect increasing human pressures, leading to greater vulnerability to flooding. Proactive land use management, combined with flood mitigation strategies, is essential to reduce the negative impacts of these changes and protect local populations.

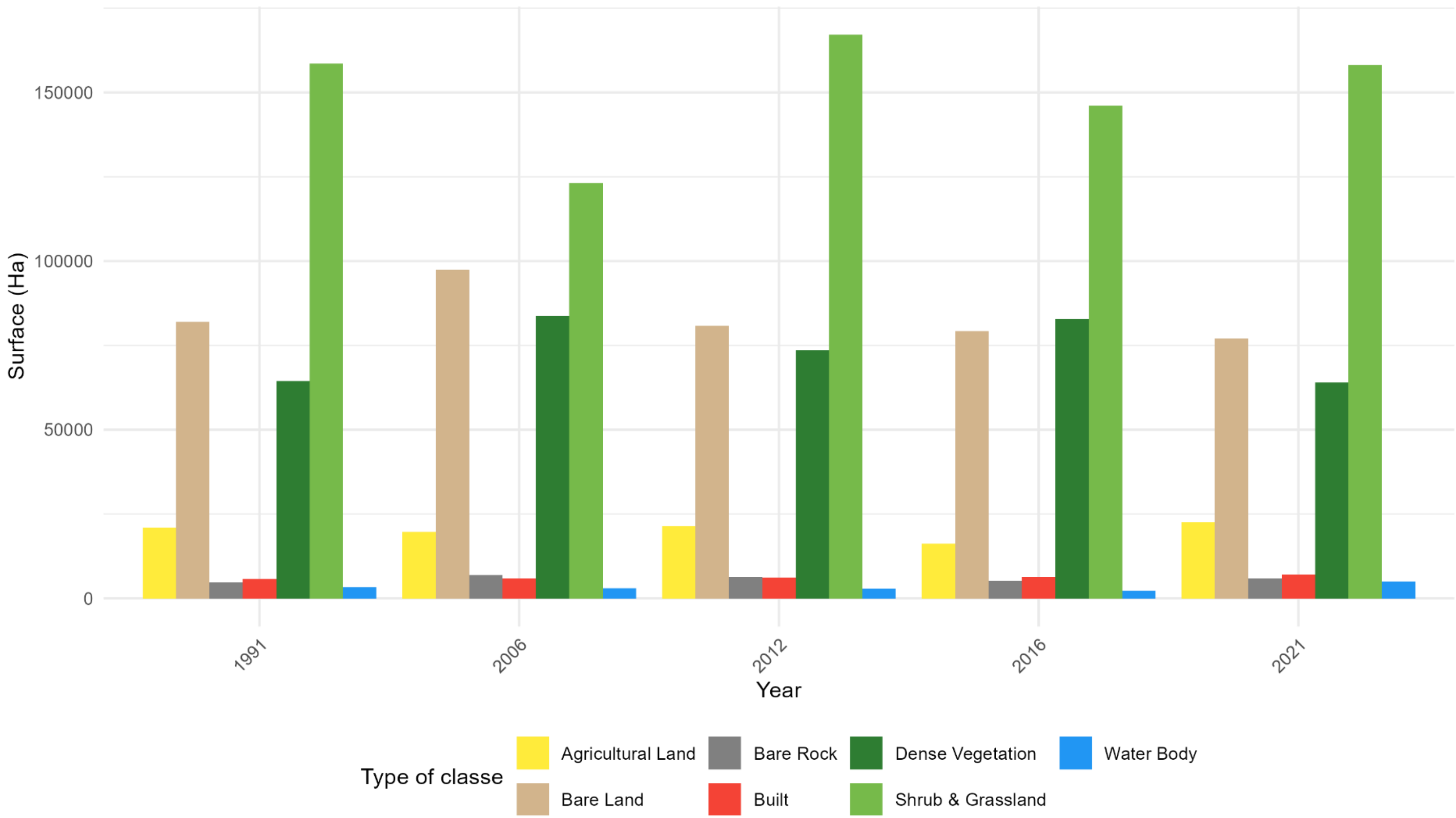

Figure 4.16: Comparison of land use and land cover change in lokoja

4.1.6 Assess Flood Vulnerability and Risk Patterns

(i) Topographical and hydrological factors

Elevations in Niamey vary between 180 and 300 metres (Figure 4.11), with low areas located mainly in the city centre, particularly in the south-east and east. The analyses show that 34.29% of the area is classified as presenting a moderate risk of flooding, followed by low risk (20.82%), high risk (17.14%), very low risk (15.63%) and very high risk (12.11%) categories (Table 4.20). These results show that Niamey is mainly exposed to moderate risks, partly due to the relatively uniform altitude, which limits areas of extreme water accumulation. Niamey's slopes ranged from 0 to 40 degrees, with 80.70% of the region falling into the high to very high slope classes. These sloping areas encourage increased retention of runoff, thus increasing overall vulnerability to flooding. In the AHP model, the slope is weighted at 24%, highlighting its key role in amplifying flood risk. This dominance of steep slopes calls for development strategies to reduce erosion and control flows. The TWI for the city of Niamey varies between 2.8 and 23. With a weighting of 16%, this indicator shows a predisposition of low, flat areas to accumulate moisture, increasing the risk of flooding. This relationship highlights the need for proper management of saturated areas, particularly in densely populated areas. The Drainage density in Niamey varies from 0 to 11 km/km², with high-density areas covering 15.32% of the surface area and very low-density areas accounting for 38.7%. This predominance of low density suggests a reduced capacity to evacuate surface water, which limits the intensity of run-off but can increase local water accumulation. These data suggest that drainage networks need to be improved, particularly in densely urbanised areas.

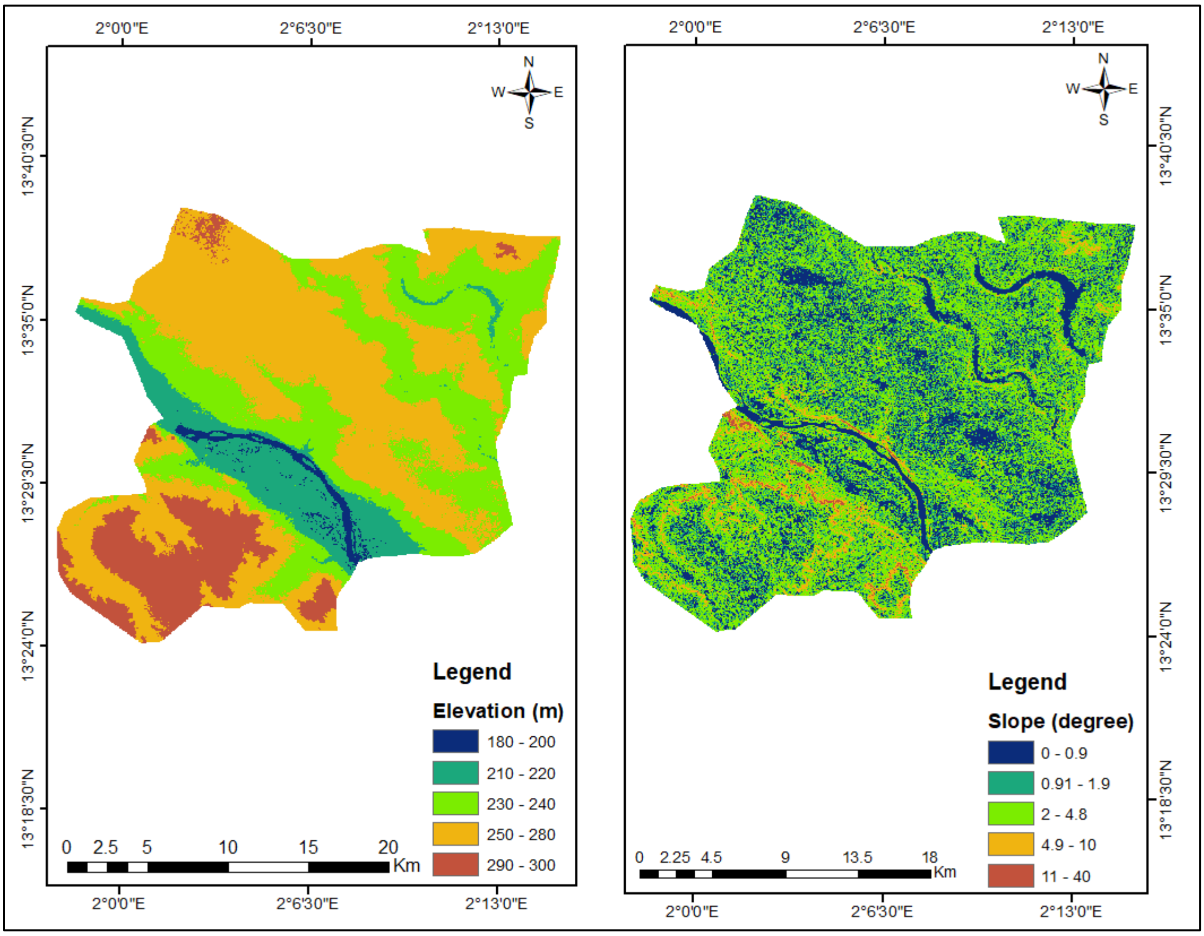

Figure 4.17: Thematic layers used for elevation and slope in Niamey

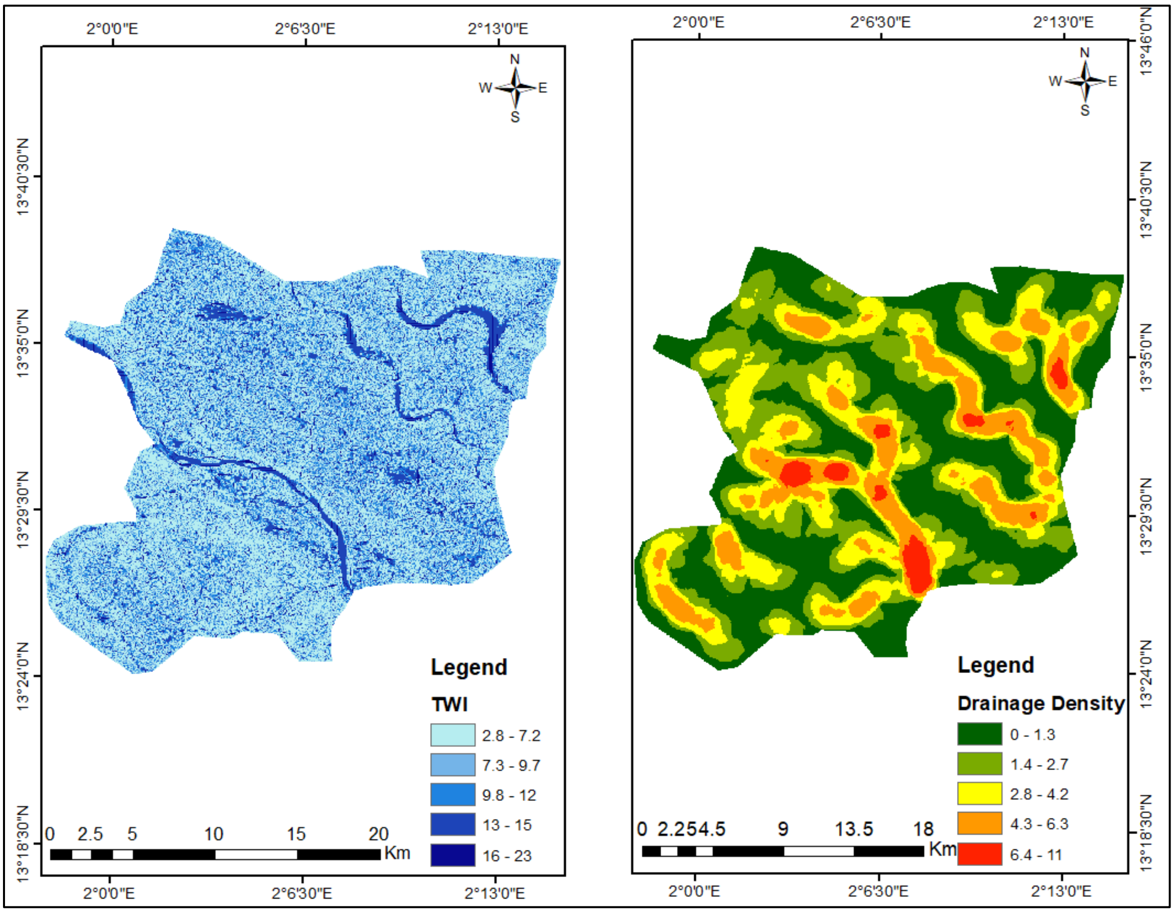

Figure 4.18: Thematic layers for Topographical wetness index (TWI) and Drainage density in Niamey

Lokoja is much more variable in elevation, with an altitude ranging from 19 to 544 meters (Figure 4.13). Areas at very high risk of flooding cover 28.19% of the region, followed by high (26.57%), moderate (23.57%), low (11.22%) and very low (10.70%) risk classes (Table 4.21). Unlike Niamey, very low altitudes are concentrated in the north and extreme southeast. This altitudinal variability contributes to greater water accumulation, aggravating the impact of flooding. Lokoja is even more exposed than Niamey to the risks associated with steep slopes, with 84.85% of its surface area in the high to very high slope categories (Figure 4.13). This parameter, weighted at 24%, highlights a terrain that favours rapid and uncontrolled run-off, increasing the risk of flash flooding. Better slope management, such as the installation of soil stabilisation structures, is essential.

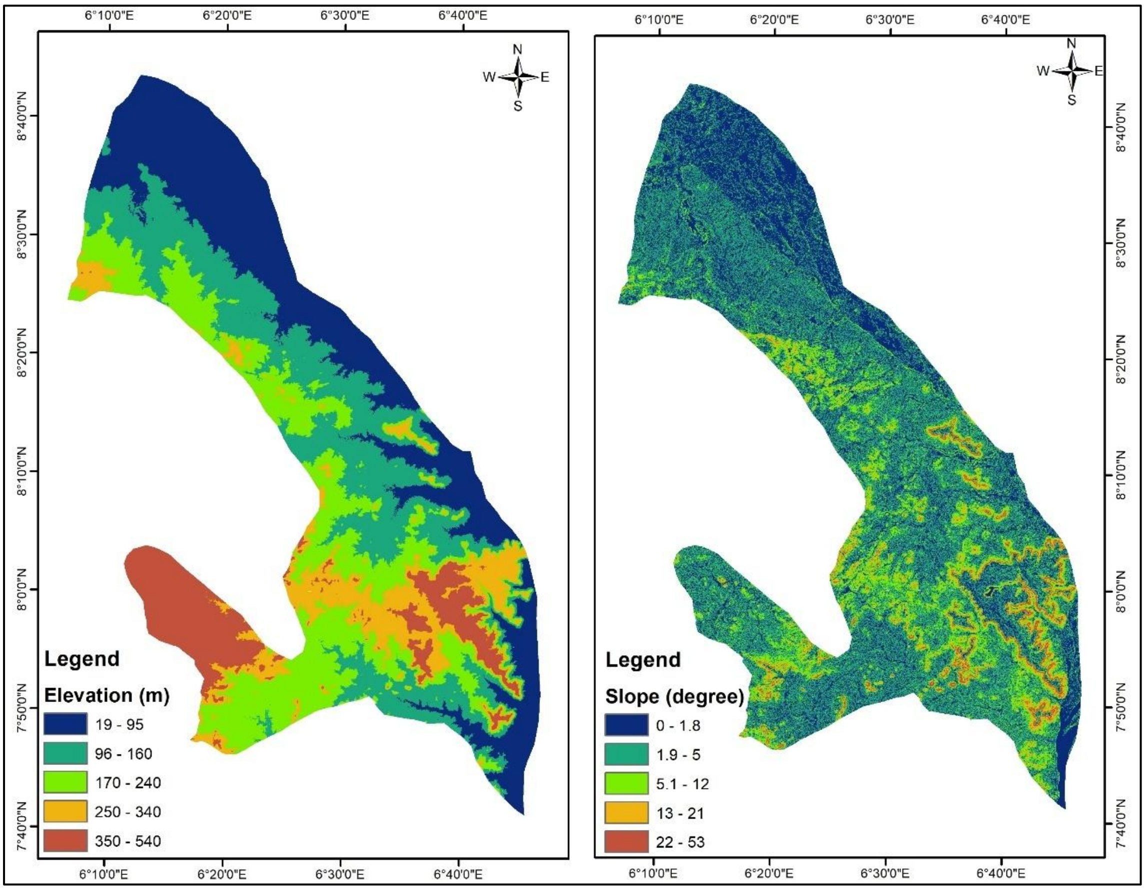

Figure 4.19: Thematic layers used for elevation and slope in Lokoja

The TWI at Lokoja varies between 3.2 and 23, similar to that of the Niamey area. The 16% weighting underlines the importance of this index in identifying areas where water is concentrated. Targeted interventions in these areas could reduce vulnerability. The Drainage density repartition Lokoja varies from 0 to 2.5 km/km². High-density areas cover 25.54% of the surface area, indicating an increased capacity to evacuate run-off water. However, very low-density areas (28.10%) remain significant. Improving water infrastructure, particularly in poorly drained areas, could limit the risks.

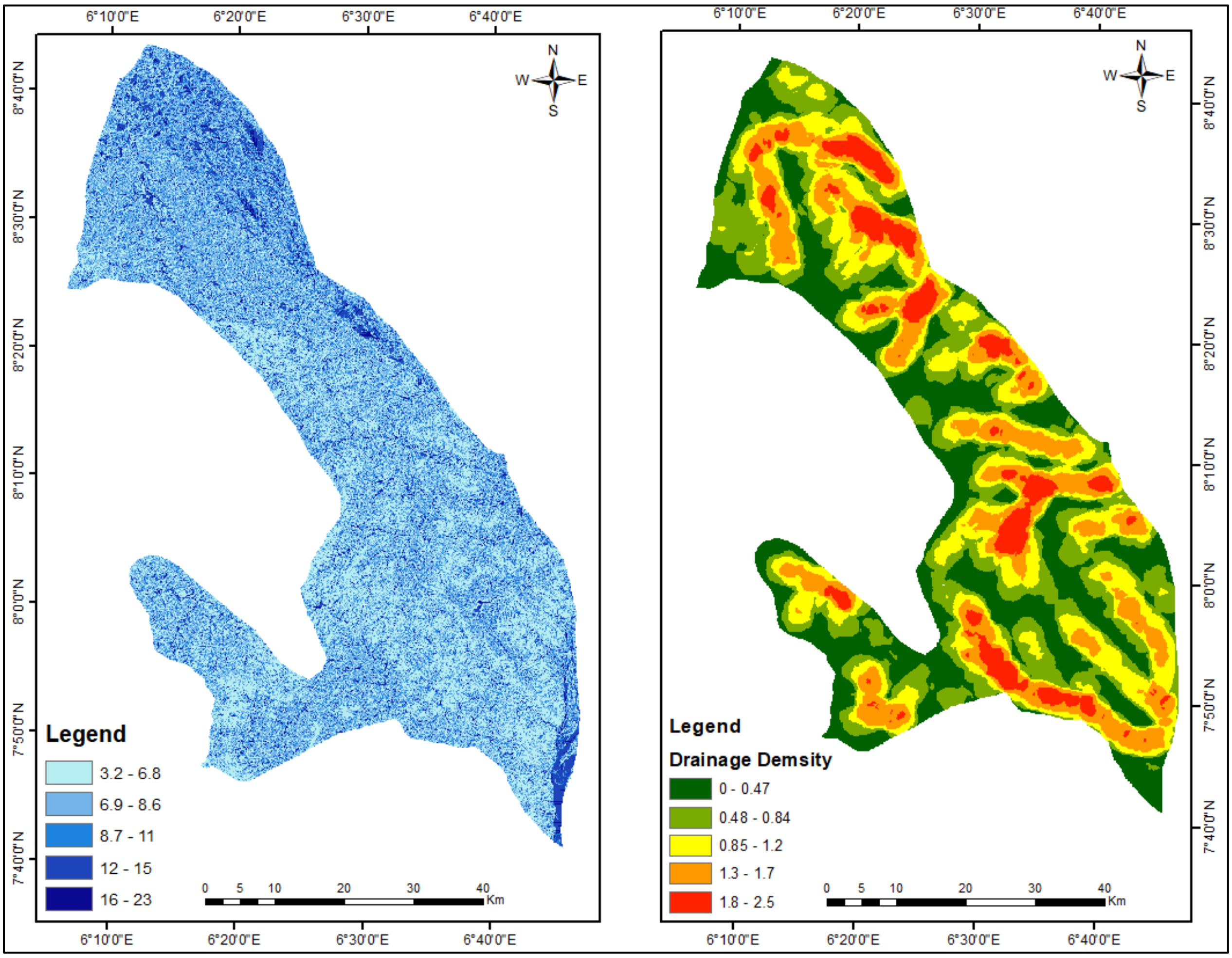

Figure 4.20: Thematic layers for Topographical wetness index (TWI) and Drainage density in Lokoja

(ii) Rainfall factors and soil

The Rainfall in Niamey (Figure 4.15) is mostly classified as moderate (48.48%), followed by high (22.33%) and low (17.84%). Weighted at 4%, it triggers flooding, especially during heavy seasonal rainfall. Rainfall increases the potential for soil saturation, particularly in inadequate drainage systems. Rainfall in Lokoja (Figure 4.16) is similar to that in Niamey, with a dominance of moderate and high rainfall classes. Weighted at 4%, this factor remains central to flood risk, particularly in areas where urban infrastructure is insufficient to manage run-off. The soil type (Figure 4.15) parameter is presented in Figure and is classified into seven categories based on the available soil types, namely clay, sandy loam, clay loam, sandy clay loam, sandy loam, silt, and loamy sand. In contrast, in Lokoja (Figure 4.16) , the predominant soil types are clay, sandy clay, clay loam, sandy clay loam, loam, and sandy loam. In this study, the soil type was assigned a weight of 2 %.

