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Flood Risk Assessment and Zoning for Niamey and Lokoja Metropolises in Niger and Nigeria

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Abstract: With the increasing frequency of floods in recent decades, particularly in West Africa, many regions have faced unusual and recurrent flooding events. Communities in flood-prone areas experience heightened insecurity, loss of property, and, in some cases, serious injuries or fatalities. Consequently, flood risk assessment and mitigation have become essential. This comparative study between Niamey and Lokoja employs Geographic Information Systems (GIS) and the Analytical Hierarchy Process (AHP) to delineate flood susceptibility, vulnerability, and risk zones. The study utilized a comprehensive range of thematic layers, with weight percentages assigned to each parameter as follows: 29% for elevation, 24% for slope, 15% for the Topographic Wetness Index (TWI), 9% for drainage density, 9% for distance from rivers, 4% for both precipitation and the Normalized Difference Water Index (NDWI), and 2% each for the Normalized Difference Vegetation Index (NDVI) and soil type. To validate these weightings, a consistency ratio was calculated, ensuring it remained below 10%. The findings reveal that 32% of the Niamey study area is at risk of flooding, compared to approximately 15% in Lokoja. The results highlight a very high flood potential, particularly in areas near the Niger River, with this potential decreasing as elevation increases. Given the current prevalence of extreme weather events in West Africa, it is crucial to employ effective tools to mitigate their adverse impacts. This research will assist decision-makers in quantifying the spatial vulnerability of flood-prone areas and developing effective flood risk assessment and mitigation strategies in the region.

Keywords: flood risk; characterization; zoning; multi-criteria analysis decision; extreme events

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1. Introduction

Floods are natural phenomena that occur when the level of a water body exceeds its usual threshold, inundating land that is typically dry. This rise in water levels can result from various factors, including excessive runoff from heavy rainfall, seawater intrusion, or rising river levels [1]. Floods rank among the world's most significant natural disasters, leading to substantial social and economic losses. Between 1995 and 2020, floods affected more than 2.5 billion people globally, accounting for 11% of all disaster-related deaths, translating to over 170,000 fatalities [2]. For instance, following the extreme rainfall events of 2020, more than 2.7 million people in 18 West and Central African countries, including Niger and Nigeria, experienced severe impacts [3]. The Intergovernmental Panel on Climate Change (IPCC) has projected an increase in the frequency and magnitude of extreme weather events, particularly floods and droughts, across the African continent due to climate change [4]. Africa is particularly vulnerable to the consequences of climate change for several reasons: its fragile ecosystems, the population's reliance on agriculture sensitive to climatic variations, and rapid population growth, all of which significantly impact land resources [5]. Moreover, the increasing intensity of extreme weather events, notably heavy rainfall, often affects already degraded soils, leading to flooding [6]. Research by [7–9] highlights a significant rise in both the frequency of floods and their impacts in the Sahelian region.

However, the recent surge in flooding cannot be solely attributed to climate change. While climate change undeniably intensifies rainfall and disrupts hydrological patterns, other factors, such as severe land and vegetation degradation, also heighten the region's vulnerability. This degradation diminishes the soil's water-holding capacity, increasing runoff and the risk of flooding [10,11]. Additionally, Sub-Saharan Africa is experiencing rapid population growth, leading to the development of informal settlements and urban expansion into flood-prone areas where land is often inexpensive or free [12]. Consequently, communities remain at risk of future flooding. Thus, analyzing the evolution of risks associated with extreme events, particularly floods, is crucial for informed decision-making and the development of effective disaster risk reduction strategies. In regions such as Niger and Nigeria, flooding has posed a significant challenge for the past decade. Unfortunately, disaster management primarily focuses on post-disaster assistance and response efforts, with insufficient emphasis on risk planning. This lack of proactive measures contributes significantly to the population's vulnerability [13]. The absence of effective planning hinders authorities' ability to anticipate and respond to disasters, ultimately compromising the resilience of at risk communities and exacerbating the social, economic, and environmental impacts of extreme events. Flood risk assessment plays a crucial role in implementing measures to mitigate the impact of flooding, especially in urban areas. Various methodological approaches were proposed in the literature to reduce flood effects. Flood risk can be estimated using three main approaches: (1) an analysis of flood frequency, (2) the study of flood dynamics, and (3) the creation of flood vulnerability and risk maps [14]. In this study, we favor the mapping approach, which provides better geographical visualization of the risks and serves as a key tool in effective flood risk management strategies. Numerous studies have assessed vulnerability and risks related to flood impacts [14–17]. The integration of Geographic Information Systems (GIS) with multi-criteria decision-making (MCDM) was widely adopted in recent research. This methodology results in a flood risk map that illustrates the spatial distribution of risk areas and their intensity levels, ranging from very low- to very high-risk [14]. This approach incorporates various factors contributing to flood phenomena, including the morphological and hydrological conditions of the terrain, as well as socio-economic conditions represented as spatial layers [18]. The advantage of this method lies in its ability to produce a detailed and reliable map of the risk areas.