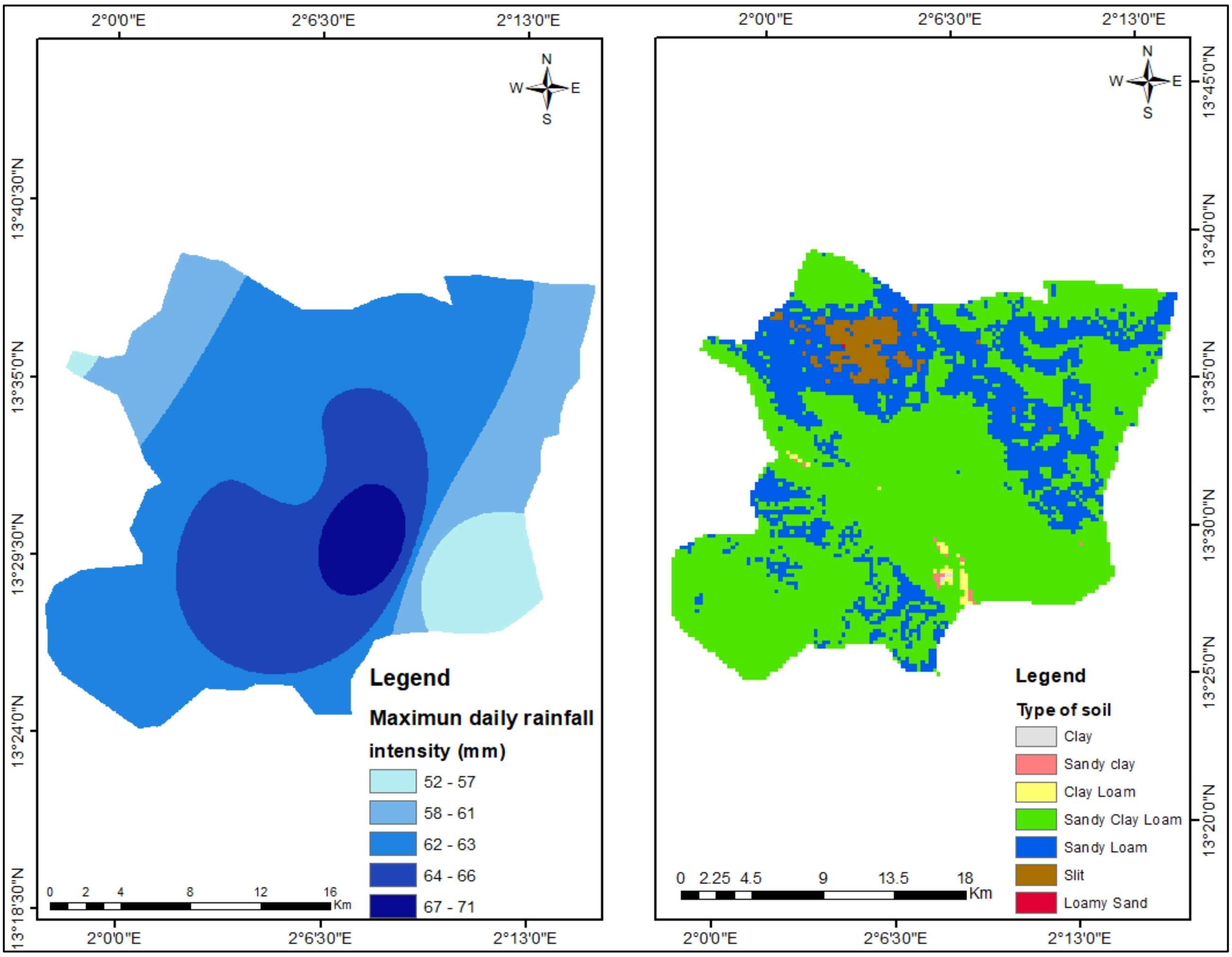

Figure 4.21: Thematic layer for rainfall and soil for Niamey

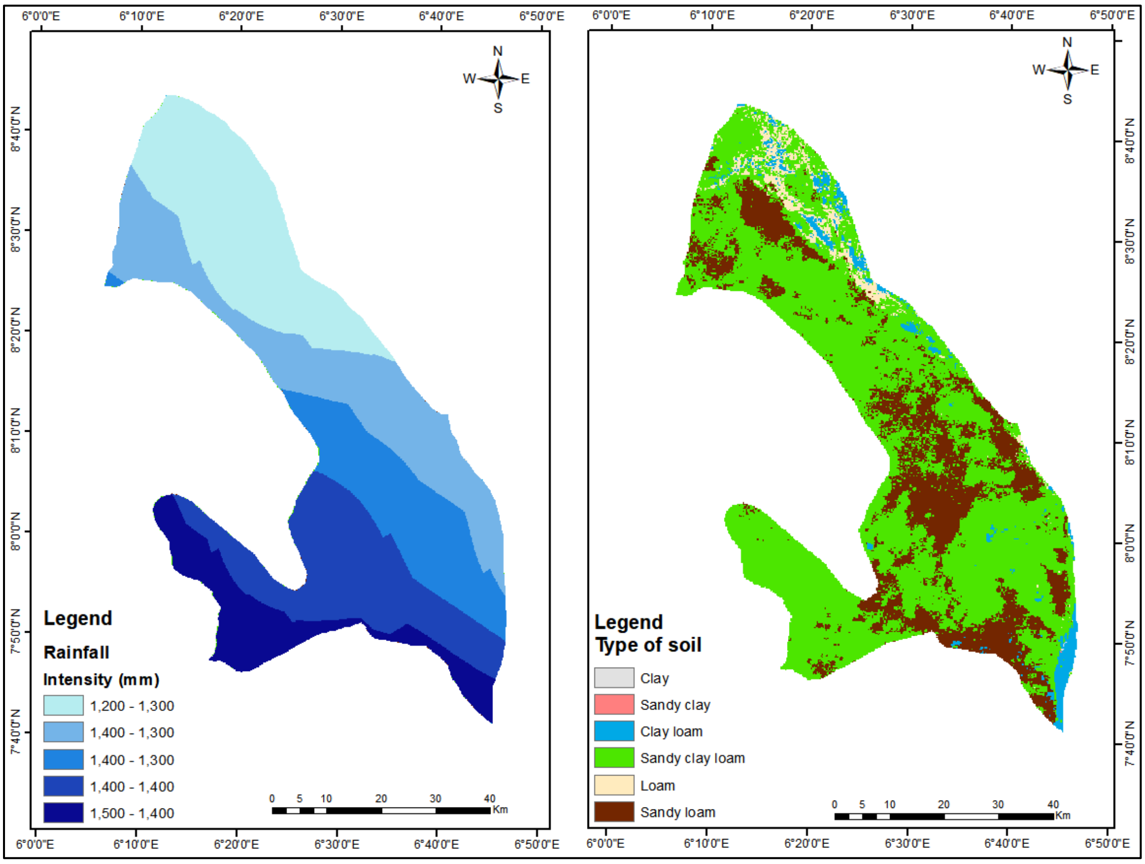

Figure 4.22: Thematic layer for rainfall and soil for Lokoja

(iii) Vegetation and water indices

The NDWI in Niamey, ranging from -0.5 to -0.2 (Figure 4.23), indicates dominance of areas with very little water. This reflects a low water storage capacity at the surface, increasing the risk of flash flooding. The NDVI, fluctuating between -0.3 and 0.3, shows limited vegetation, with a predominance of negative values associated with increased vulnerability. These parameters highlight the importance of investing in nature-based solutions such as reforestation to reduce risk; The NDWI at Lokoja varies between -0.43 and 0.17 (Figure 4.24). The low class is the most represented, indicating a moderate presence of surface water. The NDVI varies between -0.16 and 0.5, with negative values less frequent than in Niamey, which could slightly mitigate the risk of flooding. However, these indices indicate the need to strengthen water and vegetation management to limit the impact.

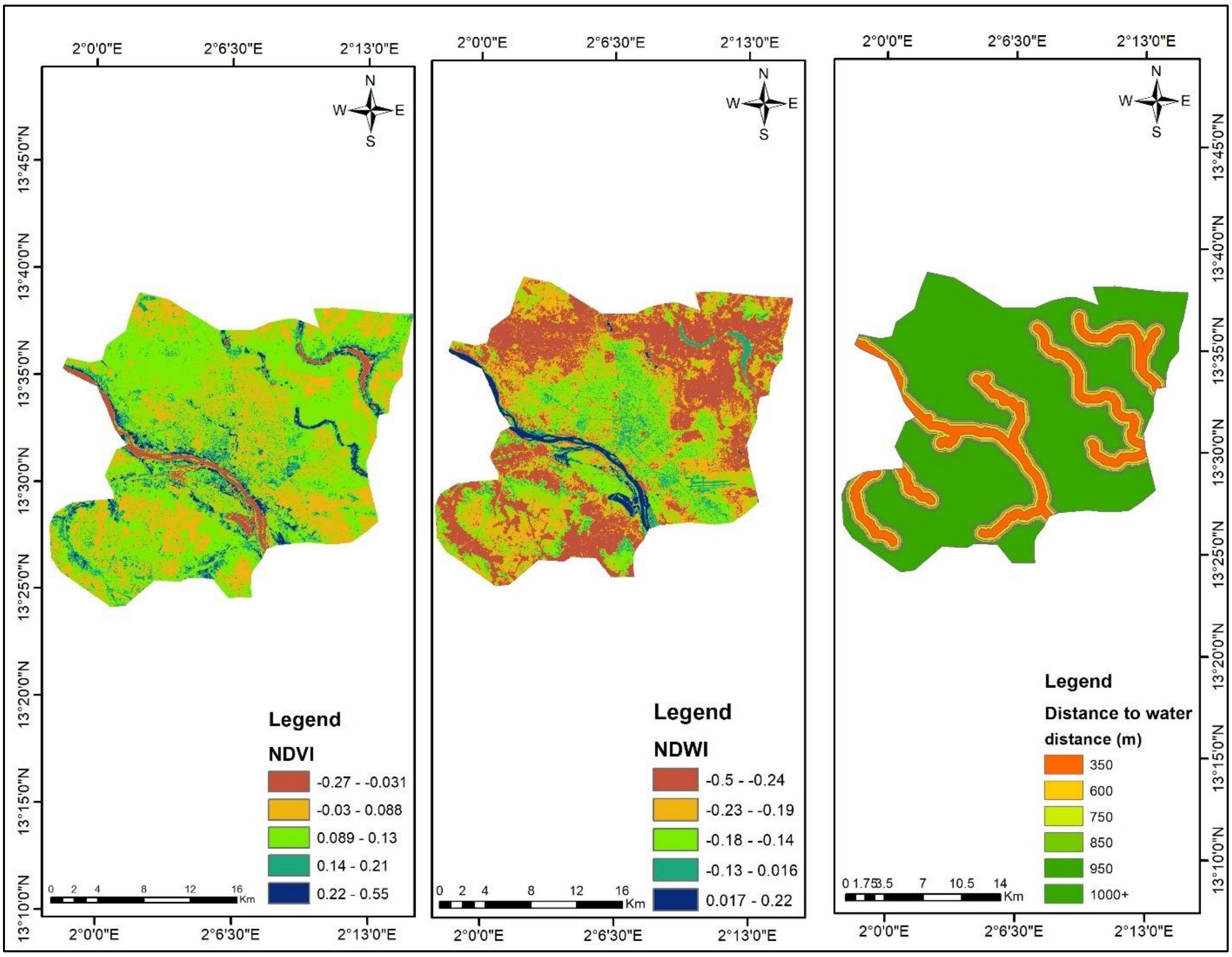

Figure 4.23: Thematic layer NDVI, NDWI and the distance to water in Niamey

The higher variability of altitudes in Lokoja explains its very high risk of flooding, in contrast to Niamey, where altitudes are more homogenous. The steep slopes prevalent in both towns amplify run-off and require similar development solutions. The higher drainage density in Lokoja increases its drainage capacity but also highlights the risk of intense runoff. Niamey shows increased vulnerability due to lower vegetation cover, while Lokoja benefits slightly more from vegetation.

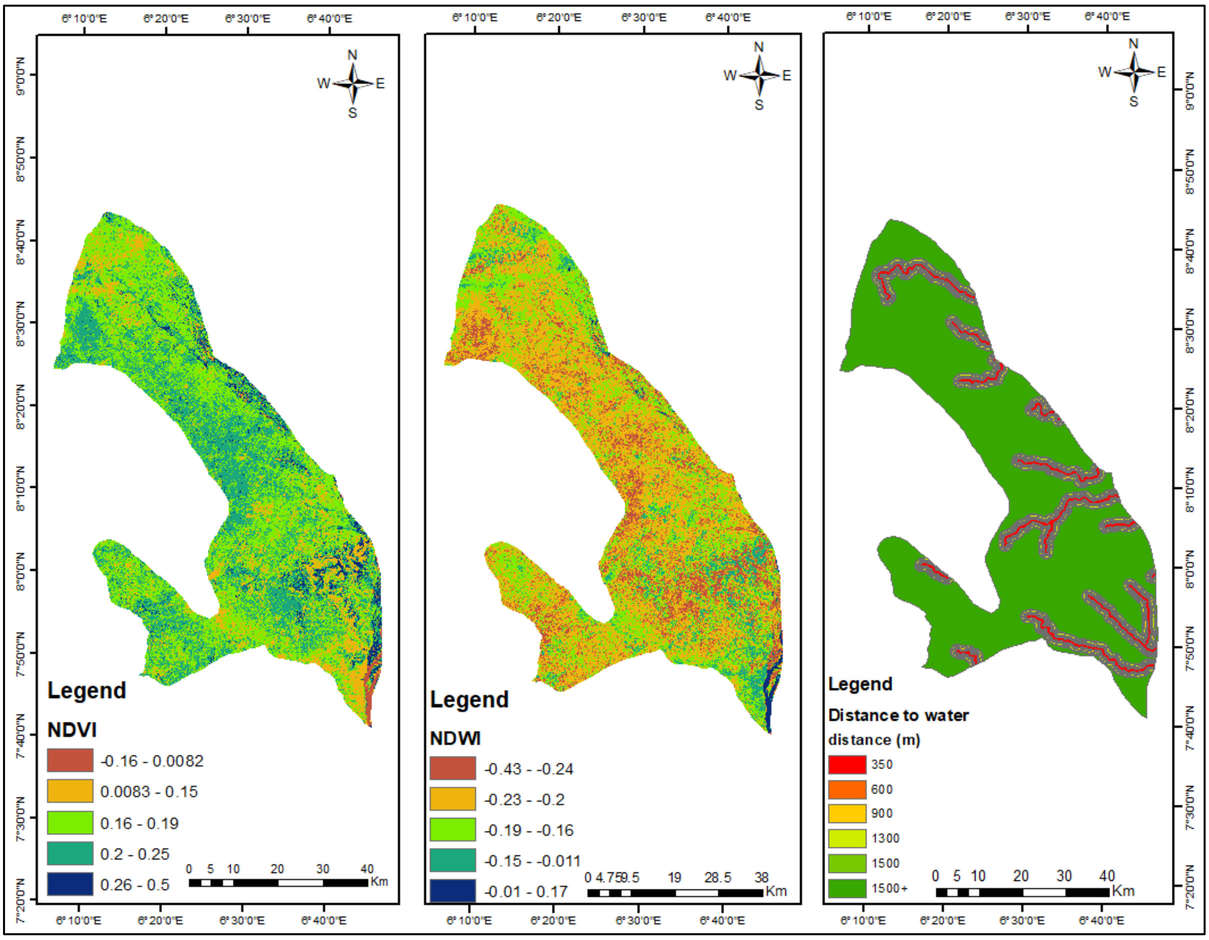

Figure 4.24: Thematic layer NDVI, NDWI and the distance to water in Lokoja

Table 4.13: Pairwise comparison matrix for flood susceptibility

Factor	S	E	TWI	DR	DD	Rainfall	NDWI	NDVI	SOIL	Vp	Cp	Weight
S	1	0.33	3	4	4	6	7	8	8	3.27	0.24	24%
E	3	1	3	4	4	5	6	7	7	3.91	0.29	29%
TWI	0.33	0.33	1	3	3	4	5	6	6	2.08	0.16	16%
DR	0.25	0.25	0.33	1	1	3	4	4	5	1.20	0.09	9%
DD	0.25	0.25	0.33	1	1	3	4	4	5	1.20	0.09	9%
Rainfall	0.14	0.20	0.25	0.33	0.33	1	1	3	3	0.58	0.04	4%
NDWI	0.14	0.17	0.20	0.25	0.25	1	1	4	4	0.55	0.04	4%
NDVI	0.13	0.14	0.17	0.25	0.25	0.33	0.25	1	1	0.29	0.02	2%
SOIL	0.13	0.14	0.17	0.2	0.2	0.33	0.25	1	1	0.28	0.02	2%
Sum	5.40	2.82	8.45	14	14	23.67	28.50	38	40	13.35	1	100%

Saaty scale on relative importance, 1 : equal important, ...9 : extreme important where The S is the Slope E the Elevation, TWI is the topographic wetness index, DR is the distance to river, DD is the drainage density, NDWI, is the normalised water index, , NDVI is the normalised difference vegetation index

Table 4.14 : Pairwise comparison matrix for flood vulnerability

	LULC	Pop	Distance to Road	Vp	Cp	Weight (%)
LULC	1	3.00	4.00	2.29	0.61	61
Pop	0.33	1	3.00	1.00	0.27	27
Distance to Road	0.25	0.33	1	0.44	0.12	12
Sum	1.58	4.33	8.00	3.73	1.00	100

Table 4.15: The Consistency check for flood vulnerability

Lambda Max	N	Consistency Index (CI)	Consistency Ratio (CR)
3.07	3	0.04	0.06

4.1.6.1 Flood Vulnerability Layers

The thematic land use and land cover map in figure 4.25 for Niamey area identified six major categories, as shown. In Niamey, inhabited areas represent the second-largest land use category after bare land. Conversely, in Lokoja (figure 4.28), built-up areas rank third after bare land and tree cover.

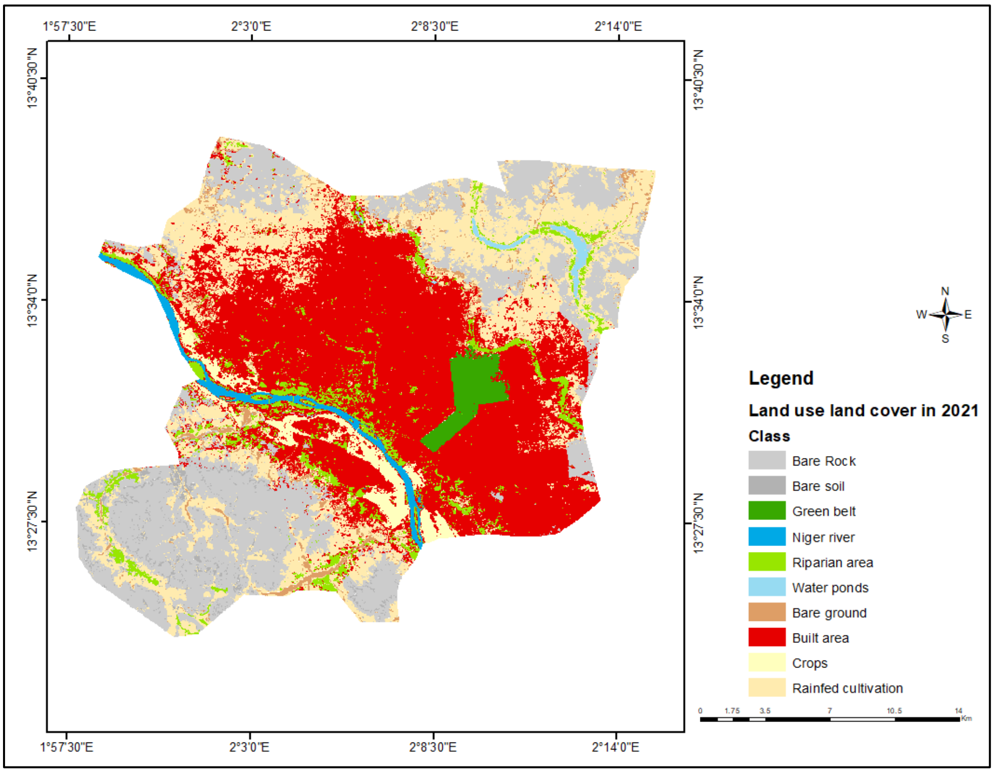

Figure 4.25: land cover layer used for flood vulnerability in Niamey

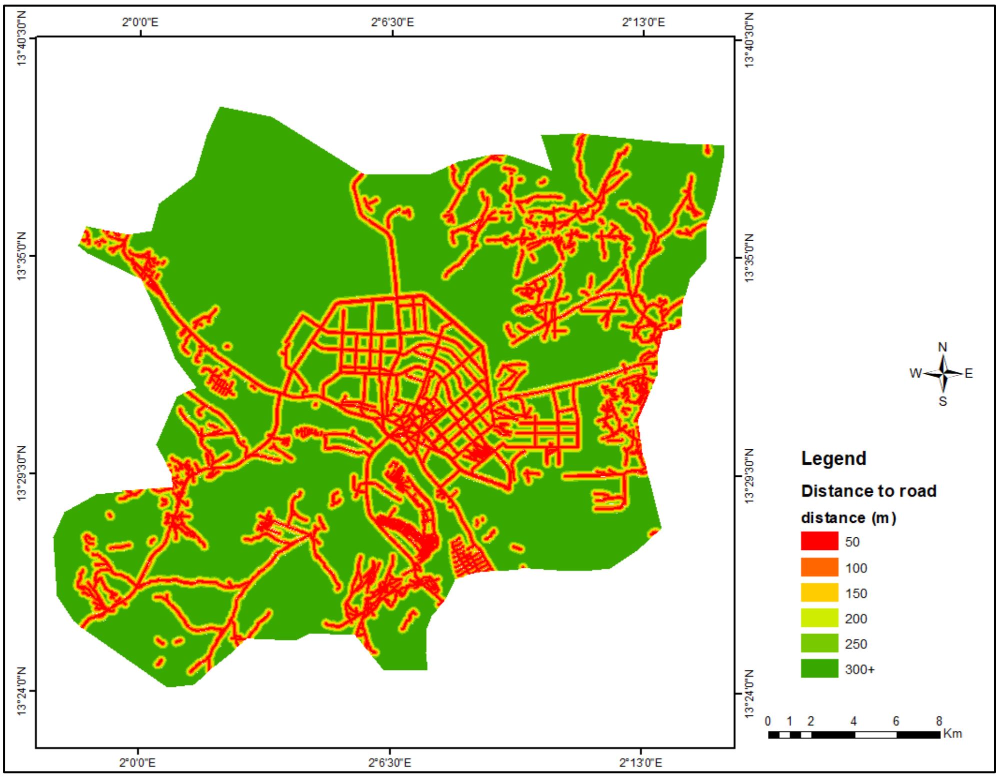

Figure 4.26: Distance to road used for flood vulnerability in Niamey

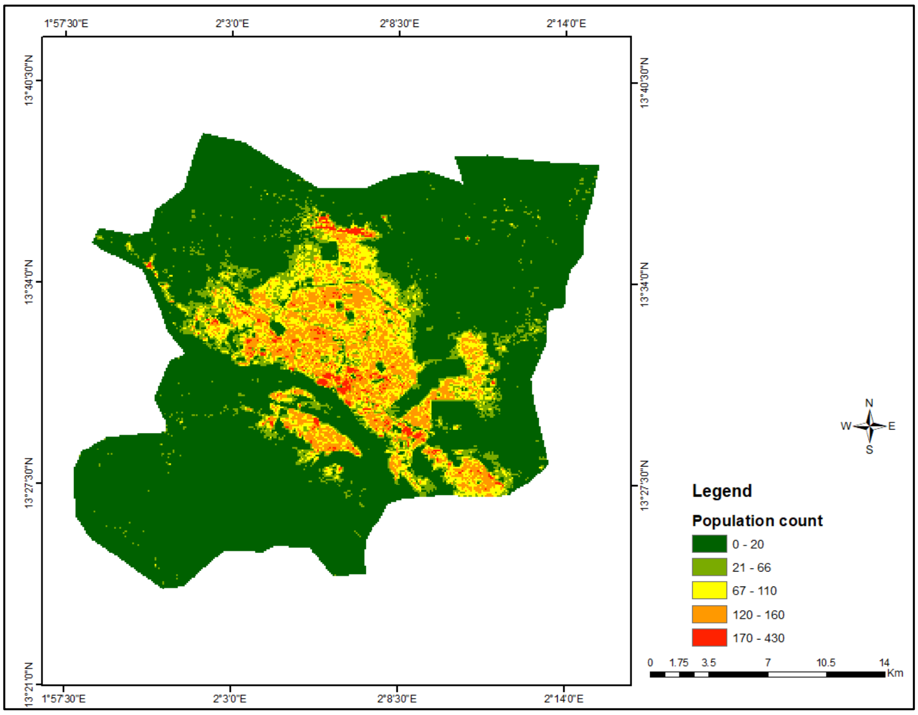

Figure 4.27: Population distribution used for flood vulnerability in Niamey

The land use map was reclassified on a scale from 1 (very low vulnerability) to 5 (very high vulnerability) using the reclassification tool. Each land cover class was assigned a specific level of flood vulnerability. Water bodies, such as rivers, lakes, and ponds, were classified as having very low vulnerability (1) because these areas do not experience additional damage during flood events. Unlike agricultural or built-up areas, aquatic surfaces are considered the least vulnerable according to the flood vulnerability scale applied in this study. In contrast, built-up areas were categorised with high vulnerability (4), while flood-prone vegetation was classified as having very high vulnerability (5). Bare soils were considered moderately vulnerable (3), and forested areas, due to their water absorption capacity, were classified with low vulnerability (2). The classification results indicate that the majority of Niamey's surface area falls within moderate (57.68%) and high vulnerability levels (38.68%), with only 0.07% of the area classified as very highly vulnerable. In Lokoja, low (43.02%) and moderate (36.84%) vulnerability levels dominate, while highly vulnerable areas account for 18.32%, and very highly vulnerable areas represent only 0.54% of the surface

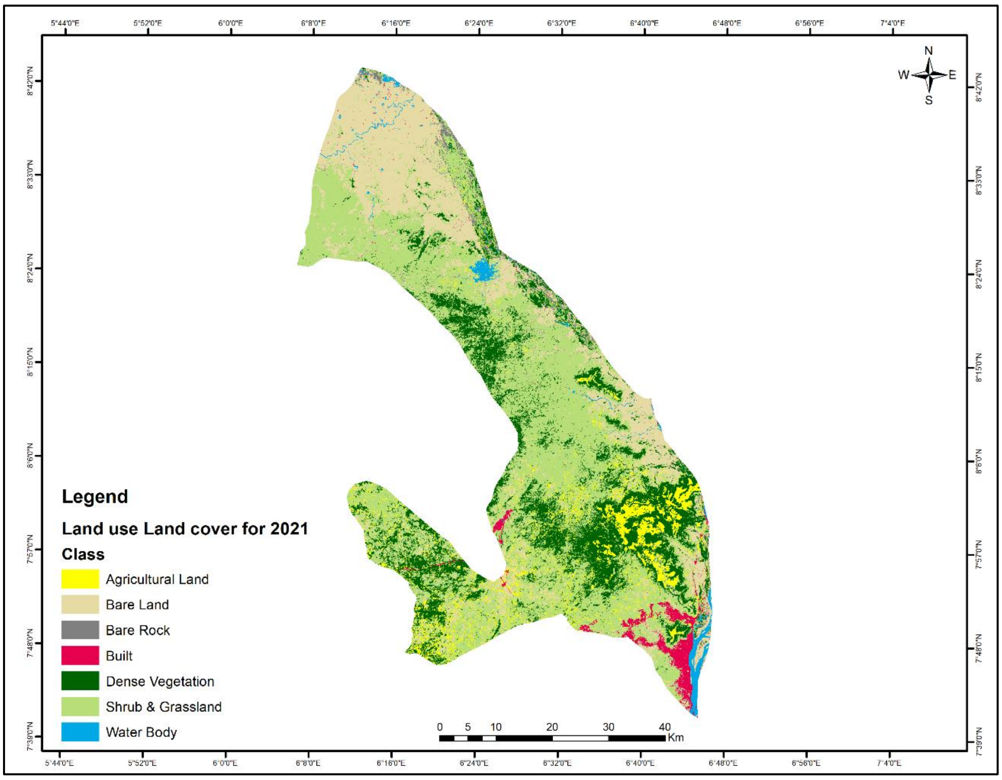

Figure 4.28: land cover layer used for flood vulnerability in Lokoja

Furthermore, the analysis of the spatial distribution of the population has enabled the characterisation of the socio-economic aspect by identifying areas with high population density, where the pressure on natural resources and infrastructure is particularly intense. The map showing this distribution was drawn up using freely accessible data from Global Human Settlement (consulted on 15 October 2024 at (https://human-settlement.emergency.copernicus.eu/download.php?ds=pop). It shows a population density ranging from 0 to 433.9 in Niamey (figure 4.27) and from 0 to 410.9 in Lokoja (figure 4.30). The map layers were then reclassified into five categories - very low, low, medium, high and very high - with the percentage of each city's total area corresponding to each category detailed (Tables 4.22 for Niamey and 4.23 for Lokoja). A direct relationship between high population density and extreme vulnerability has been established, leading to the classification of areas with very high concentrations as highly vulnerable in this study. In addition, the distribution of distances from roads was mapped by creating buffer zones around the main roads. Figures 4.26 and 4.29 present the proximity classes to roads, divided into five levels of accessibility: very low, low, medium, high, and very high. Thus, this study offers municipal planners a means to identify areas most exposed to risks, promoting a more efficient allocation of resources for prevention and crisis management. By categorising vulnerability levels, it constitutes a valuable tool for prioritising interventions, strengthening infrastructure in high-risk areas, and designing adaptation strategies suited to local contexts. It also contributes to increasing the resilience of communities to extreme events by integrating risk reduction measures into urban planning. Weights and eigenvectors have been calculated for all the vulnerability criteria, and their values are available in Table 4.22 and 4.23. The assigned weights are 61% for land use and land cover (LULC), 27% for population distribution and 12% for distance to roads. Table 4.17 shows the consistency rate and consistency index for the vulnerability map, with a consistency rate (CR) of around 6 %. The weights and eigenvectors have been calculated for all the vulnerability criteria, and their values are available in table 4.16. The assigned weights are 61% for land use and land cover (LULC), 27% for population distribution and 12% for distance to roads.

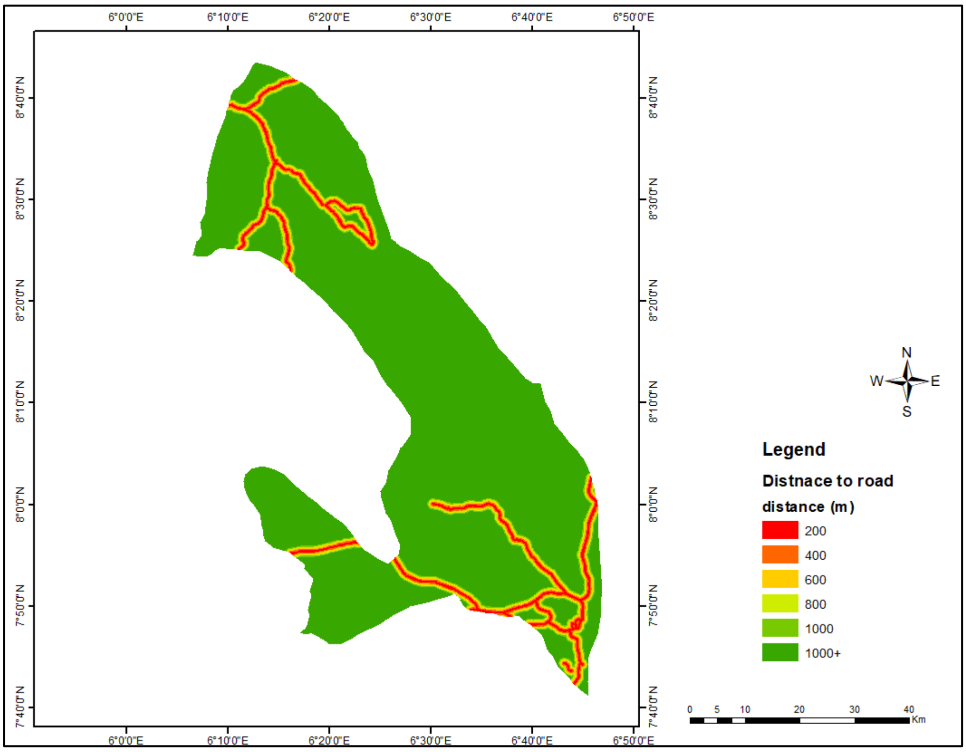

Figure 4.29: Distance to road used for flood vulnerability in Lokoja

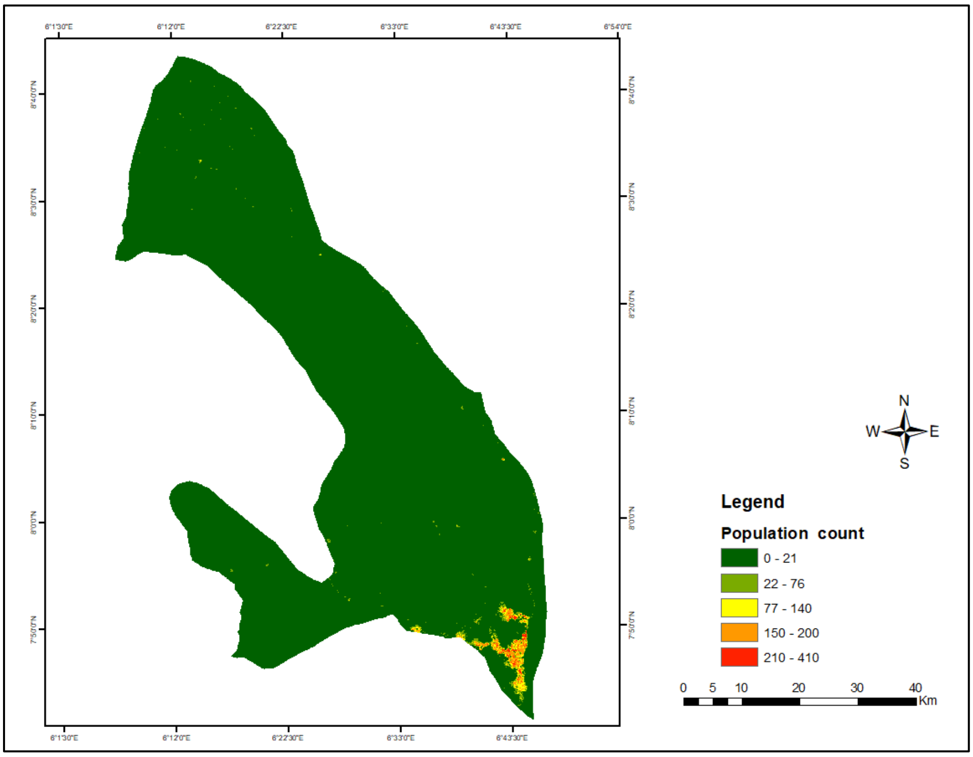

Figure 4.*30*: Population distribution used for flood vulnerability in Lokoja

4.1.6.2 Flood susceptibility

The consistency ratio demonstrated satisfactory coherence between the layers, with a value of 0.06 (below 0.10), as indicated in Table 4.18. The final flood susceptibility map was generated for both study areas using the weighted overlay method. Based on the results, the study areas were subdivided into five flood susceptibility classes: very low, low, moderate, high, and very high (in Lokoja figure 4.31 and in Niamey 4.32). In this analysis, the highest weight was assigned to elevation (29%), followed by slope (24.5%), topographic wetness index (15.6%), drainage density (9%), distance to the river (9%), precipitation (4.3%), NDWI (4%), NDVI (2.2%), and soil type (2.1%). The study area is characterised by the presence of the Niger River, which is the main cause of significant flooding. These floods generally occur along the riverine areas. The "high" and "very high" flood susceptibility classes are predominantly observed in these areas.

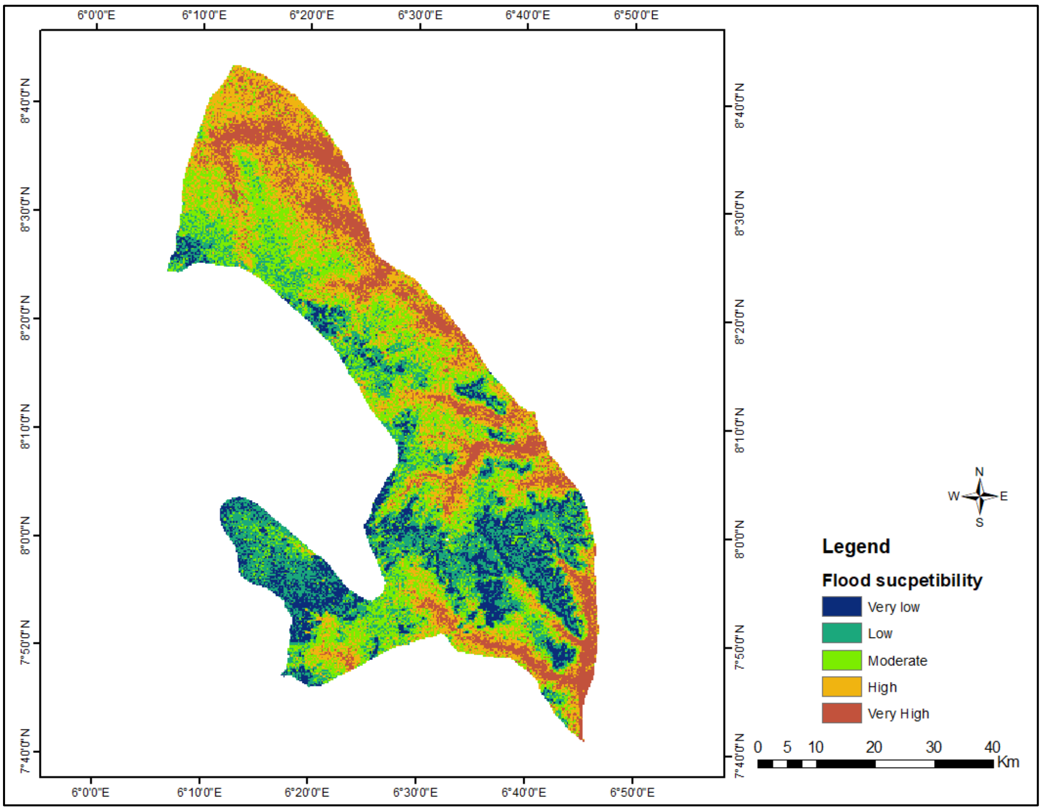

Figure 4.31: Flood susceptibility zonation map for Lokoja

The flood susceptibility map results show index values ranging from 1.14 to 4.88 for Niamey and from 1.11 to 4.79 for Lokoja. The flood susceptibility distribution for Niamey is as follows: very low (17 %), low (20 %), moderate (27 %), high (17 %), and very high (9 %). For Lokoja, the percentages are: very low (24 %), low (24 %), moderate (25 %), high (18 %), and very high (9 %).

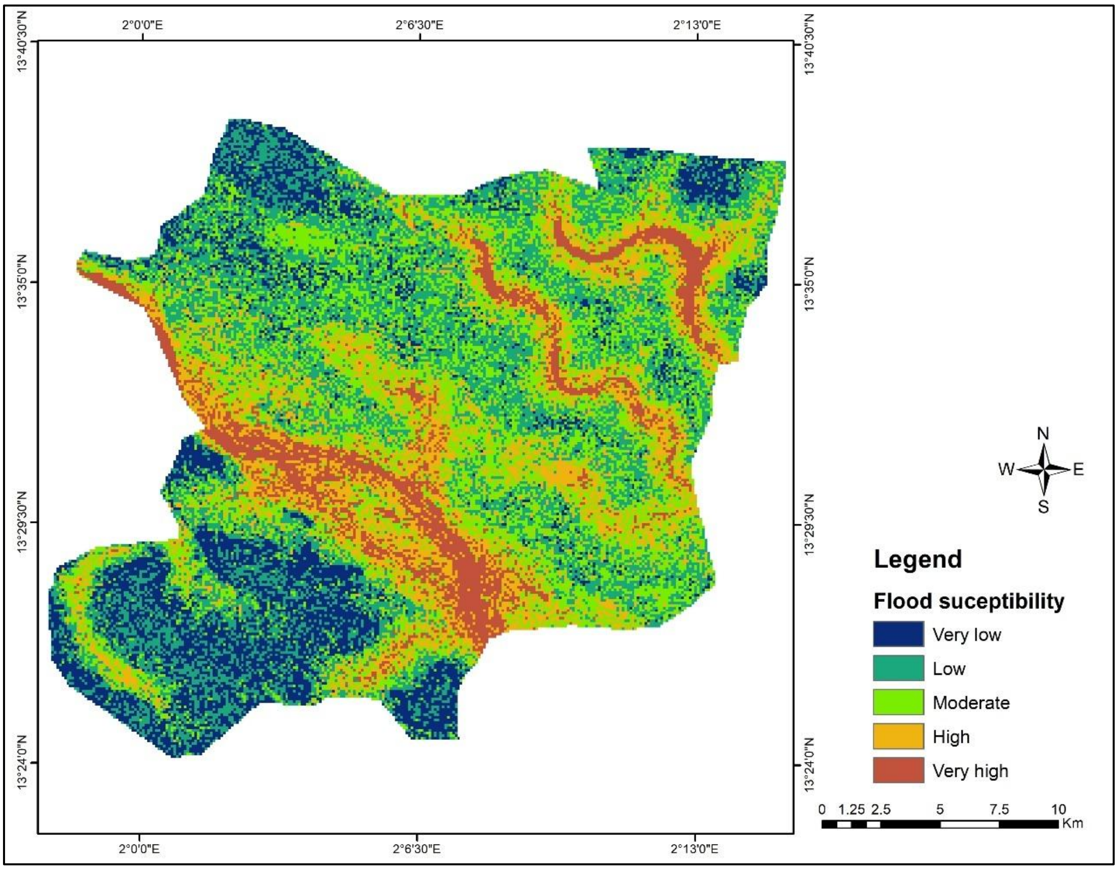

Figure 4.32: Flood susceptibility zonation map for Niamey

Table 4.18: Main results of the Consistency check for flood susceptibility

Lambda Max	N	Consistency Index (CI)	Consistency Ratio (CR)
9.72	9	0.09	0.06

4.1.6.3 Flood risk results

The primary outcome of this study is the development of a flood risk zoning map, created by combining susceptibility map with vulnerability map. The resulting risk map is classified into five categories: very low, low, moderate, high, and very high, as shown in the figure 4.33 and 4.34 (respectively for Niamey and Lokoja). In the Niamey area, high and very high flood risk zones account for 25 % and 7 % of the total area, respectively, while in Lokoja, these zones cover 12 % and 3 % of the study area.

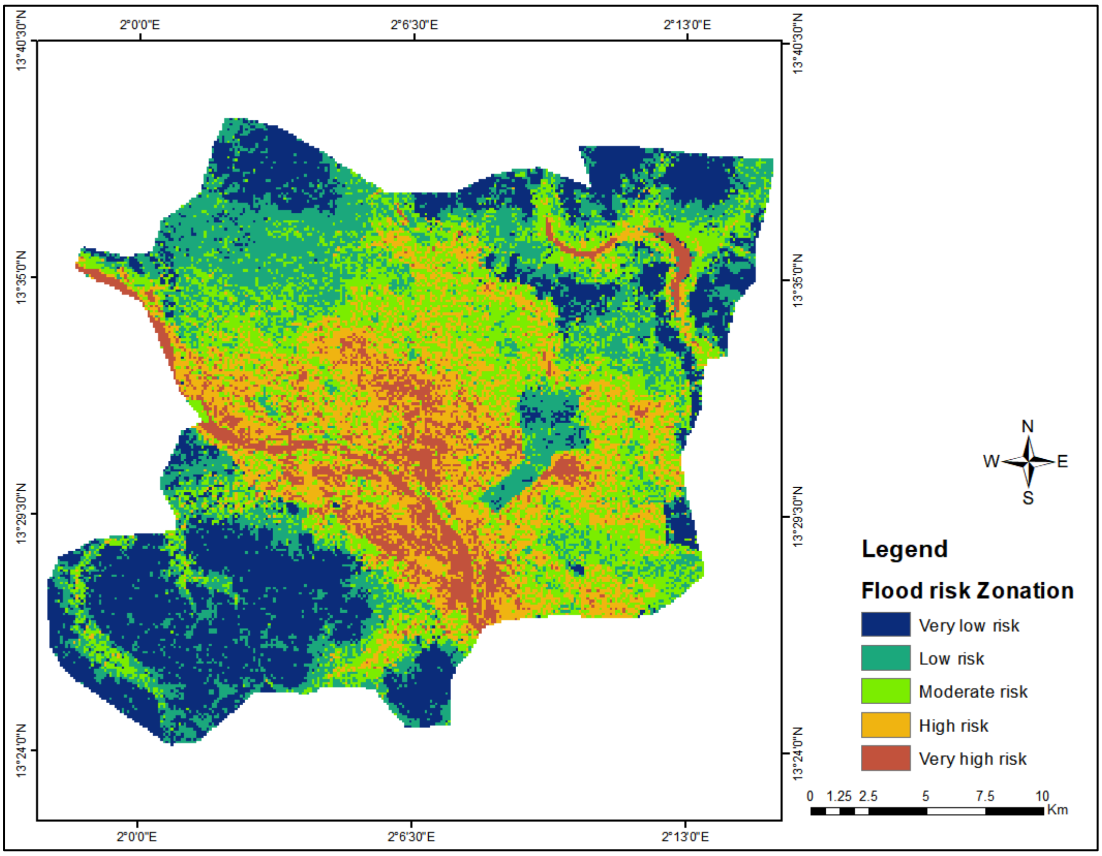

Figure 4.33: Flood risk zonation map for Niamey

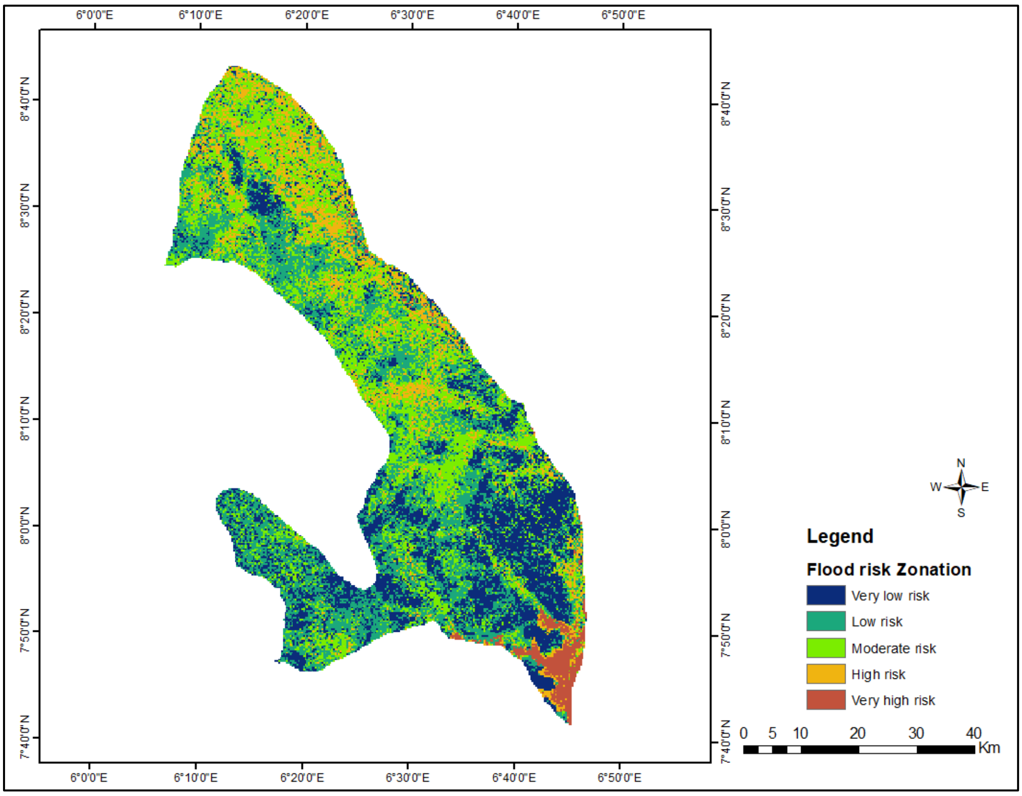

Figure 4.34: Flood risk zonation for Lokoja

The very low, low, and moderate flood risk classes represent 10 %, 26 %, and 31 % of the area in Niamey, and 23 %, 33 %, and 28 % as shown by the table 4.16 in Lokoja. High and very high-risk zones are distributed across the entire study area but are particularly concentrated along river corridors. These high-risk areas are primarily characterised by low elevation, gentle slopes, and high drainage density. The figure illustrates the blocks most affected by high flood risk

Table 4.16: Spatial distribution Area of flood susceptibility, flood vulnerability and for flood risk zonation, for Niamey and Lokoja Metropolises

Study Aera	Level	Flood susceptibility		Flood vulnerability		Flood risk zonation	
		Area (Km^2)	Area (%)	Area (Km^2)	Area (%)	Area (Km^2)	Area (%)
Niamey	Very Low	86	17	131	24	54	10
	Low	166	30	134	24	145	26
	Moderate	151	27	138	25	173	31
	High	96	17	98	18	138	25
	Very High	51	9	50	9	38	7
Lokoja	Very Low	370	11	2223	66	784	23
	Low	708	21	988	29	1117	33
	Moderate	905	27	70	2	952	28
	High	835	25	58	2	403	12
	Very High	532	16	28	1	85	3

Table 4.17: Selected criteria and associated weighting of each factor used in developing the flood susceptibility map in Niamey

Factor	AHP Weight for each factor	Reclass class	Flood Susceptibility level	Area in km²	Area in percentage (%)
Elevation	29	5	Very high	67.37	12.14
		4	High	95.43	17.19
		3	Moderate	190.86	34.38
		2	Low	115.87	20.87
		1	Very Low	87.03	15.68
Slope	24	5	Very Hight	212	38
		4	Hight	233	42
		3	Moderate	82	15
		2	Low	24	4
		1	Very Low	4	1
Twi	16	1	Very Low	264	48
		2	Low	125	23
		3	Moderate	92	17
		4	High	62	11.12
		5	Very High	12	2.24
Drainage density	9	1	Very Low	215.21	39
		2	Low	145.23	26.09
		3	Moderate	111	20
		4	Hight	72	13
		5	Very High	13	2
Distance to river	9	5	Very high	69	12.41
		4	High	47	8.45
		3	Moderate	28	5.03
		2	Low	37	6.65
		1	Very low	375	67.44
Rainfall	5	1	Very Low	39.15	7.04
		2	Low	99.31	17.84
		3	Moderate	269.86	48.49
		4	High	124.31	22.34
		5	Very High	23.91	4.3
NDWI	4	1	Very Low	199	36
		2	Low	156	28
		3	Moderate	146	26
		4	Hight	41	7
		5	Very High	15	3
NDVI	2	1	Very Low	9	2
		2	Low	4	1
		3	Moderate	403	72
		4	Hight	112	20
		5	Very High	28	5
Soil	2	1	Very Low	15.94	2.86
		2	Low	157.56	28.31
		3	Moderate	379.25	68.14
		4	Hight	2.43	0.43
		5	Very High	1.31	0.23

Table 4.18: Selected criteria and associated weighting of each factor used in developing flood susceptibility map in Lokoja

Factor	AHP Weight for Each Factor	Reclass Class	Flood Susceptibility Level	Area in km²	Area in Percentage (%)
Elevation	29	5	Very high	957.224	28.18
		4	High	893.545	26.31
		3	Moderate	800.6	23.57
		2	Low	381.323	11.23
		1	Very Low	363.551	10.70
Slope	24	5	Very High	1748	51.47
		4	High	1125	33.12
		3	Moderate	293	8.63
		2	Low	152	4.48
		1	Very Low	68	2.00
TWI	16	1	Very Low	1282.12	37.75
		2	Low	1193.67	35.15
		3	Moderate	489.109	14.40
		4	High	341.94	10.07
		5	Very High	78.39	2.31
Drainage density	9	1	Very Low	951.32	28.01
		2	Low	871.96	25.67
		3	Moderate	708.335	20.86
		4	Hight	606.624	17.86
		5	Very High	258.017	7.60
Distance to river	9	1	Very Low	1029.06	30.30
		2	Low	598.211	17.61
		3	Moderate	629.686	18.54
		4	Hight	185.002	5.45
		5	Very High	954.44	28.10
Rainfall	5	1	Very Low	879	25.88
		2	Low	824	24.26
		3	Moderate	574.813	16.92
		4	High	714.65	21.04
		5	Very High	404.64	11.91
NDWI	4	1	Very Low	480.6	14.15
		2	Low	1556.74	45.83
		3	Moderate	1032.03	30.39
		4	Hight	299.068	8.81
		5	Very High	27.6	0.81
NDVI	2	1	Very Low	25.88	0.76
		2	Low	433.4	12.76
		3	Moderate	1572	46.28
		4	Hight	1218.26	35.87
		5	Very High	146.908	4.33
Soil	2	1	Very high	1000.46	29.46
		2	High	632.303	18.62
		3	Moderate	815.162	24.00
		4	Low	772.18	22.74
		5	Very low	177.904	5.24

Table 4.19: Selected criteria and associated weighting of each factor used in developing flood vulnerability map in Niamey

Factor	AHP Weight for each factor	Reclass class	Flood Susceptibility level	Area in km²	Area in percentage (%)
LULC	0.61	1	Very low	131	24.00
		2	Low	10	2.00
		3	Moderate	167	30.00
		4	High	237	43.00
		5	Very High	12	2.00
Population distribution	0.27	1	Very low	410	74.00
		2	Low	42	8.00
		3	Moderate	44	8.00
		4	High	51	9.00
		5	Very High	9	2.00
Distance to Road	0.12	1	Very low	355	64.00
		2	Low	39	7.00
		3	Moderate	45	8.00
		4	High	53	10.00
		5	Very High	65	12.00

Table 4.20: Selected criteria and associated weighting of each factor used in developing flood vulnerability map in Lokoja

Factor	AHP Weight for each factor	Reclass class	Flood Susceptibility level	Area in km²	Area in percentage (%)
LULC	0.61	1	Very high	816.02	24.03
		2	High	1524.40	44.90
		3	Moderate	948.56	27.90
		4	Low	74.84	2.20
		5	Very low	30.94	0.91
Population distribution	0.27	1	Very low	3364.00	99.00
		2	Low	19.00	1.00
		3	Moderate	14.00	0.00
		4	High	14.00	0.00
		5	Very High	4.00	0.00
Distance to Road	0.12	1	Very low	3025.95	88.62
		2	Low	89.10	2.60
		3	Moderate	91.82	2.68
		4	High	94.90	2.77
		5	Very High	99.35	2.91

4.1.6.4 Implications of the results

The results of the analysis of susceptibility to flooding show that altitude and slope play a crucial role in the distribution of areas at risk. In Niamey, where altitudes vary between 180 and 300 metres, around 34.38% of the surface area is at medium elevation, favouring the accumulation of run-off water, compared with 15.68% at very low elevation, amplifying the risk of fluvial flooding. On the other hand, Lokoja, with altitudes ranging from 19 to 544 metres, has a significant proportion of very highly susceptible areas (28%). This heterogeneous topography, combined with very low altitudes, concentrates risks around river areas and catchment basins. The slopes accentuate this dynamic: in Niamey, 80% of the surface is classified as having a 'high to very high' slope, increasing the retention of water. In Lokoja, 84% of the surface area has similar slopes, accelerating run-off and exacerbating rainwater flooding. These two parameters, with respective weightings of 29% and 24% in the AHP model, confirm their major influence on susceptibility to flooding. These results indicate that sustainable management must focus on controlling runoff and reducing impacts in low-lying areas and along watercourses. This requires solutions such as retention basins and measures to slow down run-off.