2. Study Area and Data

This study focuses on two metropolitan cities, Niamey, the capital of Niger, and Lokoja, the capital of Kogi State in Nigeria, both located in West Africa. Niamey is situated in the extreme west of Niger along the banks of the Niger River, with coordinates between 13°20′–13°35′ N and 2°00′–2°15′ E (Figure 1). The city has experienced rapid expansion over the past few decades, making it one of the most populous cities in the country. Administratively, Niamey comprises five communal districts, four of which are frequently affected by flooding from the Niger River. The city's topography is relatively flat, with altitudes ranging from 180 to 250 m, making some areas particularly prone to water inundation. Climatically, Niamey receives an average annual rainfall of 300 to 600 mm, with the rainy season lasting from May to September. The average temperature is 30.8 °C, with the highest temperatures recorded in April [19]. Historically, Niamey has been plagued by flooding, especially during the rainy season, due to frequent river overflows, extreme rainfall, and, in some cases, a rising water table. Severe floods occurred in 2010, 2012, 2020, 2022, and 2024, primarily during the rainy season, displacing many residents and resulting in loss of life [20–22].

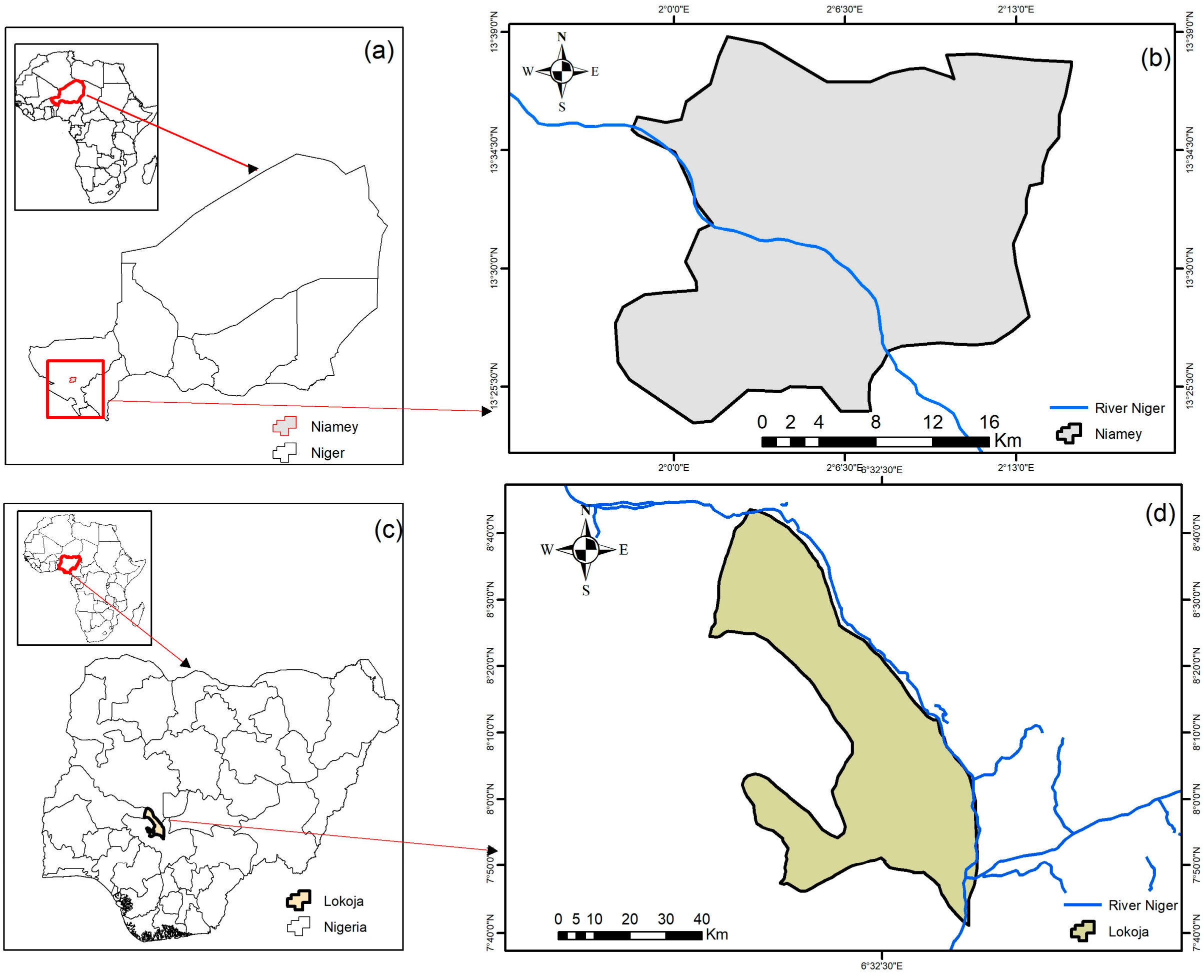

Figure 1. Map of Niger (**a**) and Nigeria (**c**) showing Niamey and Lokoja as projected in (**b**,**d**) with the river Niger, respectively.

Lokoja (Figure 1), located at coordinates 7°45′–7°52′ E and 6°39′–6°46′ N, features hilly terrain with altitudes ranging from 30 to 400 m above sea level. It receives an average annual rainfall of 1000 to 1500 mm, with its rainy season extending from April to November and an average annual temperature of 27 °C [23]. Like Niamey, Lokoja has faced significant flooding in 2012, 2021, and 2024. Both Niamey and Lokoja share notable similarities, particularly in their vulnerability to hydrological hazards due to their strategic locations along the Niger River. Both cities regularly experience flooding, which is exacerbated by river overflow and extreme rainfall during the rainy season, a situation worsened by climate change. Rainfall patterns have become increasingly irregular, alternating between droughts and