The Topographical Moisture Index (TWI), although moderately weighted at 16%, shows areas conducive to water concentration. In Niamey, the TWI ranges from 2.8 to 23, and in Lokoja from 3.2 to 23. Areas with high TWI, often located near watercourses, are more prone to waterlogging. Drainage density, meanwhile, shows a marked contrast: in Lokoja, it is 2.5 km/km² compared with 11 km/km² in Niamey. Although the high density in Niamey suggests a greater capacity to capture water, the predominance of very low-density areas (39%) in the city complicates efficient drainage. In Lokoja, high-density areas (25.54%) amplify the risks by concentrating water flows. Effective planning of drainage infrastructure is essential. In Lokoja, this requires solutions to reduce rapid run-off, while in Niamey, investment in more robust drainage systems is crucial.

Analysis of the Normalised Water Index (NDWI) and the Normalised Vegetation Index (NDVI) shows that these parameters contribute little (4% and 2% weighting respectively) to overall susceptibility. In Niamey, the low NDWI values (-0.5 to -0.2) indicate a low soil absorption capacity. In Lokoja, the NDVI shows that there are fewer areas of dense vegetation, amplifying the risks associated with exposed soil. Vegetation management, including reforestation or soil stabilisation campaigns, can moderate the impact of flooding, particularly in vulnerable areas. Vulnerability is strongly influenced by land use (61%), population density (27%), and distance to roads (12%). In Niamey, around 43% of the surface area is classified between moderate and high levels of vulnerability, mainly in densely populated areas with poor infrastructure. In Lokoja, however, 95% of the area is classified as low vulnerability, underlining a greater structural resilience despite the high risk of susceptibility. These results call for policies to reduce socio-economic inequalities in Niamey, including appropriate infrastructure and educational programmes on risk management. The maps combining susceptibility and vulnerability show that Niamey has a significant proportion of moderate (31%), high (25%) and very high (7%) risk areas, concentrated around the river corridors.

In Lokoja, although low-risk areas predominate (56%), high-risk and very high-risk areas account for 12% and 3% respectively. The results highlight contrasting but complementary dynamics between Niamey and Lokoja. The AHP approach combined with GIS has enabled an in-depth analysis of the parameters influencing flooding. However, to maximise the impact of the proposed solutions, it is essential to adopt an integrated approach: Natural solutions (reforestation, soil conservation); Awareness campaigns to strengthen the resilience of local communities. Ultimately, these analyses provide a valuable tool for decision-makers and urban planners in both regions, enabling them to put in place policies based on solid scientific data. If properly coordinated, these actions could not only reduce the impact of flooding, but also promote the sustainable management of natural resources in the Niger basin.

4.1.7 Evaluation of flood risk based on extreme rainfall or heavy rainfall

The analysis of standardised anomalies for the various indices is illustrated by the figures (4.39, 4.40, 4.41). For the RX1DAY index, the Boubon and Lokoja stations show an increase of 2.9 % and 2.6 % respectively, while all the other stations show a constant trend, with no significant change. Concerning the RX5DAY index, rainfall trends remained constant for all stations. As for the R95P index, the anomalies show an increase of 2 % at the Boubon and Lokoja stations, while the Kollo, Niamey Ville and Niamey Airport stations show no significant change.

4.1.7.1 Breakpoint of extreme rainfall

Figure (4.36, 4.37, 4.38) illustrates the analysis of breakpoints using the Pettitt test on the extreme precipitation index time series. This test, which is widely used to detect changes in time series, was applied here for maximum precipitation over 1 day (RX1DAY), 5 days (RX5DAY) and very wet days (R95P). Tables 4.24, 4.25 and 4.26 summarise the breakpoints observed for each station. However, no statistically significant breakpoints were observed for these indices (p-value < 0.05), with p-values exceeding this limit. Although most of the p-values are above the 0.05 threshold, the results show a change in the variations in the time series at different dates. Analysis of RX1DAY revealed breakpoints in 2011 for Boubon and Niamey Ville, in 2006 for Kollo, and in 2003 for Lokoja. These results indicate an increase in extreme one-day rainfall events at these stations, particularly in the 2000s. However, Niamey Airport showed no significant break with a p-value of 0.99, indicating relative stability for this index at this station. The results for RX5DAY show a significant no break point for the Lokoja station in 2005 and for Niamey Airport in 2014, suggesting an intensification of rainfall events over a 5-day period. The breakpoints identified for the R95p index (very wet precipitation) also show non-significant breakpoints, whereas changes in variability at the Kollo in 2014 and Niamey Airport in 2006 stations suggest a change in very wet precipitation regimes in these regions, with a transition to periods of more intense precipitation after these dates. This finding differs to a certain extent from studies carried out in West Africa, where changes in climatic extremes have been observed. For instance, Mouhamed *et al*., (2013),in their work on the evolution of climatic extremes in the Sahel, showed an increase in extreme rainfall from the 1990s in some regions of the Sahel. The study reveals breaks in extreme rainfall associated with episodes of increased humidity, particularly in the Senegal River basin. However, this increase is not uniform across the region, and some areas show no significant change.

These results are therefore partially consistent with the observations in this study, where the absence of significant breakpoints is noted at several stations. In addition, the research done by Descroix *et al*. (2012) on rainfall in Niger and hydrological changes in the River Niger basin also suggests increases in extreme rainfall and a change in the hydrological regime in certain regions from the 1990s onwards. However, as in this study, these changes are not systematically accompanied by marked statistical breakpoints for all stations or all indices. This demonstrates the diversity and complexity of climatic responses to global change in the Sahelian region. Fofana *et al*,(2022) study, carried out in similar regions of West Africa (Mali), detected significant increases in extreme rainfall indices, such as R95P and RX5DAY, in recent periods, which contrasts with our results where no station showed a significant break for these indices. The absence of breakpoints in our analyses may reflect the greater natural variability at the stations studied or local characteristics that affect the climatic response in these specific areas. In addition, the study by Ndiaye *et al*, (2023), which analysed trends in extreme rainfall about global warming, found breakpoints in some regions of the Sahel. The variations observed between this study and previous work could be explained by several factors, including the temporal and spatial resolution of the data, the period studied, and the analysis methods used, while this study focused on a more restricted period (1982-2021) and on specific stations, work such as that by Lebel *et al.*, (2003) covers longer periods and larger areas, which may make it possible to detect changes that are not observable on a smaller scale. In another aspect, the statistical methods used can also influence the results, as highlighted by studies using different techniques, such as the Pettitt test, analysis using the Theil-Sen method, or Mann-Kendall tests, to identify trends in climate data.

Table 4.21: Breakpoints related to rx1day for the various station

	RX1DAY	
Station	**P-Value**	**Breaking Point**
Boubon	0.57	2011
Kollo	0.86	2006
Lokoja	0.31	2003
Niamey Ville	1	2011-2013
Niamey Airport	0.99	2017

Table 4.22: Breakpoints related to rx5day for the various station

	RX5DAY	
Station	**P-Value**	**Breaking Point**
Boubon	1	1992
Kollo	1	1998-2014
Lokoja	0.37	2005
Niamey Ville	1	2011
Niamey Airport	0.57	2014

Table 4.23: Breakpoints related to R95P for the various station

	R95P	
Station	**P-Value**	**Breaking Point**
Boubon	1	2016
Kollo	1	2014
Lokoja	0.22	1985
Niamey Ville	1	1997
Niamey Airport	0.95	2006

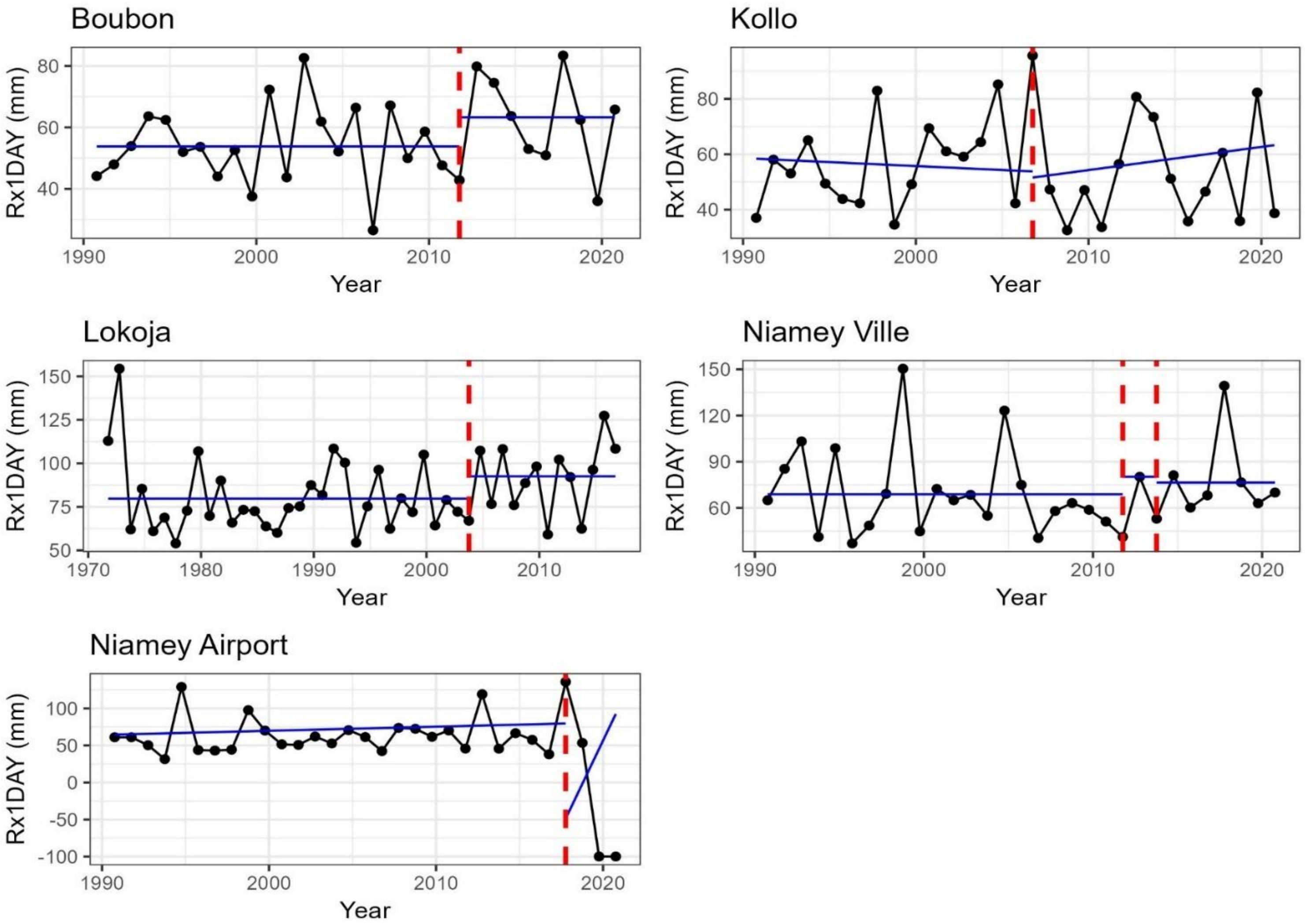

Figure 4.36: Breakpoint detected in Rx1day rainfall index for the various stations

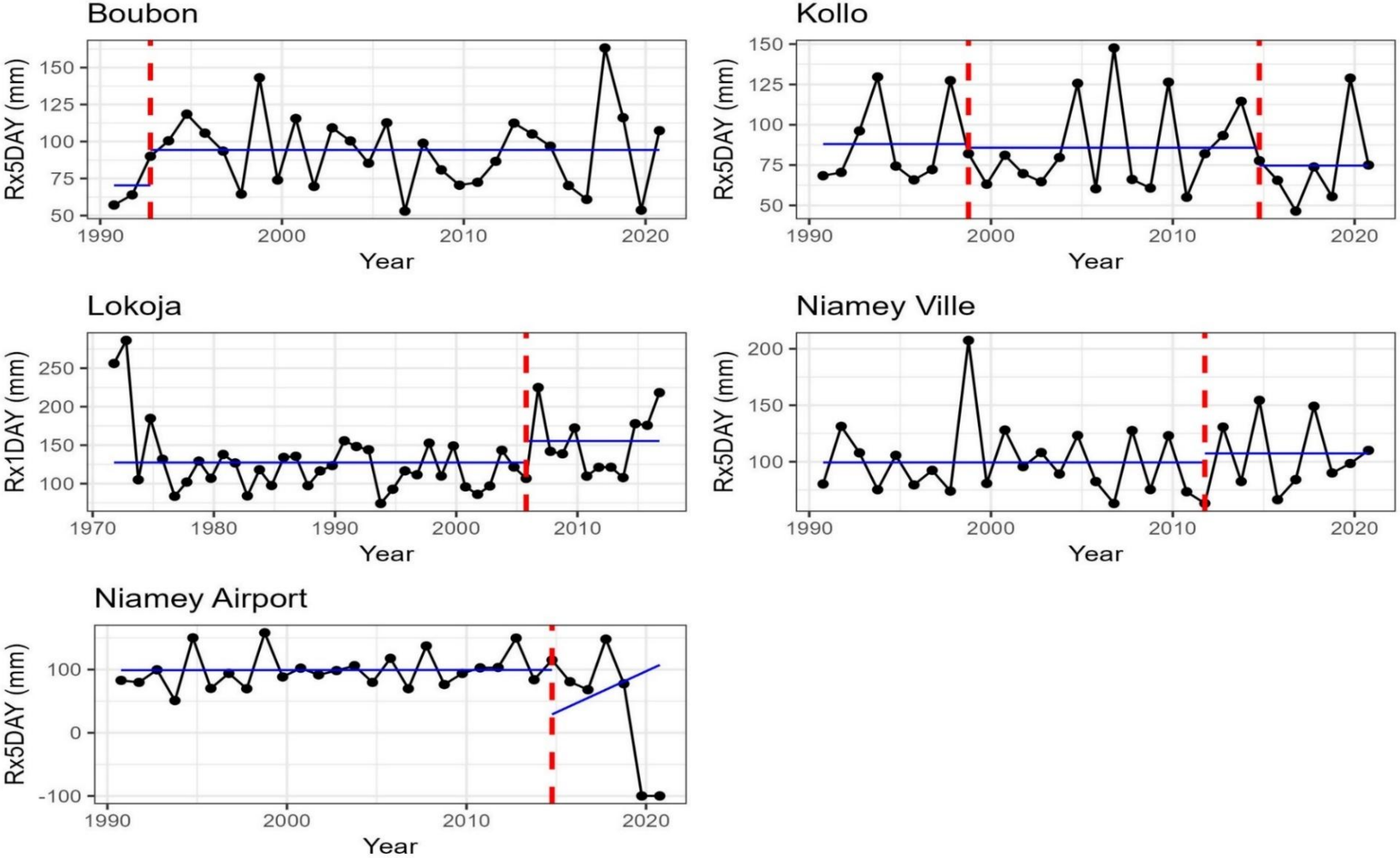

Figure 4.37: Breakpoint detected in the Rx5day rainfall index for the various stations

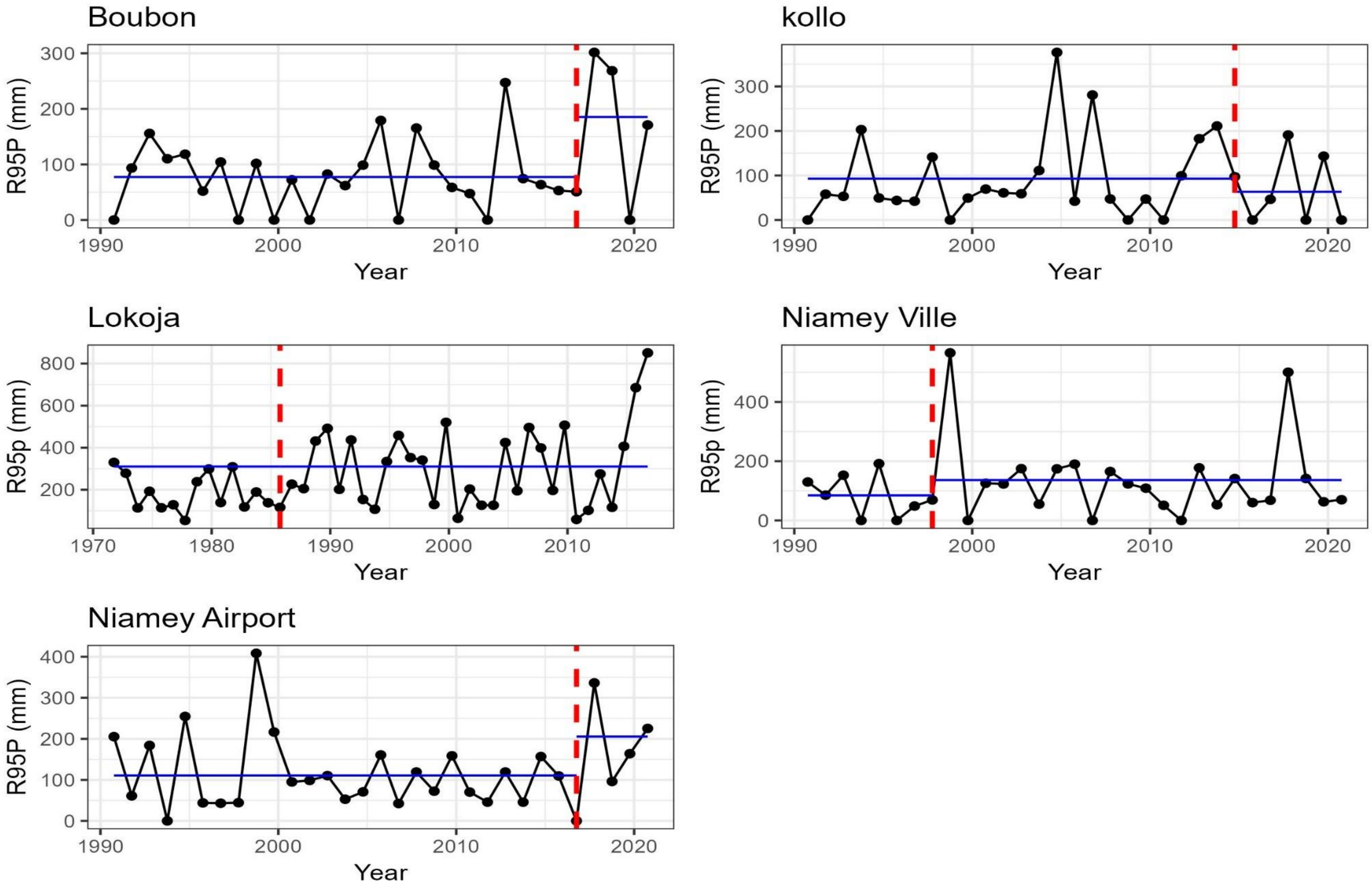

Figure 4.38: Breakpoint detected in R95p rainfall index for the various stations

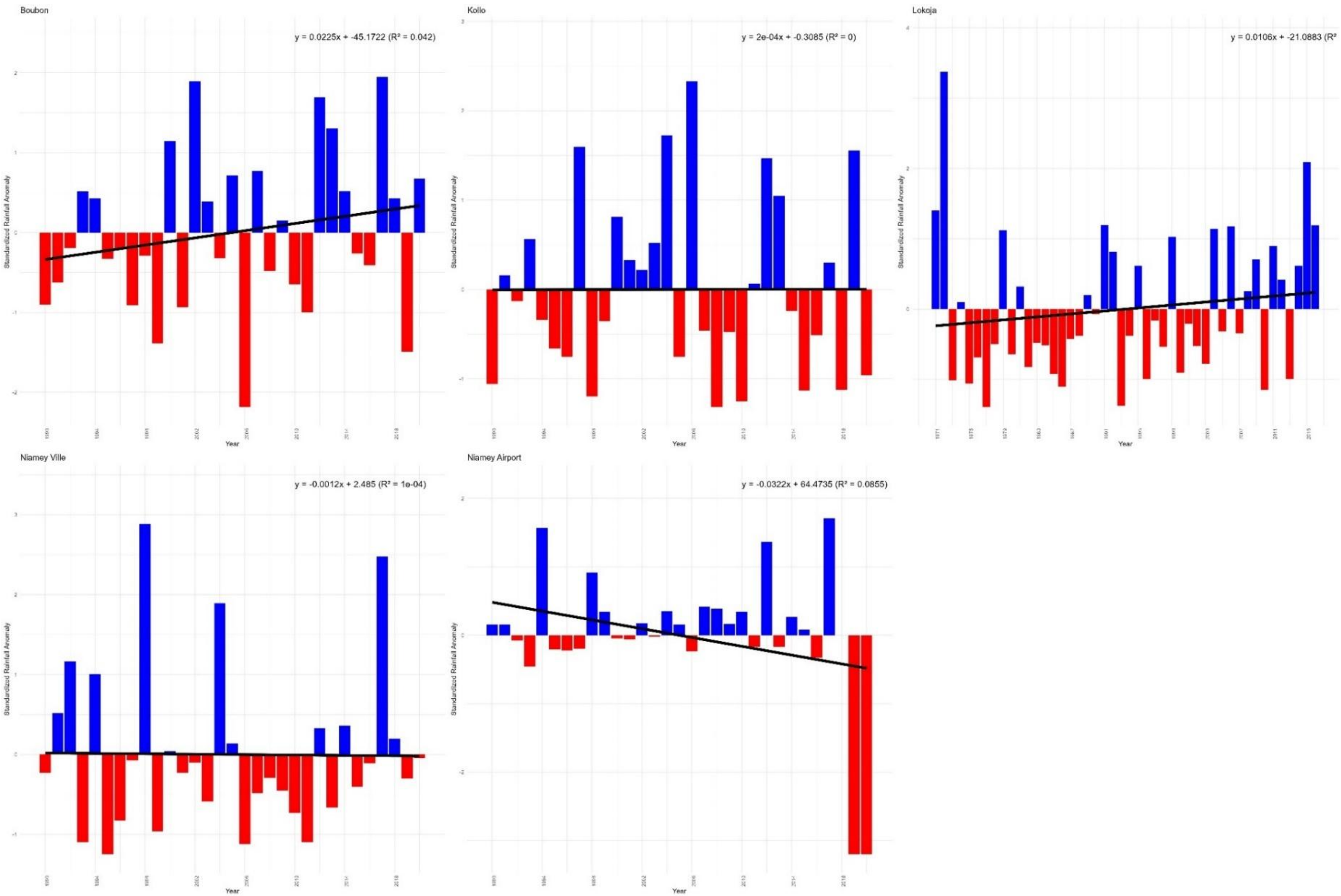

Figure 4.39: Standardised Precipitation Anomaly (SPA) for RX1DAY

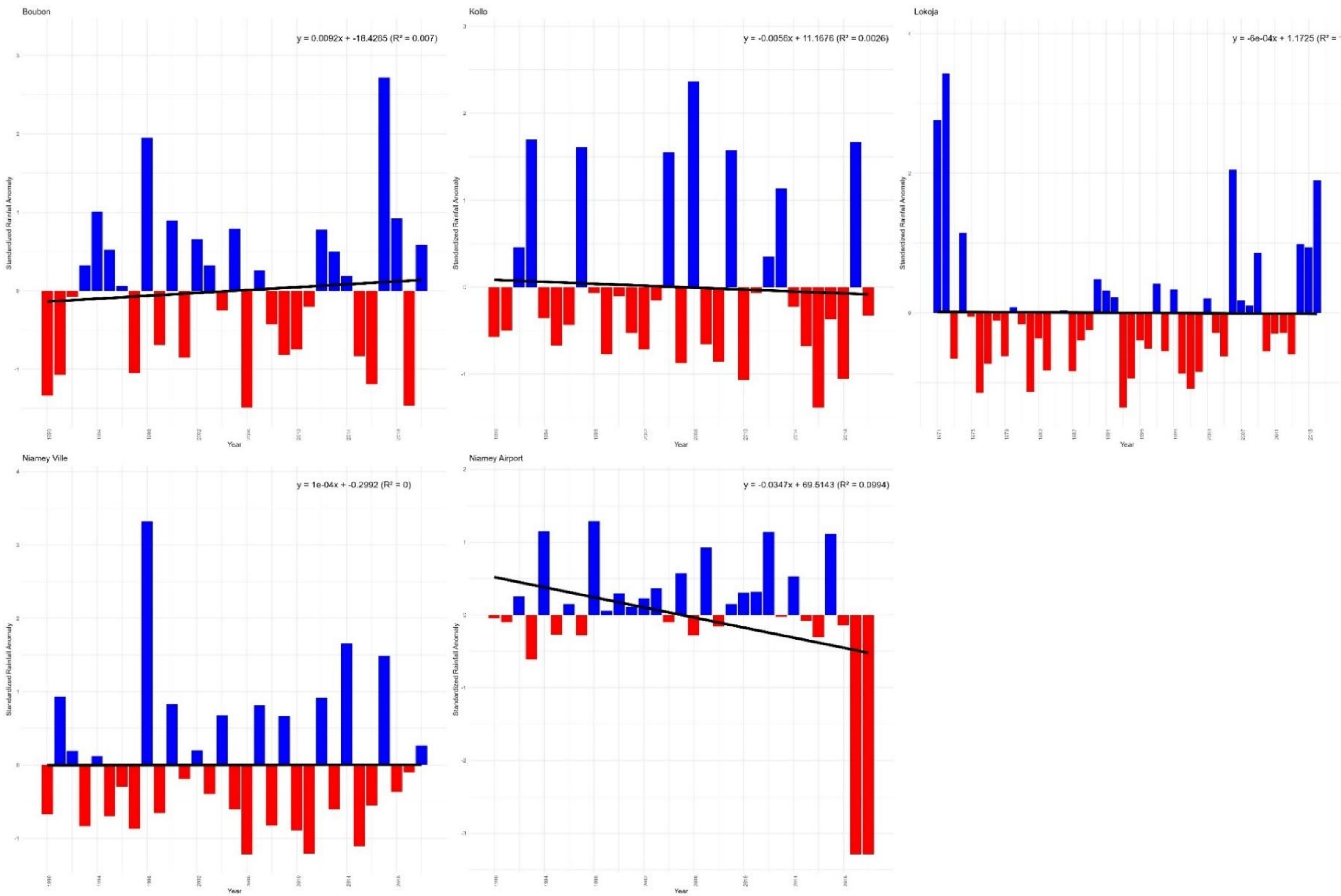

Figure 4.40:Standardised Precipitation Anomaly (SPA) for RX5DAY

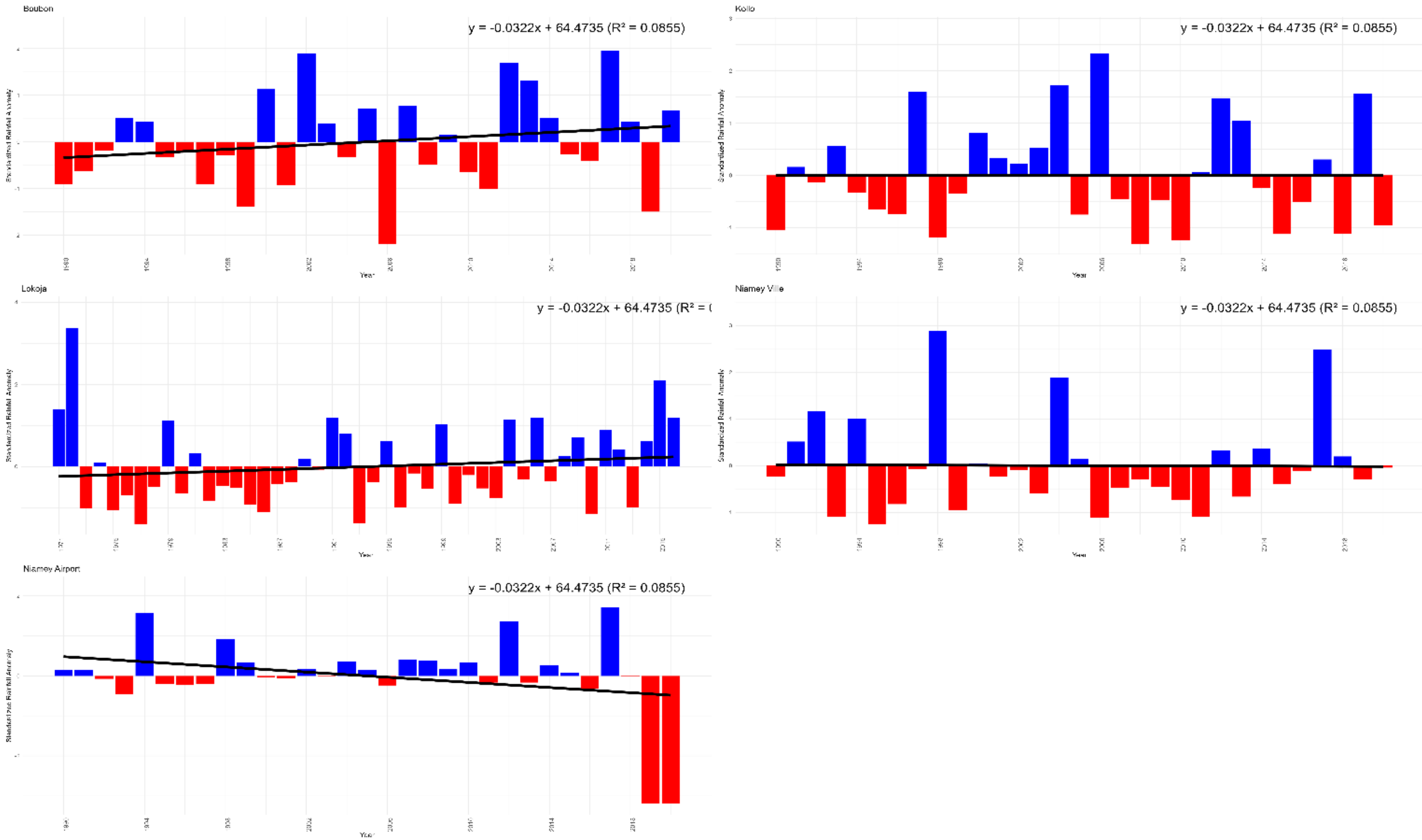

Figure 4.41: Standardised Precipitation Anomaly (SPA) for RX5DAY

4.1.8 Development of flood scenario under rainfall variability

The intensity and distribution of rainfall play a key role in the dynamics of flooding within a region, as they directly influence surface runoff, infiltration rates and the accumulation of water in low-lying areas. Understanding how different levels of rainfall influence vulnerability to flooding is essential to effectively assess and manage flood risk. High rainfall volumes can lead to rapid soil saturation, increased runoff and overflowing watercourses, increasing flood risk in vulnerable areas. Conversely, smaller amounts of rainfall can have a minimal impact, but their cumulative effects over time can still contribute to localised flooding. Identifying the spatial distribution of flood-prone areas according to rainfall intensity is essential for developing adaptation strategies, improving urban planning and enhancing disaster preparedness to mitigate the adverse effects of flooding.

The maps (Figure 4.42) illustrate the spatial distribution of the impact of Niamey rainfall according to the four different rain intensity classes. When rainfall exceeds 100 mm, water accumulation is very marked. The areas most affected are rivers and low-lying areas, indicating a high vulnerability to flooding. For rainfall of between 50 and 100 mm in the figure, the accumulation pattern remains similar but with a slight decrease in the intensity of accumulations. The effect of precipitation becomes more moderate when rainfall is between 20 and 50 mm, with a notable but less intense accumulation of water. Finally, when rainfall is less than 20 mm, water accumulation is very low and limited to certain specific areas. According to Table 4.2, the highest flood susceptibility category covers an area of 284.68 km², representing 51.11% of Niamey's territory. This area is characterised by water depths ranging from 0.2 to 18.62 m, indicating high exposure to flooding, particularly in the lowlands and areas adjacent to the River Niger. The 'high' class covers 243.69 km², or 43.75%, with similar depths of up to 18.06 m. This means that almost 95% of Niamey's territory is highly exposed to flooding, highlighting a marked vulnerability. Areas of moderate and low susceptibility cover 205.79 km² (36.95%) and 104.11 km² (19%) respectively, indicating that only a limited fraction of the city is at reduced risk.

Figure 4.43 illustrates the spatial distribution of the impact of rainfall in Lokoja according to four rainfall intensity classes. When rainfall exceeds 100 mm, water accumulation is very marked, with maximum values reaching 21.67. The areas most affected are rivers and low-lying areas, indicating a high vulnerability to flooding. For rainfall of between 50 and 100 mm, the accumulation pattern remains similar but with a slight reduction in the intensity of accumulations. The effect of precipitation becomes more moderate when rainfall is between 20 and 50 mm, with a notable but less intense accumulation of water. Finally, when rainfall is less than 20 mm, water accumulation is very low and limited to certain specific areas. In Lokoja, the trend is similar to Niamey, but the spatial scale is larger. The 'very high' class covers 1648.45 km², or 48.54% of the study area, with depths probably comparable to those in Niamey although they are not detailed here. The 'high' class represents 1493.62 km² (43.97%), which means that more than 92% of Lokoja's territory is exposed to major flooding. In contrast to Niamey, moderately exposed areas are more extensive at 1159.81 km² (34.15%), while low susceptibility areas cover 955.24 km² (28.12%).

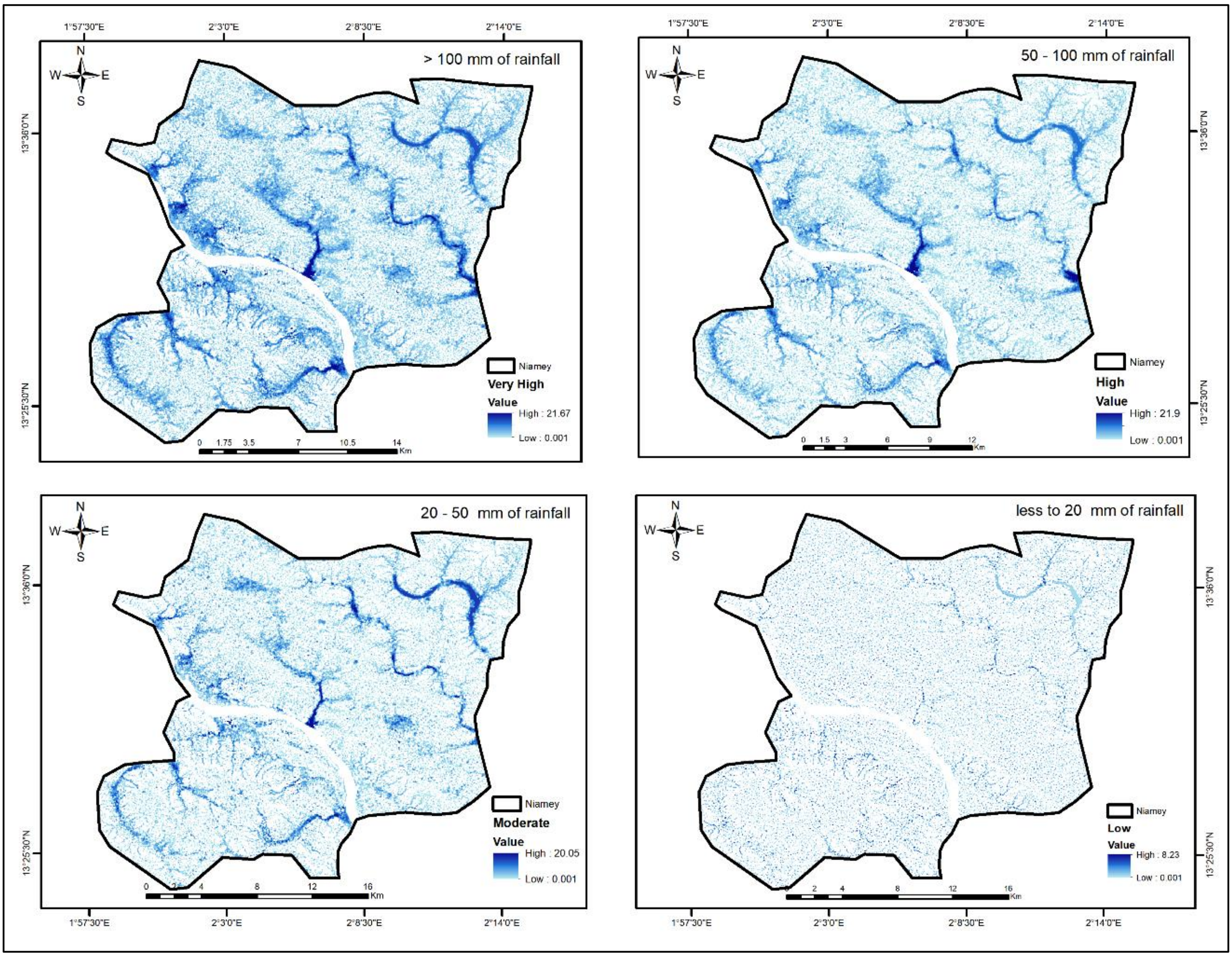

Figure 4.42 : Distribution of Rainfall-Runoff in Niamey as a function of Rainfall Intensity

The result results indicate that the risk of flooding is directly proportional to the intensity of rainfall. Heavy rainfall leads to rapid saturation of the soil and a rapid rise in river water levels, which increases flooding in vulnerable areas. The effect of rainfall is also influenced by topography and soil permeability, which explains the variation in water accumulation in different parts of the area analysed. An analysis of the maps shows a clear relationship between rainfall intensity and water accumulation. The areas located along rivers are the most affected and show a systematic accumulation, which indicates the importance of the hydrographic network in the dynamics of flooding. This concentration of flooding in certain areas is also influenced by the slope of the land and land use. Impermeabilized surfaces, such as urban areas, reduce water infiltration and increase surface run-off, thereby amplifying the risk of flooding. the result confirmed a direct correlation between the intensity of rainfall and the extent of flooding. Violent events (>100 mm) lead to rapid saturation of the soils and a sudden rise in water levels, exacerbated by the topography and low permeability due to urbanised areas. The geomorphological configuration thus explains the concentration of accumulations in catchment areas and alluvial plains. For example, artificial surfaces increase runoff by 40-60% compared with vegetated areas, exacerbating flooding.

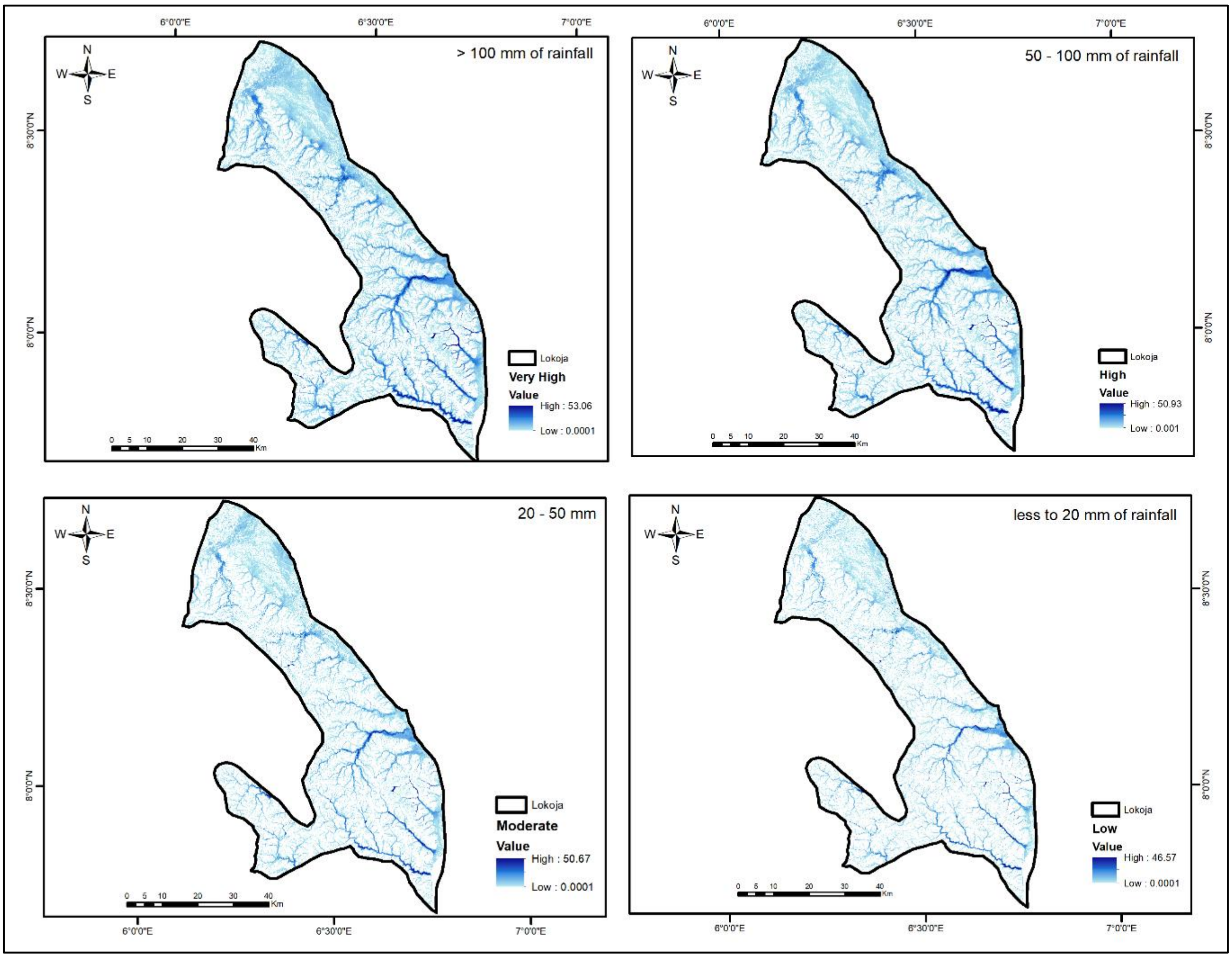

Figure 4.43: Distribution of Rainfall-Runoff in Lokoja as a function of Rainfall Intensity

The results demonstrate the major need for urban planning and flood risk management. Precise identification of the most vulnerable areas enables effective land-use planning decisions, particularly by limiting urban expansion in high-risk areas. For example, critical infrastructure should not be built in areas identified as most likely to be flooded during heavy rainfall.

These maps are also essential for developing flood adaptation strategies. Incorporating them into early warning systems would enable floods to be anticipated and targeted evacuation and protection plans to be implemented. The critical thresholds identified can be used to calibrate these systems, triggering specific measures when certain rainfall levels are reached. In addition, the development of stormwater management infrastructure, such as retention basins and improved drainage systems, could be prioritised in the most vulnerable areas to mitigate the impact of flooding.

From an environmental point of view, the importance of preserving and restoring natural areas capable of absorbing excess water, such as wetlands and forests, is emphasised. Sustainable management of these areas would play a key role in reducing run-off and improving rainwater infiltration. In the context of climate change, where the frequency and intensity of extreme precipitation events are likely to increase, these analyses provide a solid scientific basis for adapting public policies and strengthening the resilience of communities exposed to flooding. They can also be used to develop long-term strategies for dealing with the growing hydrological challenges in urban areas.

4.1.9 Development of flood risk management and adaptation strategies

(a) Evaluation of extant flood risk management in Lokoja

The assessment results of flood management strategies in Lokoja, Nigeria, presented in Table 4.24, reveal that affected households prioritise proactive and systemic measures. The three highest ranked strategies are (1) government preventive action before disasters (mean = 3.32), followed by the implementation of flood-appropriate health and education policies (mean = 3.32), and (3) funding post-flood renovations (mean = 3.30). These high scores, with low standard deviations (0.66 to 0.716), indicate a strong consensus on the need for anticipation and economic support to build resilience. Community measures, such as local action plans (mean = 3.21) and early warning systems (mean = 3.16), were also validated by respondents, although the latter show greater variability in responses (standard deviation up to 0.7763). In contrast, engineering solutions (watercourse modification, green infrastructure) and resilient infrastructure (adapted buildings, dykes) score significantly lower (means < 3.00), with marked disagreement on the ability of buildings to withstand flooding (mean = 2.34).

These results highlight two major expectations: anticipatory governance (avoiding crisis reactions) and sustainable investment in key sectors (health, education, and renovations). The low priority given to physical infrastructure suggests either a lack of awareness of its role or an urgent need to strengthen its implementation. Finally, the high standard deviation for some measures (resilient infrastructure, standard deviation = 1.0162) reflects divergent perceptions, underlining the importance of approaches tailored to local contexts.

Table 4.24: Existing flood risk management practices in Lokoja

Statement	**Average Agreement score**	**Priority Ranking**	**Agreement Level**	**Std. Deviation**
Government action in every disaster (Damage control)	3.32	1st	Agreed	0.66
Orchestre program on health education systems (Flood related)	3.32	1st	Agreed	0.641
Provision of financial resources for renovation (Damage control)	3.30	3rd	Agreed	0.716
Create a community-based disaster management action plan (emergency protocol)	3.21	4th	Agreed	0.738
Dissemination of information about incidence (early warning system)	3.16	5th	Agreed	0.7763
Engineer Practices a. modification of the existing river level and floodplain	3.02	6th	Agreed	0.8097
b. provision of green infrastructure	3.01	7th	Agreed	0.8804
C. Development of existing flood infrastructure	2.98	8th	Agreed	0.8338
D. Customize building design	2.99	9th	Agreed	0.868
Establishment of emergency call lines	2.99	9th	Agreed	0.8404
Have good solid waste disposal facilities & services	2.84	11th	Agreed	0.8907
We have self-stored relief materials	2.84	11th	Agreed	0.914
e. Design wetlands management	2.82	13th	Agreed	0.8835
We adapt our infrastructure that is flood-resistant	2.81	14th	Agreed	1.0162
f. construction of vegetation buffer	2.81	14th	Agreed	0.9544
Establishment of **an** emergency at the local and state level	2.80	16th	Agreed	0.912
We have an artificial river levee or embankment	2.77	17th	Agreed	0.8856
We have good infrastructure that **is** flood-resistant	2.70	18th	Agreed	0.8955
We have buildings that can withstand the impact of flood	2.34	19th	Agreed	0.5941

(b) Developed flood risk management and adaptation strategies

Strengths Weaknesses Opportunities Threats (SWOT) Analysis

The SWOT analysis (Table 4.25) was used to formulate adaptive strategies for flood risk management in Lokoja by cross-referencing the strengths, weaknesses, opportunities and threats identified. The key strategies include:

(i) SO (Strengths-Opportunities) strategies: Exploit proactive government policies (mean = 3.32) to link disaster plans, funding and technical resources. Community emergency plans (mean = 3.21) could be extended through partnerships with NGOs, while natural levees (mean = 3.02) could be improved with local involvement to control flooding.

(ii) WO Strategies (Weaknesses-Opportunities): Fill the gaps by integrating green infrastructure (green roofs, absorbent walls) to manage waste and reduce risks, or by creating partnerships to finance artificial wetlands.

(iii) ST (Strengths-Threats) strategies: In the face of unpredictable weather, combine local warning systems (average = 3.16) with modern meteorological tools. Temporary shelters (mean = 3.01) could be strengthened in response to mass displacements.

(iv) WT (Weaknesses-Threats) strategies: Mitigate economic losses by promoting resistant construction (mean = 2.34) and reinforcing artificial dykes (mean = 2.77) using low-cost methods and local labour. The results highlight the importance of combining technical expertise, proactive government policies and community participation. For example, the gap between the high scores for proactive policies (3.32) and the low scores for resilient infrastructures (2.34) reveals a critical need for awareness-raising and targeted investment. Priority strategies include modernising warning systems, adopting green infrastructure and building local capacity through public-private partnerships. This holistic approach aims to reduce household vulnerability while capitalising on existing resources for sustainable adaptation to flooding. This approach is in line with improving preparedness, reducing vulnerabilities, and ensuring long-term safety and well-being for rural households.

Table 4.25: Flood risk management analysis based on SWOT

SWOT Factors	Strengths (S)	Weaknesses (W)
Opportunities (O)	SO Strategies (Use Strengths to Exploit Opportunities)	WO Strategies (Overcome Weaknesses by Exploiting Opportunities)
Government can provide new health/education policies (Mean: 3.32)	Advocate for proactive policies linking disaster plans with financial and technical resources.	Integrate green infrastructure (such as rain gardens, green walls and green roofs) to manage waste and reduce risks.
Create more community-owned disaster emergency plans (Mean: 3.21)	Use community-based plans as models for wider adoption and funding by NGOs.	Develop partnerships to fund green roofs, walls, and wetlands mitigating flood impacts.
Innovatively modify existing natural river levee (Mean: 3.02)	Upgrade natural levees with community involvement for improved flood control.	Establish comprehensive waste management facilities to handle flood-related waste.
Threats (T)	ST Strategies (Use Strengths to Mitigate Threats)	WT Strategies (Minimise Weaknesses to Avoid Threats)
Rising unpredictability of flood patterns due to climate change.	Combine local early warning systems (Mean: 3.16) with advanced meteorological tools.	Initiate public-private partnerships to promote flood-resistant construction practices.
Increased flood magnitudes leading to shelter inadequacy.	Reinforce temporary shelter locations in and around our communities (Mean: 3.01) to accommodate increasing displacement needs.	Reinforce artificial levees (Mean: 2.77) using cost-effective methods and local labour.
Structural damages causing economic and livelihood losses.	Enhance disaster response by integrating community knowledge with technical expertise.	Promote buildings that can withstand impact of flood (Mean: 2.34).