extreme rainfall events, leading to heightened vulnerability in both cities. Rapid and unplanned urbanization further exacerbates this issue, as infrastructure struggles to keep pace with population growth, leaving communities, especially in informal settlements, more susceptible to flooding. Moreover, both cities are heavily reliant on water resources for economic activities, including agriculture, fishing, and river transport. The impact of flooding on these vital sectors threatens the livelihoods of local communities, making effective flood risk management a crucial issue for the future of Niamey and Lokoja.

3. Method

3.1. Generation of Vulnerability Maps

3.1.1. Vulnerability Analysis

The flood hazard susceptibility and vulnerability maps were generated using climate and spatial datasets including the average maximum rainfall, the land use/occupation map, SRTM (Shuttle Radar Topography Mission), soil data, total population data, and satellite images (Table 1). SRTM was used to prepare terrain data, notably elevation, slope, drainage density, distance to a river, and topographic moisture index, and USGS satellite images were used to prepare Normalized Difference Water Index (NDWI) and Normalized Difference Vegetation Index (NDVI) [24–26]. The thematic layers, namely elevation, slope, rainfall, topographic moisture index, drainage density, distance to river, NDVI, NDWI, and soil, were selected to study flood susceptibility and vulnerability as the land use and land cover layers. All the layers were processed in the ArcGIS environment [27] for the analysis of flood susceptibility and risk thematic layers. Flood risk criteria used in this study were selected based on a literature review and discussions with experts, the parameters (such as elevation, slope, rainfall, topographic moisture index, drainage density, distance to river, NDVI, NDWI, and soil) employed were selected based on their relevance to flood risk and importance [28,29]. Each criterion was established by considering a physical and natural phenomenon that might affect vulnerability, precisely regarding the degree of susceptibility and exposure linked to human activities.

Table 1. A description of the parameters used in the zoning of susceptibility and vulnerability in Lokoja and Niamey.