(c) Evaluation of extant flood risk management in Niamey

The results presented in Table 4.26 indicate the perceived flood risk management strategies by affected rural households in Niamey. Respondents agreed to 68.42% of the listed strategies, reflecting a considerable awareness and acceptance of measures aimed at mitigating flood impacts. Among these strategies, the highest-ranked included the belief that, based on their experience with past flood disasters, households adapt their infrastructure to withstand future flooding (mean = 2.03). This suggests that households take proactive measures to modify or reinforce their structures to mitigate flood risks effectively. The second highest-ranked strategy was the presence of a dike or artificial embankment (mean = 2.02). This indicates the importance of structural solutions in managing flood risks, as dikes and embankments serve as physical barriers to prevent water overflow into residential areas. Such measures are particularly crucial in regions prone to recurrent flooding, offering communities a tangible means of protection. The third significant strategy was the availability of wetlands and floodplains (mean = 2.01), which highlights the role of natural landscapes in flood risk management. Wetlands and floodplains act as natural buffers, absorbing excess water during heavy rains and reducing the severity of floods. Their importance underscores the need for ecological conservation alongside infrastructure development.

Despite this awareness, there remains a significant gap in effectively translating knowledge into action. Many individuals do not actively listen to flood-related information, and those who do often fail to take it seriously as reported during the interview. This shows the urgent need for comprehensive public awareness campaigns to emphasise the risks and promote proactive engagement in flood preparedness. Moreover, the State must prioritise preparedness by annually allocating resources for isolation housing to protect vulnerable populations during floods. This proactive measure could significantly reduce the risk of human loss, which is the most critical and costly consequence of flooding. Effective coordination between communities and the government is essential to improve flood resilience and ensure the safety and well-being of rural households in Niamey.

Table 4.26: Existing flood risk management practices in Niamey

Statement	Average Agreement score	Priority Ranking	Agreement Level	Std. Deviation
Government action in every disaster (Damage control)	2.03	Agree	1st	0.236
Orchestre program on health education systems (Flood related)	2.02	Agreed	2nd	0.17
Provision of financial resources for renovation (Damage control)	2.01	Agreed	3rd	0.148
Create a community-based disaster management action plan (emergency protocol)	2.01	Agreed	3rd	0.142
Dissemination of information about incidence (early warning system)	2.01	Agreed	3rd	0.148
Engineer Practices a. modification existing river level and floodplain	2.01	Agreed	3rd	0.121
b. provision of green infrastructure	2.01	Agreed	3rd	0.142
C. Development of flood existing infrastructure	2.01	Agreed	3rd	0.154
D. Customise building design	2.00	Agreed	9th	0.121
Establishment of emergency call lines	2.00	Agreed	9th	0.128
Have good solid waste disposal facilities & services	2.00	Agreed	9th	0.135
We have self-stored relief materials	2.00	Agreed	9th	0.135
e. Design wetlands management	2.00	Agreed	9th	0.128
We adapt our infrastructure that is flood resistant	1.99	Not agreed	14	0.096
f. construction of vegetation buffer	1.99	Not agreed	14	0.135
Establishment of emergency at the local and state level	1.99	Not agreed	14	0.135
We have an artificial river levee or embankment	1.99	Not agreed	14	0.154
We have good infrastructure that is resistant	1.99	Not agreed	14	0.154
We have buildings that can withstand impact of flood	1.99	Not agreed	14	0.165

(d) Developed flood risk management or adaptation strategies in Niamey

(i) Strengths Weaknesses Opportunities Threats (SWOT) Analysis

The result in Table 4.27 was analysed using a SWOT matrix to develop appropriate flood risk management and adaptation strategies for Niamey. This approach identifies strengths, weaknesses, opportunities, and threats, providing actionable insights for managing flood risks effectively.

i. Strength-Opportunity (SO) Strategies: These strategies leverage strengths to exploit available opportunities. For instance, the provision of financial resources for renovation purposes (mean: 2.01) can support the upgrading of community-owned disaster contingency plans and the construction of flood-resistant infrastructure. Greener infrastructure, such as rain gardens, green walls, and roofs (mean: 2.01), can be utilised not only for flood control but also for conserving natural vegetation and wetlands (mean: 2.00). Additionally, community-owned disaster contingency plans (mean: 2.01) can be enhanced by incorporating local flood early warning systems (mean: 1.99), ensuring better preparedness for disaster response.

ii. Weakness-Opportunity (WO) Strategies: These strategies aim to overcome identified weaknesses by utilising opportunities. For example, funds can be allocated to train communities in using emergency equipment and disaster kits (mean: 1.99), enhancing their disaster preparedness. Local participation in creating and managing green infrastructure can mitigate resource and expertise gaps. Improving local knowledge through education policies on emergency responses can ensure that communities are better prepared to handle flood-related challenges effectively.

iii. Strength-Threat (ST) Strategies: These strategies use strengths to address identified threats. Adapting flood-prone infrastructure to withstand flooding (mean: 2.03) is critical, coupled with campaigns to raise awareness about the risks posed by floods. Temporary shelters, prepared annually, should be strengthened (mean: 2.00) and integrated into community disaster plans with financial support. Utilising existing financial resources and technical expertise can mitigate the impact of rising flood magnitudes and displacement.

iv. Weakness-Threat (WT) Strategies: These strategies focus on minimising weaknesses to avoid threats. Innovative modifications to natural river dikes (mean: 1.99) can enhance flood control while addressing climate adaptation. Lack of proactive government actions (mean: 1.99) should be countered by advocating for timely disaster response measures. Investing in robust disaster kits, flood-resistant materials, and early warning mechanisms is crucial. Strengthening disaster education and resilient construction practices will further minimise the risks associated with structural damage and economic losses.

Table 4.27: Developing flood risk management using SWOT Matrix

SWOT Factors	Strengths (S)	Weaknesses (W)
Opportunities (O)	SO Strategies (Use Strengths to Exploit Opportunities)	WO Strategies (Overcome Weaknesses by Exploiting Opportunities)
Provision of financial resources for renovation purposes (Mean: 2.01).	Leverage financial resources to upgrade community-owned disaster contingency plans and build flood-resistant infrastructure.	Allocate funds for training communities to enhance the use of emergency equipment and disaster kits (Mean: 1.99).
Development of greener infrastructure such as rain gardens, green walls, and roofs (Mean: 2.01).	Use greener infrastructure for flood control while conserving natural vegetation and wetlands (Mean: 2.00).	Encourage local participation in creating and managing green infrastructure.
Creation of community-owned disaster contingency plans (Mean: 2.01).	Enhance contingency plans by incorporating local flood early warning systems (Mean: 1.99).	Improve local knowledge and provide education policies for emergency responses.
Threats (T)	ST Strategies (Use Strengths to Mitigate Threats)	WT Strategies (Minimise Weaknesses to Avoid Threats)
Increasing flood risks due to changing climate and not serious with flood information	Adopting flood-prone infrastructure to withstand flooding (Mean: 2.03) and each individual must be made aware of the situation.	Developing innovative modifications to natural river dikes (Mean: 1.99) for climate adaptation.
Structural damages, loss of live and inadequate disaster responses.	Strengthen temporary shelters (prepared each year to provide isolation housing) (Mean: 2.00) and integrate financial support into community disaster planning.	Improve access to flood-resistant materials and educate communities on resilient construction practices.
Lack of proactive government actions (Mean: 1.99).	Advocate for proactive governmental measures to ensure timely actions against disasters.	Invest in robust disaster kits and early warning mechanisms.

(e) Developed adaptation strategies using MCDA

The multi-criteria analysis (MCA) method, combined with the AHP method, was used to identify the priorities for flood adaptation based on the relative importance of each criterion. each criterion was assigned a weighting. based on the results (table 4.28), the involvement: Early Warning System: 19.49; Emergency Management: 14.6; Community Action Plan: 10.21; Flood Resistant Infrastructure: 35.46; Customised Building Design: 7.17; Existing Flood Infrastructure: 5.05; Green Infrastructure: 3.97; Wetlands Management: 2.38; Vegetation Buffer: 1.60.

Table 4.28 : Pairwise comparison matrix

Factors	EWS	EM	CAP	FRI	CBD	EFI	GI	WM	VB	Weight
Early Warning System (EWS)	1	2	3	0.2	4	5	6	7	8	0.19
Emergency Management (EM)	0.5	1	2	0.25	3	4	5	6	7	0.15
Community Action Plan (CAP)	0.33	0.5	1	0.2	2	3	4	5	6	0.1
Flood Resistant Infrastructure (FRI)	5	4	5	1	5	7	7	8	9	0.35
Customised Building Design (CBD)	0.25	0.33	0.5	0.2	1	2	3	4	5	0.07
Existing Flood Infrastructure (EFI)	0.2	0.25	0.33	0.14	0.5	1	3	3	4	0.05
Green Infrastructure (GI)	0.17	0.2	0.25	0.14	0.33	1	1	3	4	0.04
Wetlands Management (WM)	0.14	0.17	0.2	0.13	0.25	0.33	0.33	1	3	0.02
Vegetation Buffer (VB)	0.13	0.14	0.17	0.11	0.2	0.25	0.25	0.33	1	0.02

The weights obtained show the relative importance of each criterion in adapting to flooding. The results show a high priority for flood-resilient infrastructure, followed by early warning systems and emergency management. This suggests that adaptation strategies need to focus on robust and immediately effective solutions to reduce the impact of flooding in the areas studied.

Flood-resistant infrastructure is the main priority (35.46%), which means that adaptation strategies must prioritise protective structures, such as reinforcing dykes, efficient drainage channels, and infrastructure designed to withstand flooding. These measures help reduce the physical vulnerability of exposed areas and ensure greater resilience in the face of recurrent flooding. However, building infrastructure alone is not enough to protect people effectively if it is not accompanied by good governance and community involvement.

The early warning system has a weighting of 19.49%, with the second factor playing a key role in flood prevention and management. The development of this factor enables risks to be detected quickly and information to be disseminated to populations at risk. To be more effective, this system must include advanced hydrological monitoring tools and rapid means of communication such as SMS alerts and radio and TV broadcasts. However, putting these technologies in place is not enough if communities do not know how to react in the event of an alert. It is therefore necessary to organise awareness campaigns and simulations to familiarise residents with evacuation protocols and safety measures. Even with effective infrastructures and alerts, floods can still occur. A good emergency management system (14.68%) ensures that the emergency services are well prepared to respond quickly and effectively. This involves training emergency response teams, setting up temporary accommodation centres and rapidly distributing relief supplies to victims. Coordination between local authorities, NGOs and international agencies is essential to avoid chaos and ensure an effective response to disasters. In addition, setting up well-equipped emergency accommodation centres would guarantee a dignified and safe reception for disaster victims, thereby reducing the humanitarian impact of the floods.

The Community Action Plan (CAP), which accounts for 10.21%, plays a central role in making people more resilient in the face of flooding. It is a participatory approach in which local communities are directly involved in the planning and implementation of adaptation strategies. The importance of this criterion shows that the commitment of local residents is essential to ensure the success of prevention and adaptation measures. A well-designed CAP includes training (raising people's awareness) of the risks of flooding, organising self-help networks and setting up community monitoring groups capable of alerting the authorities in the event of danger. Involving local residents in risk management strengthens their ability to react quickly and make decisions that are adapted to their local situation. However, adaptation strategies should not be limited to physical infrastructure and emergency measures.

Criteria relating to natural solutions, such as wetland management (2.38%) and vegetation barriers (1.60%), were given lower weights, although their role in flood resilience remains crucial. These measures play a complementary role by slowing run-off and absorbing excess water. Protecting and restoring natural ecosystems can reduce flood intensity in the long term and provide additional environmental benefits, such as improving water quality and preserving biodiversity, while planting vegetation on riverbanks and floodplains can enhance soil stability and limit erosion, thereby helping to reduce flood intensity.

Integrating these different elements into an effective adaptation strategy requires a balanced approach. Investments must be prioritised based on their impact, but it is crucial to adopt a global vision that combines solid infrastructure, effective warning systems, well-organised emergency management and the active involvement of local communities. The success of adaptation strategies depends not only on decisions taken by governments and institutions, but also on the active participation of citizens, who are the first to be affected by these risks. It is essential to combine technical interventions, such as building dams and improving urban drainage, with adaptation strategies based on awareness-raising, participatory governance and environmental protection. What's more, the effectiveness of these strategies needs to be regularly assessed through field studies and adjustments based on feedback. The consistency of the results obtained using the consistency indices (CI) and the consistency ratio (CR) indicates that the judgements are reliable and that the weightings reflect a logical assessment of the priorities.

4.2 Discussion of results

4.2.1 Trend

Niamey is an area characterised by rainfall that generally begins in May, and peaks in the summer, June and July, in some cases reaching September (Leblanc *et al*., 2008) Lebel, 2020). In Lokoja, the rainy season generally begins a little earlier than in Niamey towards the end of April or the beginning of May and continues until October. The results of this study, which demonstrate a marked spatio-temporal variability in rainfall, resonate with previous work on West African climatology. For example, Lebel (2020) points out that the seasonal migration of the Intertropical Convergence Zone (ITCZ) explains the differences in seasonality between Niamey and Lokoja, an observation that is consistent with the earlier onset of rainfall in Lokoja, which is influenced by humid flows from the Gulf of Guinea.

The intermediate coefficients of variation (CV) (18.55% to 27.82%) reflect the 'transitional' nature of the Sahelian climate, as described by Lebel *et al.* (2003), where rainfall oscillates between persistent aridity and extreme wet episodes. The strong positive skewness of the data (skewness > 2 at Niamey Ville and Lokoja) corroborates the conclusions of G. Panthou *et al* (2014), who attribute the recent intensification of rainfall extremes in West Africa to global warming, amplifying convective phenomena. Furthermore, the downward trend in rainfall in Niamey Ville (-3.07%) contrasts with the increase observed in Say or Lokoja (+3.50% to +3.93%), a dichotomy reminiscent of the work of Herrmann *et al*., (2005) on the uneven re-vegetation of the Sahel after the droughts of the 1980s, linked to divergent local responses to global climate forcing. Finally, the extreme anomalies (e.g. +3.98 at Lokoja in 2016) are part of the decadal oscillations described by Nicholson (2017), where occasional wet phases coexist with structural aridification, highlighting the complexity of regional climate dynamics. These observations call for greater integration of local data into climate models, as advocated by Adeoye, (2012) to refine adaptation strategies in the face of variability that is set to increase.

Analysing annual and seasonal trends in precipitation involves using statistical tools such as the Mann-Kendall test and Sen's slope estimator. These methods help to determine whether there is a significant trend in rainfall data over time. For example, in some areas such as Niamey Ville, Say and Lokoja, the Mann-Kendall test revealed significant upward trends in annual rainfall, indicating an increase over time. On the other hand, at other stations such as Kollo, a downward trend was observed. Sen's slope estimator quantifies the extent of these trends, showing, for example, an increase in annual rainfall at Say and Lokoja, with values of 6.05 mm and 6.8 mm respectively, while Kollo recorded a decrease of -2.86 mm.

Seasonal trends also vary considerably. During the rainy season, stations such as Say and Lokoja showed significant upward trends, indicating an increase in rainfall. In contrast, during the dry season, some stations showed decreasing trends. Sen's slope estimator helps to understand the magnitude of these trends, showing for example a positive slope of 6 mm during the rainy season at Say. These results underline the importance of understanding local and regional rainfall trends for managing water resources and adapting to climate change. Studies in different regions show varied results, with increases or decreases depending on location and season, highlighting the need for localised analyses to inform climate adaptation strategies.

Similar cases of rainfall trends can be observed in various regions of the world. For instance, in Kerala, India, studies have shown generally positive trends in annual and monsoon rainfall, but decreases in certain seasons such as summer (Sudarsan and Lasitha, 2023). In the Kilombero Basin (Tanzania) most stations showed a downward trend in rainfall, although some areas, such as the Ulanga weather station, saw significant increases (Chanzi *et al.*, 2024). Similarly, at Ikole Ekiti, Nigeria, the region showed a two-peak rainfall pattern with a decrease in annual rainfall, although not statistically significant (Chanzi *et al*., 2024). These examples illustrate the variability of rainfall trends between regions and underline the importance of localised analyses in understanding and adapting climate strategies.

4.2.2 Patterns of land use and land cover in the two cities

Between 1991 and 2021, Niamey and Lokoja experienced profound land use and cover transformations, driven by urbanisation, demographic pressures, and environmental shifts. The results of this study of land use and land cover change (LULC) in Niamey and Lokoja over the period 1991-2021 reveal complex spatial and temporal dynamics, marked by rapid urbanisation, ecosystem degradation and significant hydrological changes. These trends are consistent with observations made in other African cities facing similar demographic and environmental pressures.

In Niamey, the expansion of built-up areas (+312.88 %) is one of the fastest in Africa, driven by exceptional population growth (101 % rate, Statista) and mass rural-urban migration. This urban growth (Figure 4.11), concentrated along the Niger River, involves rapid conversion of agricultural land and natural zones into informal settlements (Salamatou *et al.*, 2015; Nasser and Adam, 2024). These informal areas, often lacking drainage systems, worsen flood risks during heavy rains. In contrast, Lokoja shows more moderate urban growth (+21 %), despite its strategic location at the Niger-Benue confluence. This difference is due to less strict land-use policies and a less dynamic local economy. The absence of strict urban planning in Lokoja allows unregulated construction in flood-prone zones, as shown in the habitat evolution map (Figure 4.15).

Rapid urban expansion dominated the landscape in Niamey, with built-up areas increasing (from 5,023.6 ha to 20,741.5 ha). This growth occurred in two distinct phases: 47.06 % from 1991 to 2006 and 54.25 % from 2006 to 2021, reflecting escalating housing demands linked to population growth. Concurrently, critical ecological zones suffered steep declines. Green belts, essential for hydrological regulation, decreased by 45.60 %, while riparian formations, stabilise riverbanks and mitigate floods, contracted by 58.55 %. Rainfed agricultural land, once a dominant feature of the region, diminished by 40.18 %, replaced by irrigated crops (+18 %) and urban infrastructure. Hydrological shifts were also notable: water ponds expanded by 14.66 %, likely due to groundwater fluctuations or ephemeral flooding, while the Niger River's area shrank by 16.87 %, signalling reduced floodplain capacity. By 2021, urban zones covered 39 % of Niamey, displacing rainfed agriculture (24 %) and natural vegetation. Bare ground, a marker of soil exposure and impermeability, surged by 175.39 %, exacerbating runoff risks during a rainfall event.

Lokoja experienced significant urban expansion, with built-up areas increasing by 21% (5767.1 ha to 1208.9 ha) between 1991 and 2021. Unlike Niamey, where rapid urbanisation dominated, Lokoja's expansion encroached on floodplains due to weak land-use policies, heightening flood risks. Concurrently, ecosystem degradation occurred: dense forests declined by 0.3. The loss of green belts (- 45.60 %) and riparian zones (- 58.55 %) is directly linked to unplanned urban sprawl. These ecosystems, once vital for flood regulation, are replaced by impermeable surfaces, increasing flood risks (Ribot *et al*., 1999). For instance, the reduction of riparian zones along the Niger River limits their ability to absorb floods, leading to overflow in peripheral neighbourhoods. At Lokoja, the reduction in dense forest (- 0.3 %) reflect the modification of the landscape, associated with unsustainable agricultural practices and logging (Gaëlle *et al*,.2021) . The conversion of forests into temporary fields weakens the soil, accelerating erosion and the sedimentation of watercourses.

4.2.3 Flood risk zoning

The integration of geographic information systems (GIS), combined with the Analytical Hierarchy analysis method (AHP), has been successfully used to delineate flood susceptibility and risk zones in a region like West Africa that is highly affected by flooding. Flood susceptibility and risk mapping is a technique commonly used in research into flood control and the implementation of flood prevention plans. In this study, the key parameters for flood susceptibility mapping were altitude, slope, topographic moisture index (TWI), drainage density and distance from rivers. Concerning vulnerability, the determining factors were land use and land cover (LULC). The assessment of vulnerability to flooding takes land use into account, as it allows areas of high exposure to be identified. Urbanised areas increase surface run-off, while natural areas, particularly those covered in vegetation, favour water infiltration. This provides a useful tool for assessing the potential impact on people, critical infrastructure and ecosystems. This study integrates both geomorphological and hydrological characteristics to determine flood magnitudes, as well as demographic and infrastructural factors to assess vulnerability.

Geographic Information Systems (GIS)-based integration, combined with the Analytic Hierarchy Process (AHP) method, was successfully employed to delineate flood susceptibility zones and flood risk zones in the study area. a region heavily affected by flooding in west Africa. As such, flood susceptibility and risk mapping is a commonly used technique in flood control research and the implementation of flood prevention plans. These parameters can be assessed and mapped with acceptable accuracy using the method employed in this study.

The indices most affected for mapping flood susceptibility in this study were altitude, slope, topographic moisture index (TWI), drainage density and distance from watercourses. As for vulnerability, the determining factors considered were land use and land cover (LULC). Land cover is used in the assessment of vulnerability to flooding because of its importance in identifying areas of high exposure based on land use. Urbanised areas are conducive to increased run-off, while natural areas, particularly those covered in vegetation, favour water infiltration. It helps to assess the impact on populations, critical infrastructures and ecosystems.

This study integrates geomorphological and hydrological characteristics to determine flood intensity, as well as demographic and infrastructure factors to assess vulnerability.

Mokhtari *et al*, (2023) identified similar parameters in their study of flood risk areas, notably altitude, slope, distance from the drainage network, rainfall, TWI, lithology, NDVI, and NDWI as determinants of susceptibility to flooding. In their study, more than 60% of the weights were attributed to three main parameters: altitude, slope, drainage density and distance from the river.

Further studies (Papaioannou *et al*., 2015; Choudhury *et al*., 2022; Afzal *et al*., 2022; Belazreg *et al.*, 2024) have also analysed flood susceptibility and vulnerability using various indices and models, such as the HEC-RAS. The GIS-based approaches and multi-criteria decision method (MCDA) have recently played a crucial role in identifying behaviours. It is essential to point out that MCDA rankings are often uncertain, due to raw data, data analysis, criteria selection or thresholds used. The scores or weights of the criteria are generally the source of most debate and uncertainty, as decision-makers are not always fully aware of the nature and extent of the criteria and they are poorly understood. A major limitation of the AHP method is how weights are assigned to the various criteria. This can influence the accuracy of the results (Chen *et al*., 2010; Mitra *et al*., 2022) .

The Altitude and the slope dominate the risk patterns, with high weights in the AHP (29 and 24% respectively), in line with the work of Tehrany *et al*., (2014) who identifies these parameters as critical for water accumulation. In Niamey, altimetric uniformity (180-300 m) explains a predominance of moderate risk (34.29%), while in Lokoja, altitudinal variability (19-544 m) amplifies very high-risk areas (28.19%). These observations are in line with studies by Mitra *et al*., (2022), who emphasise that lowlands adjacent to rivers (such as the Niger in this case) are systematically more exposed. Steep slopes (>80% of surfaces in both towns) exacerbate runoff, necessitating soil stabilisation strategies in similar contexts. The TWI index, although less weighted (16%), confirms the vulnerability of flat and wet areas, in line with the findings of Taylor *et al.*, (2011) linking water retention to topographical features. Drainage density, although variable, highlights a reduced capacity for surface water drainage in Niamey, with a predominance of low-density areas (38.7%), requiring improvements to drainage networks. Precipitation, although weighted at only 4%, acts as a trigger for flooding, particularly during the rainy seasons. This result is in line with the work of Baldassarre *et al*.,(2010), which highlights the interaction between rainfall intensity and urban drainage capacity. The dominant clay soils in Lokoja (reduced permeability) and sandy soils in Niamey (natural drainage) have a different influence on water saturation, a phenomenon described by Mitra *et al*. (2022) as key in the genesis of urban flooding. The results of the present study confirm these observations, indicating that the predominance of clay soils in Lokoja contributes to faster runoff and increased flood risk.

The negative NDVI in Niamey indicates limited vegetation cover, increasing vulnerability to flash flooding. This finding is consistent with the conclusions of Mitra *et* *al* (2022), who associate low vegetation cover with reduced infiltration and increased erosion. At Lokoja, a slightly positive NDVI (0.5) suggests a moderating role for vegetation, corroborating nature-based solutions for risk mitigation. The results of this study also highlight the need to invest in nature-based solutions, such as reforestation, to reduce risk in Niamey. The final zonation classifies 32 % of Niamey and 17 % of Lokoja as high to very high risk, concentrated along the Niger. The AHP, with a consistency ratio of 0.06 (<0.10), validates the methodological robustness, as demonstrated by Danumah *et al.*, (2016) ; Belazreg *et al.*, (2024) in various contextes. The consistency of the results with these studies reinforces the reliability of the conclusions of the present analysis.

The flood risk zoning maps for Niamey and Lokoja, derived from combining susceptibility and vulnerability maps, provide a clear spatial framework for flood management. In Niamey, 10% very low, 26% low, and 31% moderate risk zones, and in Lokoja, 23% very low, 33% low, and 28% moderate risk zones, allow for prioritised resource allocation. The AHP model highlights elevation (29%) and slope (24%) as key factors, guiding targeted interventions like retention basins and runoff control. Lokoja's 95% low vulnerability reflects structural resilience, a strong foundation for mitigation. Low NDWI (4%) and NDVI (2%) weightings suggest minimal reliance on vegetation-based solutions, focusing efforts on infrastructure. Recommendations for reforestation, drainage improvements, and awareness campaigns offer sustainable paths forward. Niamey faces significant challenges with 25% high and 7% very high flood risk zones, concentrated along river corridors, worsened by 43% moderate to high vulnerability due to dense populations and poor infrastructure. High drainage density (39% very low-density areas) hinders water evacuation. In Lokoja, 12% high and 3% very high-risk zones, driven by low elevations (10.7%) and steep slopes (51.47%), increase runoff risks. High TWI values (up to 23) indicate waterlogging risks in both cities. Socio-economic factors, particularly Niamey's 61% land use and 27% population density weightings, highlight vulnerabilities in densely populated areas. Low NDVI (46.28% moderate in Lokoja) suggests exposed soils, requiring costly reforestation. These issues demand urgent, resource-intensive infrastructure solutions.

The evaluation of flood risk management in Lokoja reveals a strong preference among households for proactive government measures. They prefer immediate action to reactive responses. Respondents ranked rapid government intervention, new health and education policies, and financial support for renovations as the most important measures. These results underline that effective flood management in Lokoja relies on planning, resource allocation and the implementation of sustainable policy reforms.

On the other hand, the SWOT analysis for Lokoja reinforces this view. It shows that harnessing government strengths and community plans can address both current vulnerabilities and future threats. The analysis recommends improving natural river embankments and setting up early warning systems. These measures could improve disaster preparedness and reduce the impact of flooding.

In Niamey, households focusing on adapting their infrastructure to better withstand flooding. They are in favour of building dykes and using natural features such as wetlands to combat flooding. Despite this awareness, many of the people interviewed are not translating their knowledge into action. This gap highlights the need for strong public awareness campaigns and more proactive involvement of public authorities.

The Niamey SWOT matrix confirmed these findings. that a combination of financial resources, green infrastructure and better emergency planning can improve community resilience. Therefore, it is essential to focus on proactive government action and training in emergency response. This approach could help mitigate the economic and human losses caused by structural damage. In like manner, the result from the multi-criteria analysis brought to the fore these strategies. Generally, flood resistance appeared to be the first priority, and the one that carries the greatest weight in adaptation efforts. Early warning systems and emergency management follow closely behind. The analysis indicates that robust physical structures, combined with effective communication and community participation, are essential to reducing the impact of flooding.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The effect of climate change has increased the frequency and magnitude of extreme event This study has provided a comprehensive evaluation and modelling of climate change effects on River Niger flood dynamics and adaptation strategies in Lokoja, Nigeria, and Niamey, Niger. The findings underscore the interplay between rapid urbanisation, land-use changes, and extreme rainfall events, collectively contributing to increasing flood vulnerability.

The study revealed a dramatic expansion in human settlements, indicating that rapid urbanisation is a key driver of heightened flood risk. Additionally, land cover changes, including the expansion of water bodies and bare lands, have altered the hydrological balance of the region. Extreme rainfall indices further confirm an increasing trend of heavy precipitation, which, combined with inadequate flood control infrastructure, places both cities at significant flood risk. The flood risk zoning analysis shows that high-risk areas are concentrated in low-lying regions, particularly along riverbanks, where flood occurrences have been increasingly severe.

The study also highlights the inadequacy of current flood risk management strategies, as revealed by low infrastructure resilience and the high-risk concentration in vulnerable areas. While some flood prevention measures are in place, their effectiveness is limited due to insufficient integration between structural and non-structural adaptation strategies. The study underscores the need for comprehensive flood risk management that integrates early warning systems, urban planning reforms, and ecosystem-based adaptation measures. The flood risk for Niamey and Lokoja respectively can be classified as:

moderate (32%) and moderate (15%) in the overall with low-risk zones in the North and very high-risk pocket areas in the south

Given the increasing frequency and severity of floods in the study areas, this research concludes that climate change adaptation strategies must be urgently strengthened to mitigate the socio-economic and environmental impacts of flooding. Effective flood risk management requires a multi-sectoral and multi-scale approach that accounts for climate variability, demographic trends, and infrastructural resilience. These findings provide a strong foundation for guiding future research and policymaking in climate adaptation and flood resilience within West African urban centres.

5.2 Recommendations

In view of the conclusion drawn, the following general and specific recommendations are proffered

5.2.1 Recommendations on policy improvement

The findings of this research have demonstrated significant implications for current policy processes, particularly concerning the development of comprehensive and coordinated strategies to strengthen regional resilience and local flood adaptation plans. By producing up-to-date flood risk maps, damage assessments and climate projections, this research has directly influenced national and regional strategies aligned with global frameworks such as the Sustainable Development Goals (SDGs). For example, it has provided usable data to achieve SDG 11 (Sustainable Cities and Communities) by identifying flood-prone areas and guiding resilient urban expansion. Similarly, it has contributed to SDG 13 (Climate Action) by modelling future flood scenarios under the impact of climate change, enabling governments to prioritise adaptation measures.

Integrated flood risk management must become the cornerstone of public policy, based on strengthened cross-border collaboration under the aegis of the Niger Basin Authority and national hydrological agencies. This involves setting up joint committees to pool the efforts of the riparian countries and sharing hydrological data in real time using tools such as shared geographic information systems, enabling collective anticipation of crises. The establishment of joint committees would also facilitate this coordination, while the real-time sharing of hydrological data via shared geographic information systems would make it possible to anticipate crises collectively,

To support this management, it is essential to improve infrastructure and urban planning by introducing strict land-use rules, limiting construction in flood-prone areas without appropriate protection. This will maintain a buffer zone and prevent encroachment on dangerous flood-prone areas. It will also enable the promotion of sustainable construction, such as ecological drainage systems based on vegetated trenches, buildings on stilts or modular flood walls designed to withstand submergence. At the same time, early warning systems equipped with suitable devices installed along the river and mobile applications to broadcast automated SMS alerts to vulnerable populations. Such a tool, which would make it possible to anticipate floods on a basin-wide scale and coordinate emergency responses, while facilitating targeted investment in the critical areas identified by your analyses, must be combined with regular disaster preparedness exercises, such as annual evacuation simulations, to ensure a rapid and organised response from communities.

The results of this study are important for programme design and national sustainable development, aiming to integrate resilient urban planning standards in line with SDG 11 for sustainable cities, contributing to the achievement of SDG 13 (climate action), serving as a strategic tool for key actors such as NEMA and SAP (early warning system), AGRHYMET and NISHA, strengthening early warning systems in West Africa. It has also enabled cities such as Niamey and Lokoja to design context-specific interventions while facilitating cross-border investments. These advances position the region as a key player in global debates on climate adaptation, while providing a replicable framework for other vulnerable river basins, such as the Senegal River and Lake Chad. Adaptation to climate change must guide all these efforts, incorporating accurate climate forecasts into long-term planning and restoring natural ecosystems, such as wetlands and riparian forests, which act like natural sponges to absorb excess water and reduce erosion.

5.2.2 Recommendations on performance improvement

The development of a socio-ecological risk index in the study is expected to improve the performance of authorities to prioritise interventions in high-risk areas, optimising the allocation of resources for infrastructure projects such as drainage systems or flood barriers. Urban planners in fast-growing cities could use the flood risk maps to impose stricter zoning regulations, thus avoiding construction in vulnerable areas and reducing economic losses linked to flooding. In addition, emergency response teams, such as hydraulic engineers and disaster managers, are expected to benefit from the predictive models of the intensity and spatial extent of floods, improving their preparedness and response times. By integrating climate projections into water resource management, the study has provided information that could support sustainable agricultural practices in the Niger basin, ensuring that communities dependent on seasonal flooding for irrigation are not disproportionately affected by extreme weather events. The study underscores the urgent need for a proactive, science-driven approach to flood risk governance in West Africa, ensuring that climate adaptation policies align with the socio-economic and environmental realities of the region.

This study showed that a significant number of people and property as well as ecosystems in the study area are likely to be exposed to flood phenomena, Sustainable urban planning is essential to anticipate climate risks. This includes designing resilient road networks and buildings, applying strict standards against uncontrolled urbanisation in flood-prone areas, and promoting green spaces (parks, green roofs) to absorb rainwater. The use of permeable materials (porous pavements, unpaved areas) and the revision of master planning schemes will reduce the pressure on existing drainage systems. This will limit development in high-risk areas, such as flood plains and low-lying areas. Assemblies should encourage the relocation of infrastructure and new settlements to safer locations

limiting construction in at-risk areas requiring pragmatic measures; offering financial incentives, such as subsidies for relocation to safe land, and developing accessible housing alternatives, for example through public building programmes in high ground or outside flood plains, while conducting awareness-raising campaigns on the dangers of at-risk housing. In addition, the optimal operation of dams must be ensured through rigorous maintenance and regular inspections.

In addition, the optimal operation of dams must be ensured through rigorous maintenance and regular inspections. To function effectively, dams need to be closely monitored and maintained through regular technical inspections and equipment upgrades. Integrating real-time monitoring systems, such as pressure sensors and connected hydrometric stations would allow operators to regulate water releases and anticipate potential overflow risks. Clear emergency protocols and coordination with local authorities would enhance crisis responsiveness.

By implementing these recommendations, flood resilience in Lokoja and Niamey can be significantly enhanced, mitigating the adverse impacts of climate change-induced flooding and fostering sustainable urban development.

5.2.3 Suggestions for further research

This study examined the effects of climate change on flooding dynamics in the River Niger and adaptation strategies. However, other critical factors, not addressed here, deserve to be explored for a holistic risk assessment. These factors include

(a) Accelerated silting of the river, linked to desertification and soil erosion, which reduces drainage capacity and accelerates the rise in water levels during floods.
(b) Seasonal variability and water stress
(c) Groundwater dynamics, particularly interactions between aquifers and surface flooding, which can locally intensify flooding or soil salinisation.
(d) The impact of hydroelectric and agricultural dams on the river's hydrological regime, which is essential for understanding contemporary flooding.

5.3 Contribution to Knowledge

The study revealed substantial expansion of urban built-up areas, which increased by 21% in Lokoja and by a remarkable 312% in Niamey. This rapid urbanisation has significantly reduced natural infiltration spaces by replacing dense vegetation and agricultural land. Consequently, detailed flood risk mapping revealed that 15% of Lokoja's territory is at high flood risk, compared to 32% of Niamey's, with the most vulnerable zones located near the riverbanks. Critically, the study further revealed a statistical turning point in extreme rainfall indices, with a recurrent two-year cycle that enhances the predictability for early warning systems. Furthermore, integrating future climate projections allows for the development of localised flood scenarios and thereby improved forecast accuracy for urban planners. Community assessments showed a moderate preference for education and policy (scoring 3.32 in Lokoja), while structural measures like dykes scored (2.03 in Niamey). These findings imply that the synergy between unplanned urban sprawl, land-use change, and climate variability intensified flood susceptibility, thereby increasing long-term environmental and societal threats for urban populations across West Africa.

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APPENDICES A

Data collection through Questionnaire

Dear Respondent

I am a PhD student at the Department of Climate Change and Human Habitat (CC&HH) at the Federal University of Technology in FutMinna.

I am currently surveying flood impacts as part of my research work.

This questionnaire has been designed to solicit your response by providing the required information by selecting the appropriate boxes. The questionnaire is purely designed for an academic exercise to help the research work of the thesis to collect data on the title of the research entitled: Evaluation of climate change impacts on flood development and propagation in some cities in Niger and Nigeria". It is your right to wish to participate or stop the survey and not to participate in the study.

The information is strictly necessary for academic research purposes and will be treated confidentially. We thank you in advance for your support and cooperation.

1. Local Government Area (LGA):
2. Name of Community:
3. Street Name:
4. GPS :
5. Gender:
   - ☐ Male
   - ☐ Female
6. How old are you?

---

7. What is your social status?

   (a) single

   b) married

   c) widowed

   d) separated

6. Highest level of Education

   a) Primary

   b) Secondary

   c) Tertiary: (i) College of Education,

   (ii) Polytechnic / College of Agriculture,

   (iii) University.

   d) Islamic school

   (e) No formal education

7. Main Occupation

(a) Fisherman

(b) Farming

c) Trader

d) Functionary: (i) Teaching, (ii) Civil Servant, (iii) Politician, (iv) Unemployed.

(e) Transport

f) others: ____

8. What is the state of ownership of your home?

a. Owner
b. Rented
c. Social housing
d. Other:

9. For how long have you being residing here?

a) 0-2years

b) 3-5years

c) 6-10years

d) Over 10 years

10. How many people live there in your home with you

____

11. Do you live in a flood-prone area?

a) Yes, I live in a known flood zone

b) No, I do not live in a known flood zone

c) I am not sure

11. How often do you get information about the local weather forecast or flood warning information?

- Every day

- Several times a week

- Once a week

- Rarely

- Never

12. Have you or anyone in your household ever experienced flood events?

a) Yes (b) No.

13. What type of flood occurs in your area?

(a) Flash, (b) River c) Pluvial

14. How often do you experience each of them?

1) Flash: a) once b) Twice a year c) don't know d) no impact e) other

2) River: a) once b) Twice a year c) don't know d) no impact e) other

3) Pluvial: a) Per rainy season b) after heavy rain c) after a long period of rain d) no impact e) don't know

15. What particular period of the year?

Month(s):

16. What materials is your house built?

1. Banco

2. bench with cement coated

3. Ciment

4. Other:

17. What are the material consequences of flooding in your home?

____

18. How often has your home suffered from the consequences of flooding in recent years?

a) Per rainy season

b) Once a year

c) Twice a year

d) Sporadically/Rarely

e) no impact

d) don't know

19. Can you rank the events that have had the most (serious) impacts on you and your home?

1. Month(s): Year(s):

2. Month(s): Year(s):

3. Month(s): Year(s):

20. How long did the flooding last?

In your home?	----------days
In the street?	----------days
others	……………

21. What do you think is the cause of flooding in your community?

(a) Heavy rainfall and surface runoff (b) Long-term normal rainfall

c) Nature of soil d) Lack of drainage facilities e) Dwelling too close to the river/river

d) Siltation/infestation of water channels f) To the silting up of the river

(i) others:

22. Do you have flood insurance?

- Yes, I have a policy

- No, I do not have a policy

- I am not sure

23. What is the extent of the consequences of the impacts of the floods on your household in general?

a) Very serious

(b) severe

(c) less severe

(d) less

e) don't know

24. What are the risks of living in a flood-prone environment?

----

25. Have you ever lost any household members during flood events?

a) Yes (b) No.

25.1 If yes person combine?

----

26. Have you ever lost animals or other animals in a flood?

(a) yes

(b) No.

26.1 If yes, how much are the losses?

27. Have you suffered any damage to your home?

a) Yes

b) No

28. What types of damage can impact your home during a flood event?

(a) Removal of walls

b) cracks in walls and windows?

c) collapse of the building or parts

(d) Other

29. What kind of loss were you incurred during the flood event?

(a) Loss of life?

b) Loss of furniture and other household appliances

c) losses of cattle(sheep, goats,..)

d) vehicle (cars, motorcycles, bicycles,...)

(e) Clothing

(f) Other: -----

30. Do you expect to be impacted again by the floods?

a) yes, I expect impacts during the next rainy season

b) No, I don't expect any impact

c) don't know

31. What future impacts did you expect?

A) damage to the walls?

b) damage to infrastructure (house, roads ...)

(c) Environmental damage

(D) Other:

32. How big do you think future floods will be?

a) With very serious impacts

b) Average impacts or moderers

c) Lower impacts

(d) Other:

e) don't know

33. Have you taken steps to prevent the flood consequences on your home?

a) Permanent actions at least one month before the most severe flood (e.g. raising the dwelling, moving to a safer location

b) Temporary actions just before or during the flood (use sandbags, stay home, move/temporarily stay in another location)

c) Permanent post-flood actions to prevent future flood impacts (e.g. moving to a safer location,)

○ None

○ Don't know/prefer not to say/other

34. Have you ever received information before or during a flood event?

(a) yes

(b) No.

34.1 [if yes] By what kind of means did you receive it?

(a) Radio or television

b) Family, friends, neighbour

(c) At work

(d)Other: -------

35. By using the information in the table below, please rate your level of agreement with your household and community being able to prevent or mitigate the impact of flooding

	Strongly Disagree	**Disagree**	**Agree**	**Strongly Agree**
From our experience on flood disaster, We adapt our infrastructure that are flood resistant				
We built natural vegetation that can buffer effects of flood				
We have wetlands and flood plains				
We have undisturbed water bodies				
We have buildings that can withstand impact of flood				
We have good infrastructure that are flood resistant				
Have good solid waste disposal facilities & services				
We have artificial river levee or embankment				
We have knowledge of emergency call lines				
We have timely and relevant information from the media about floods				
We have local knowledge of early warning about flood in my area				
We have temporary shelter locations in and around our communities				
We have self-stored relief materials				
We have access to self-owned disaster emergency kits				
We participate in community meetings				
We have access to financial resources				

We have access to inclusive informal safety nets				
We have access to social schemes				
We have access to functional health and education systems				
We have disaster management laws and policies				
We have disaster contingency plans				
We have public disaster management agencies				
We get humanitarian services & manpower assistance				
We have emergency response outfits				

36. Please rate your level of agreement on the information in the table below that shows how your household and community can development after flood events.

	Strongly Disagree	**Disagree**	**Agree**	**Strongly Agree**
Innovatively modify existing natural river levee				
Provision of more green infrastructure such as rain gardens, green walls, green roofs, etc.				
Conservation of natural vegetation, wetlands and floodplains				
Provision of more structurally sound & climate-resilient buildings				
More provision of more resilient basic building facilities such as water supply, electricity damages and drainages				
Access self & community-owned emergency kits/relief materials				
Create more community-owned disaster emergency plans				
Create more well-organised community participation & efforts				
Inclusive access to formal safety nets such as government, humanitarian agencies, etc.				
Provide financial resources to renovation purposes				
Government can provide new health/education policies & systems				
Government can advance physical planning practice				
Government can create disaster related information institutions				
Government can create flood management policies and plans				
Government can create responsive disaster management institutions				
Government could also contribute to better re-housing of disaster victims				
The government should not wait for every disaster to happen before taking action against the damage				

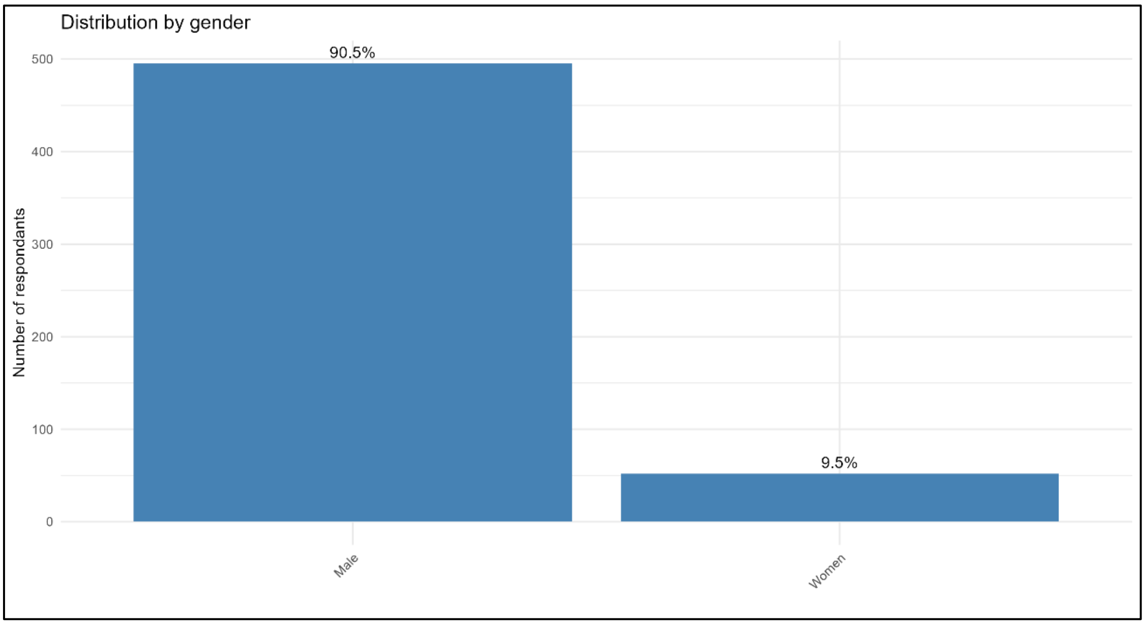
37. Do you have any other comments or would you like to share with us other events regarding the impact of the floods and also the potential issues to be taken?