Parameter	Description	Source	Mapping Output
Precipitation	Average maximum rainfall and average annual precipitation	Direction générale de la meteorology du Niger (DMN) for rainfall station, and Climatic Research Unit (CRU) gridded precipitation data	Precipitation map
Digital Elevation Model (DTM)	ALOS PALSAR from EARTHDATA and SRTM 1 Arc-second Global from Earth Explorer	EARTHDATA (NASA) from: search.asf.alaska.edu/#/ accessed on 14 December 2023) United States Geological Survey (USGS) from: https://earthexplorer.usgs.gov (accessed on 14 December 2023)	Elevation, Slope, drainage density, distance to rivers, topographic moisture index
Land Use and Land Cover	Esri Land Cover	livingatlas.arcgis.com/landcover/ (accessed on 12 May 2024)	Land use and land cover map
NDVI, NDWI	Landsat 8	USGS (accessed on 15 December 2023)	
Population	Spatial distribution of population	https://human-settlement.emergency.copernicus.eu/download.php?ds=pop (accessed on 15 October 2024)	Population map
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)	Soil map

3.1.2. Integration of GIS and AHP for Risk Characterization

The study employs a combination of a Geographic Information System (GIS) and Analytical Hierarchy Process (AHP) to identify areas at risk of flooding by integrating several criteria relevant to the flood phenomenon [16,17]. To identify the areas, Multi-Criteria Decision-Making (MCDM) was used to assess the weight of each factor's contribution due to the extent of their inconsistent data. The employed approach is based on three aspects: the creation of a pairwise comparison matrix, the calculation of the criteria weights, and the evaluation of matrix consistency. After the construction of the pairwise comparison matrix, the AHP method was used to obtain the respective importance of the various factors concerned, as is in line with [30,31]. Developed by Thomas Saaty, the Analytic Hierarchy Process (AHP) is a fundamental tool used to make pairwise comparisons in multi-criteria decision-making [32]. The weighting allows the values to be judged against each other on a scale of 1 to 9 (Table 2) based on the indices proposed [32]. When comparing one criterion with another, each factor is assigned a score, with the lower figures representing fewer essential factors and the higher figures indicating higher 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. Thus, suppose the relative importance of n was assigned to the comparison ratio between two criteria, A and B. In that case, the ratio between B and A is evaluated by the fraction of 1/n. When the element is compared in the table, it coincides with the diagonal elements and is scored with the respective value [33,34].

Table 2. Saaty scale on relative importance from [18–32].

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

3.1.3. Reclassification of Variables

To standardize the thematic layers for assessing susceptibility and vulnerability, all layers were reclassified using the Natural Breaks method to differentiate pixel values [17]. This approach categorized the data into five distinct levels, ranging from one to five, where one represents very low flood risk and five signifies very high flood risk. The reclassification of the various criteria, along with their respective areas and assigned weights, were recorded.

3.2. Flood Risk Quantification and Characterization

3.2.1. Hazard Mapping and Flood Susceptibility

The term hazard refers to climate-related physical events or trends, as well as their manifestations and potential impacts. It is defined as the likelihood that a natural or anthropogenic event, capable of causing physical impacts, results in the loss of human lives, injuries, or health effects, while also causing material damage to infrastructure, livelihoods, and ecosystems [35]. Environmental characteristics such as elevation, slope, drainage systems, and soil types [36], as well as hydrological properties, particularly, precipitation, play a critical role, especially in river overflows [36]. NDVI (Normalized Difference Vegetation Index) is employed to characterize the most flood-prone areas by identifying those with higher vulnerability [18,37]. Regions with negative NDVI values are more exposed to flooding, while those with positive values have a lower risk. Additionally, proximity to rivers is a key factor in flood susceptibility analysis, particularly in areas like the study region, which are frequently affected by the overflow of the River Niger [22]. The Topographic Moisture Index (TWI) indicates the specific geographical location of surface saturation and the spatial distribution of soil water and quantifies the effect of local topography on drainage generation [38,39]. The TWI layer was prepared from the Digital Elevation Model using the following expression:

$$\mathrm{TWI} = Ln\left(\frac{a}{\tan\beta}\right) \tag{1}$$

where α and β refer to the specific area and slope of the region. Thus, the region with the higher TWI rating shows a higher probability of a flood event. The combination of these factors thus facilitates the identification of flood-prone zones.