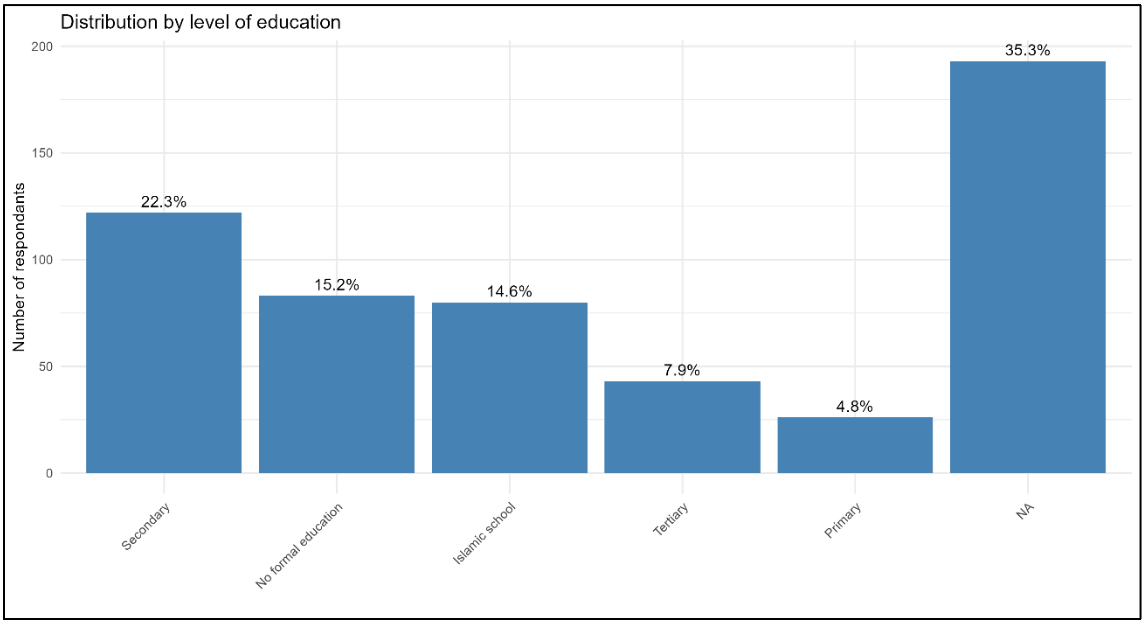
Appendix B

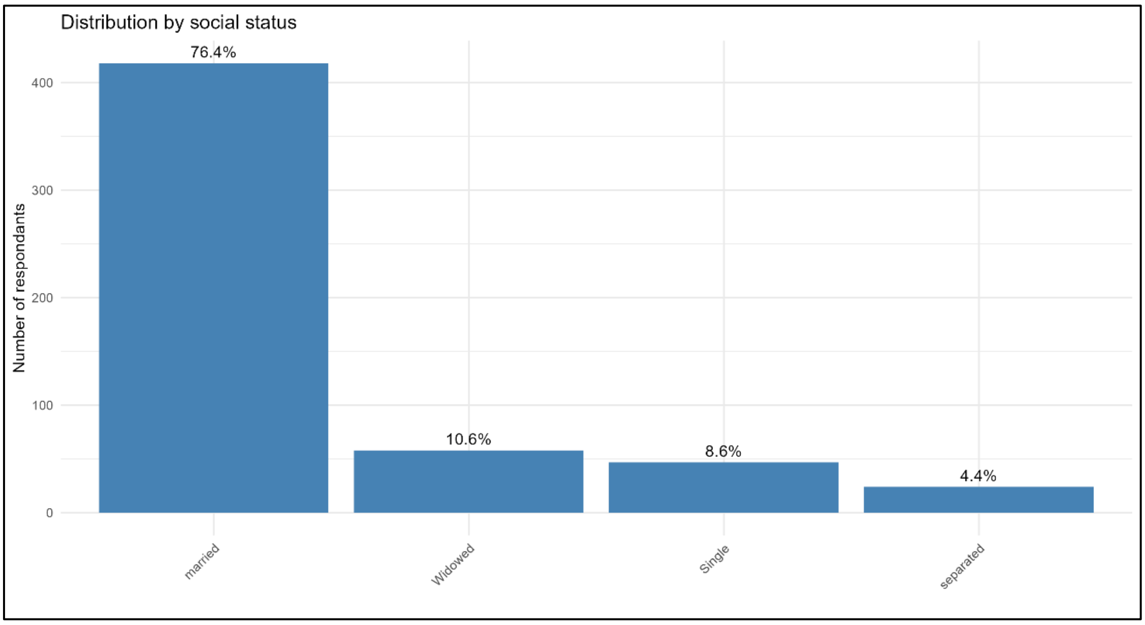
Summary of questionnaire

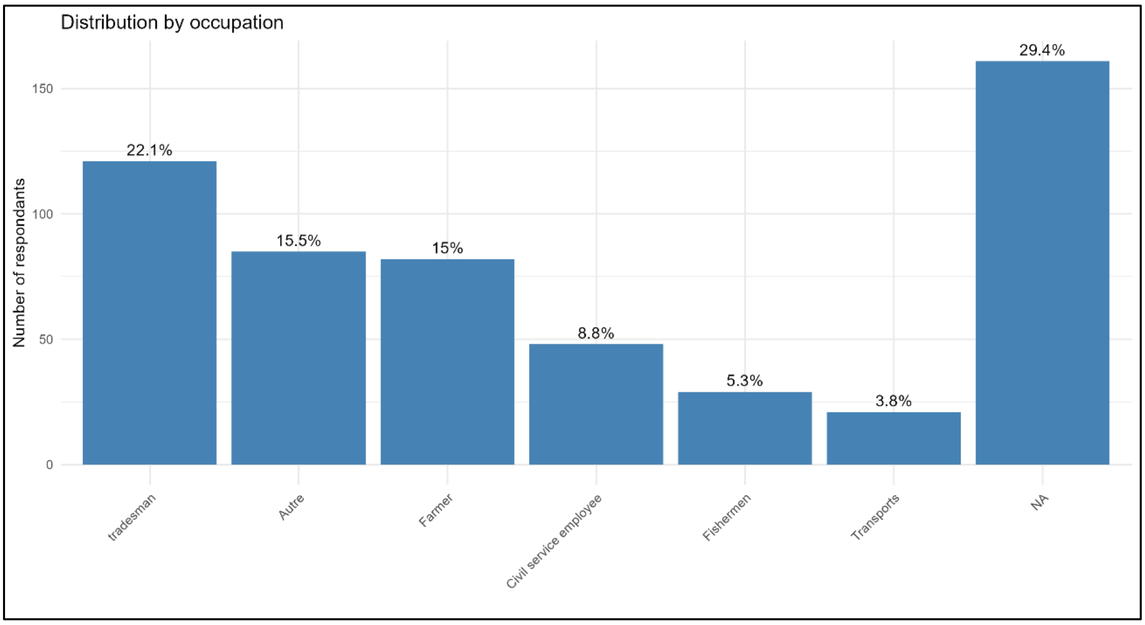
(A) Niamey

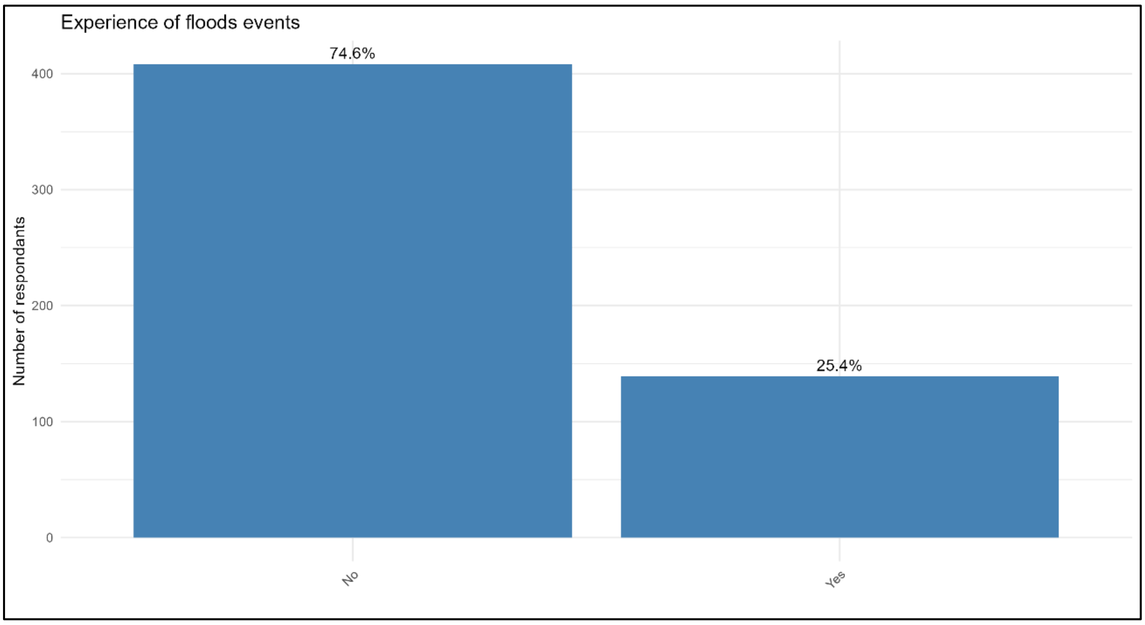
(1) Population size: 547 people

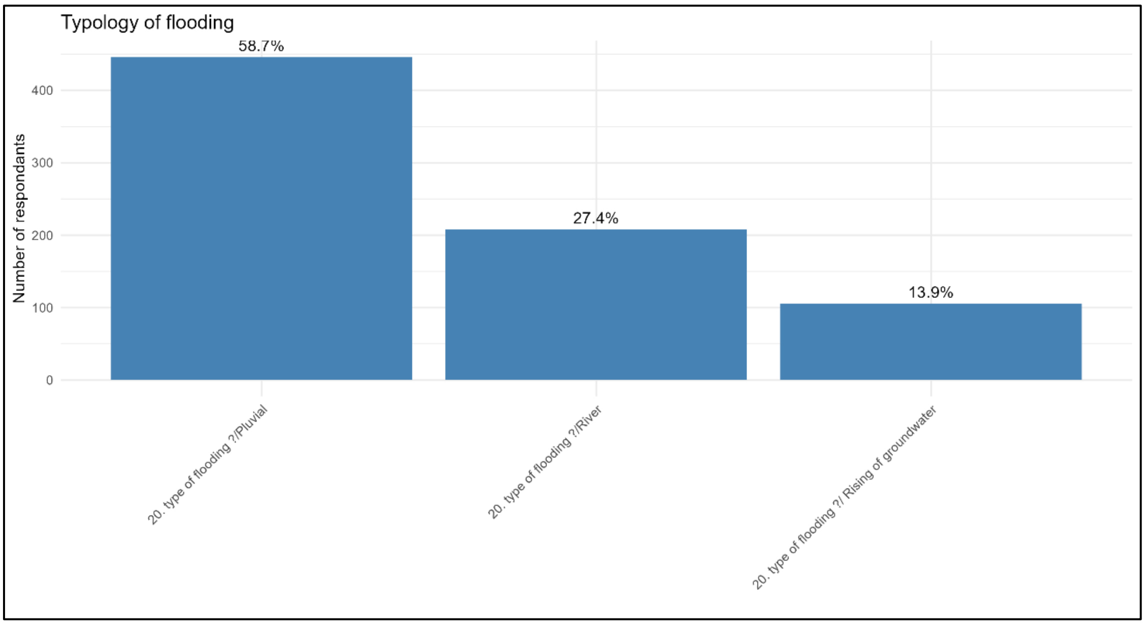





Distribution by social status
Number of respondants
0
100
200
300
400
76.4%
10.6%
8.6%
4.4%
married
Widowed
Single
separated

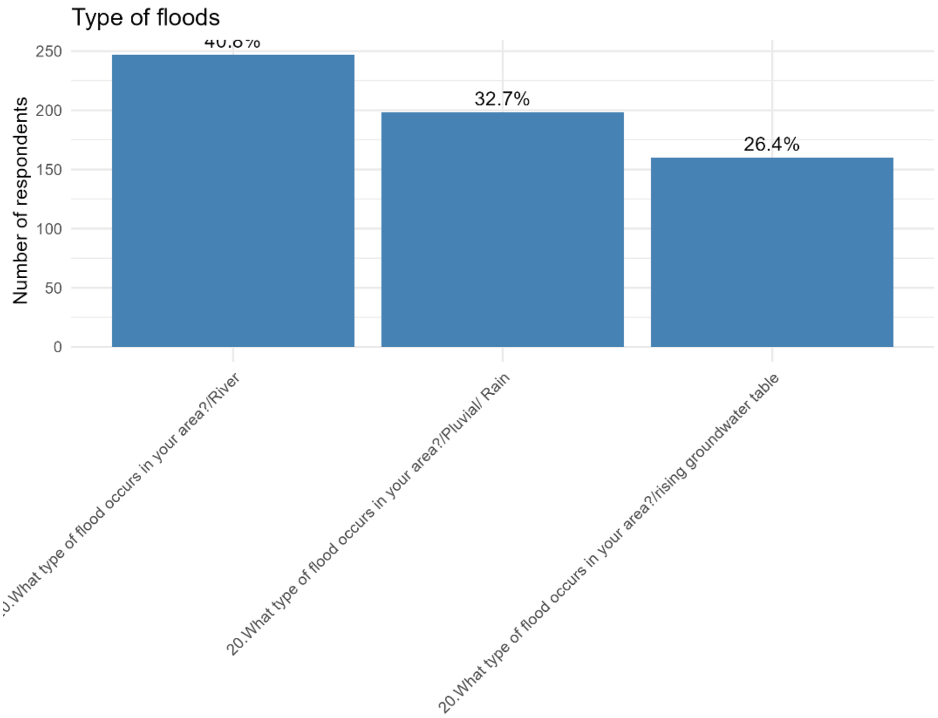

Distribution by occupation
Number of respondants
0
50
100
150
22.1%
15.5%
15%
8.8%
5.3%
3.8%
29.4%
tradesman
Autre
Farmer
Civil service employee
Fishermen
Transports
NA

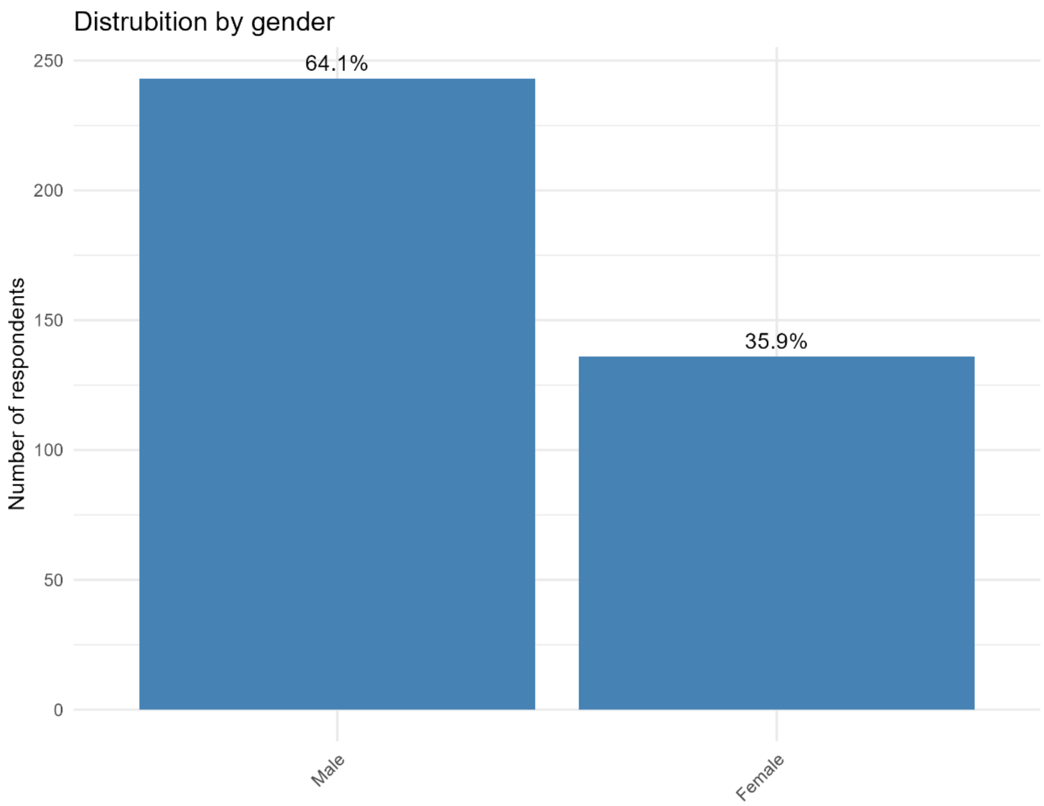

Experience of floods events
74.6%
25.4%
Number of respondants
400
300
200
100
0
No
Yes

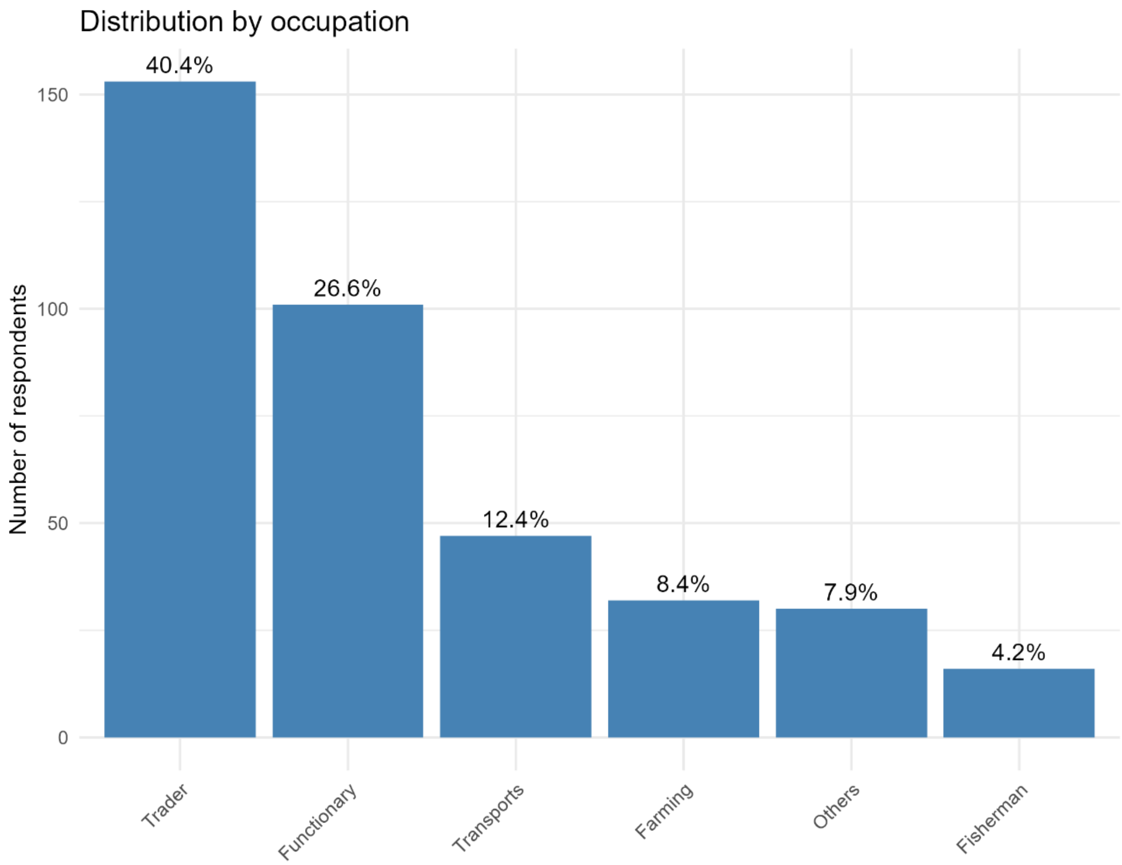

Typology of flooding
58.7%
27.4%
13.9%
Number of respondants
400
300
200
100
0
20. type of flooding ?/Pluvial
20. type of flooding ?/River
20. type of flooding ?/ Rising of groundwater

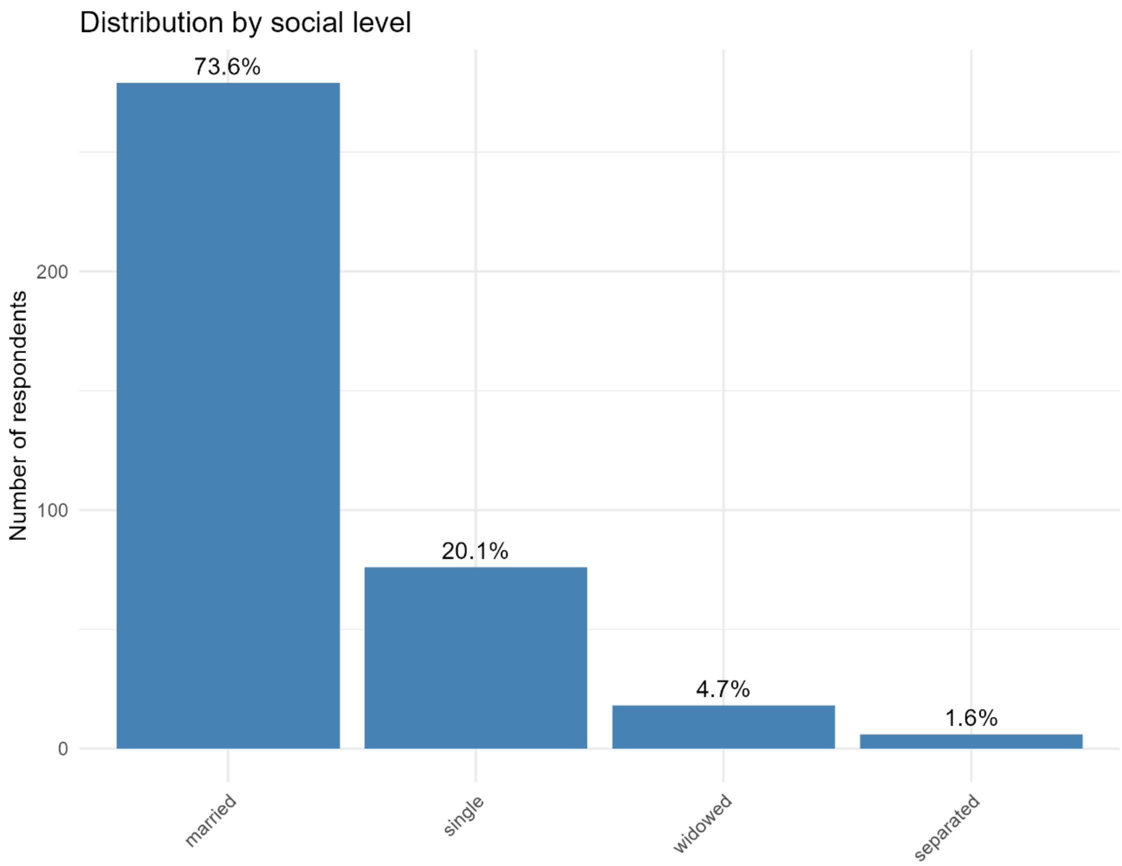
(B) Lokoja

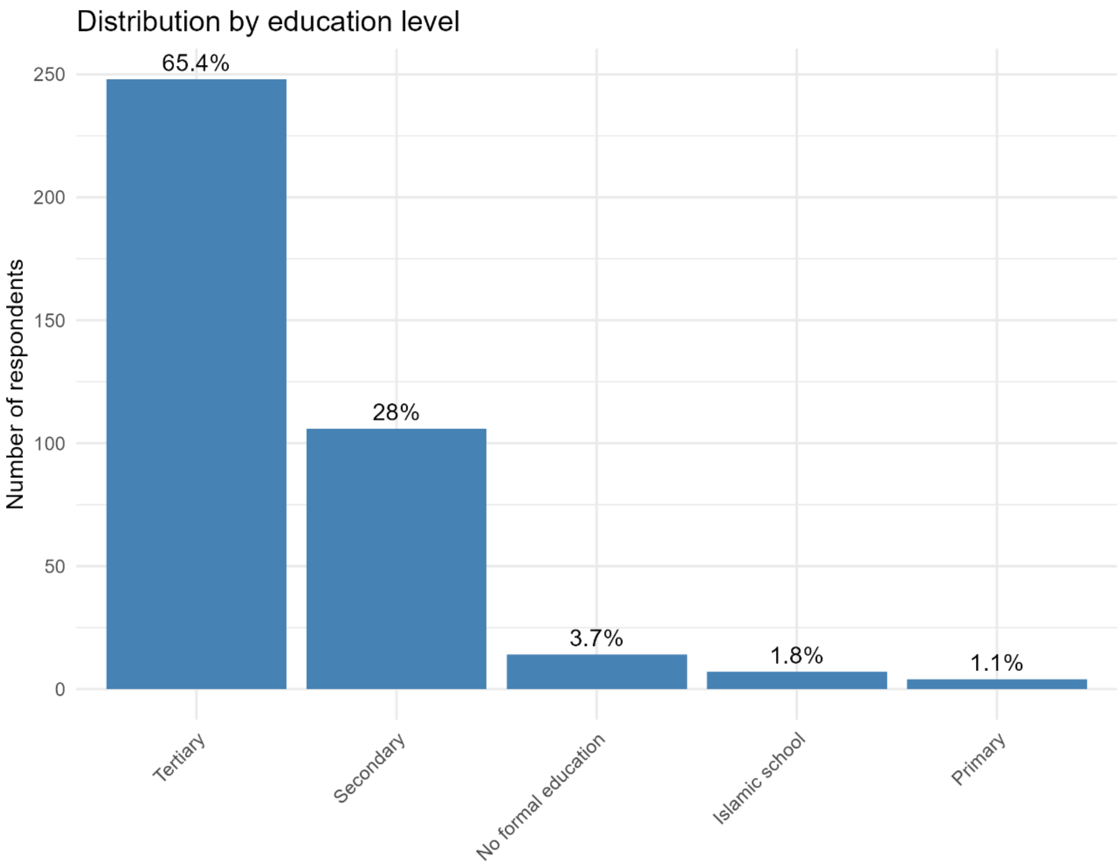
Population size: 379 peoples

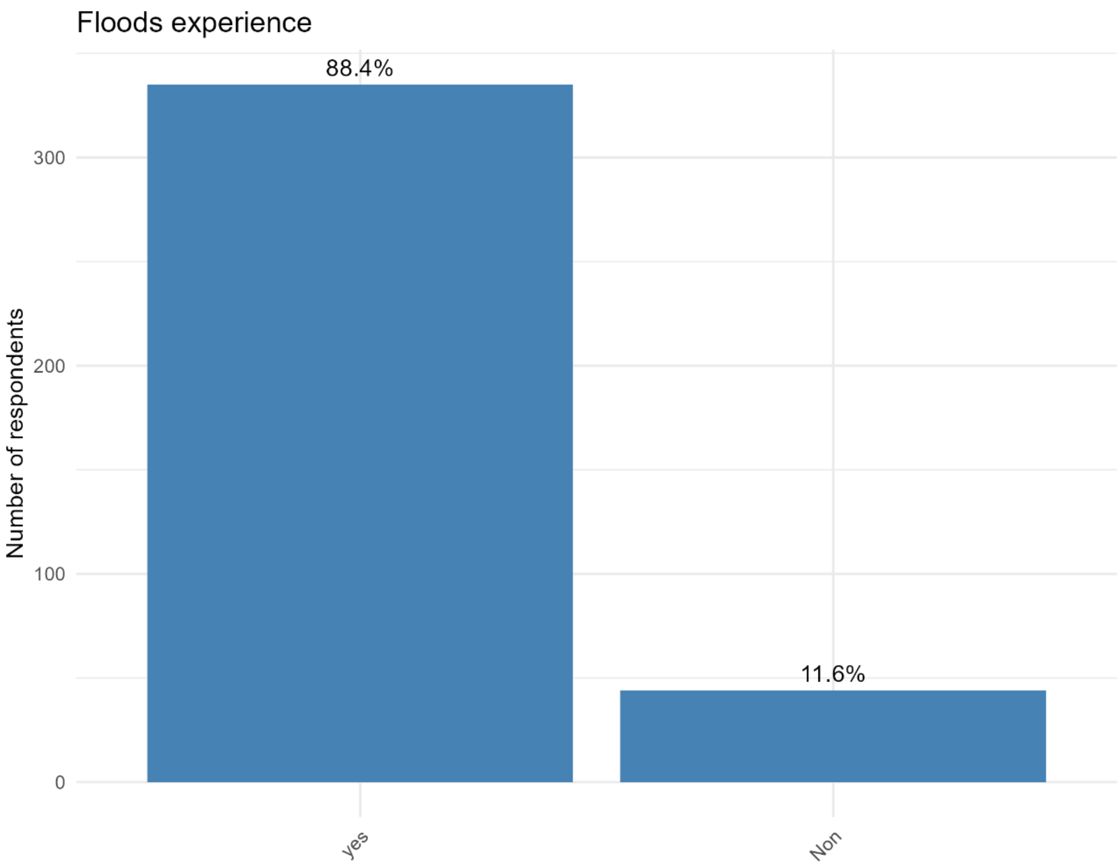





Distribution by occupation
Number of respondents
0
50
100
150
40.4%
26.6%
12.4%
8.4%
7.9%
4.2%
Trader
Functionary
Transports
Farming
Others
Fisherman


Distribution by social level
Number of respondents
0
100
200
73.6%
20.1%
4.7%
1.6%
married
single
widowed
separated


Distribution by education level
65.4%
28%
3.7%
1.8%
1.1%
250
200
150
100
50
0
Number of respondents
Tertiary
Secondary
No formal education
Islamic school
Primary


Floods experience
88.4%
11.6%
300
200
100
0
Number of respondents
yes
Non