3.2.2. Flood Vulnerability Parameters

According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [35], vulnerability refers to the sensitivity or susceptibility to damage, as well as the inability to cope with or adapt to an event. Vulnerability is a critical component of risk, as it determines whether exposure to a hazard constitutes a genuine risk [38]. In this study, land use, total population, and the distance from the road were selected as the primary criteria for analyzing the flood vulnerability. This criterion was chosen due to its direct influence on infiltration rates, runoff, and water retention, i.e., the soil's ability to absorb or drain rainfall [39]. Different land use types, such as urban, agricultural, and natural areas, determine how rainwater behaves thus affecting the susceptibility of a given area to flooding. This classification allowed the quantification of land use impacts on flood dynamics, highlighting high-risk areas due to impermeability, leading to shortening the time of concentration.

3.2.3. Flood Risk

According to [40], risk refers to the likelihood that an event will occur and result in negative consequences or expected losses, arising from a combination of natural or anthropogenic hazards [38]. Risk is commonly expressed using the following equation:

$$\mathrm{Risk} = \mathrm{Hazards} \times \mathrm{Vulnerability} \tag{2}$$

It is often described as the product of three main factors, including exposure, which specifically refers to the physical aspects of vulnerability. This study assigned specific weights to the different hematic indicator layers based on their respective characteristics. The weight assigned to each element for hazard assessment is presented in Tables 3 and 4 [24,41]

Based on this, Equations (3)–(7) were used to compute the eigenvector (vp) and the weighting coefficient (cp). The following equation demonstrates the formula used to calculate the eigenvector (Vp) and the weighting coefficient (Cp):

$$Vp = \sqrt[n]{C1 \times C2 \ldots . \times Cn} \tag{3}$$

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

$$Cp = \frac{Vp}{Vp1 + Vp2 + \cdots .. + Vn} \tag{4}$$

$$CI = \frac{(\lambda\text{max} - \text{n})}{(\text{n} - 1)} \tag{5}$$

where CI: the coherence index; n: the number of factors evaluated (n = 9 for the case of this study); and λmax: the 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:

$$\lambda Max = \frac{[E]}{n} \tag{6}$$

With [E] corresponding to the rational priority, it is obtained by dividing each global priority [D] by the corresponding priority vector. The global priority [D] is calculated by multiplying each column of the matrix by the priority vector [C], which is the average of each line [26,28]. The pairwise comparison tables were ranked with nine factors in the field of natural disasters. Their results were standardized and examined using the consistency ratio (CR) test [34,42]. The consistency ratio was calculated using the following equation:

$$CR = \frac{CI}{RI} \tag{7}$$

where CI is the coherence index, RI is the random coherence index whose value depends on the number n, and n is the number of factors. In this study, nine factors, which gave an RI value of 1.45, were used. The matrix will be coherent if the ratio is <0.1.

Table 3. Consistency ratio table.

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
RI	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: [43].

Table 4. Pairwise comparison matrix for flood susceptibility.

Factors	**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	3.03	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	3	3	4	0.67	0.05	5%
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	0.20	0.20	0.33	0.25	1	1	0.28	0.02	2%
Sum	5.40	2.82	8.45	14.03	14.03	23.67	30.5	38	41	13.44	1	100%

Saaty scale on relative importance [44]. 1: Equal importance; 9: extreme importance. S: Slope; E: elevation; TWI: topographic wetness index; DR: distance to the river; DD: drainage density; NDWI: normalized water index; NDVI: Normalized Difference Vegetation Index.

4. Results and Discussion

4.1. Flood Susceptibility and Vulnerability Analysis

Based on the thematic layer, the results revealed that elevations in Niamey varied between 180 and 300 m (Figure 2a), while Lokoja ranged from 19 to 544 m (Figure 3a). According to the classifications, Niamey is predominantly located at a medium elevation (34.38%), followed by low (20.87%), high (17.19%), very low (15.68 %), and very high (12.14%) elevations (Table A1). Conversely, the Lokoja area is dominated by altitudes classified as very high flood risk (28.18 %), followed by high (26.31%), moderate (23.57 %), low (11.23 %), and very low (10.70 %) classes (Table A2).

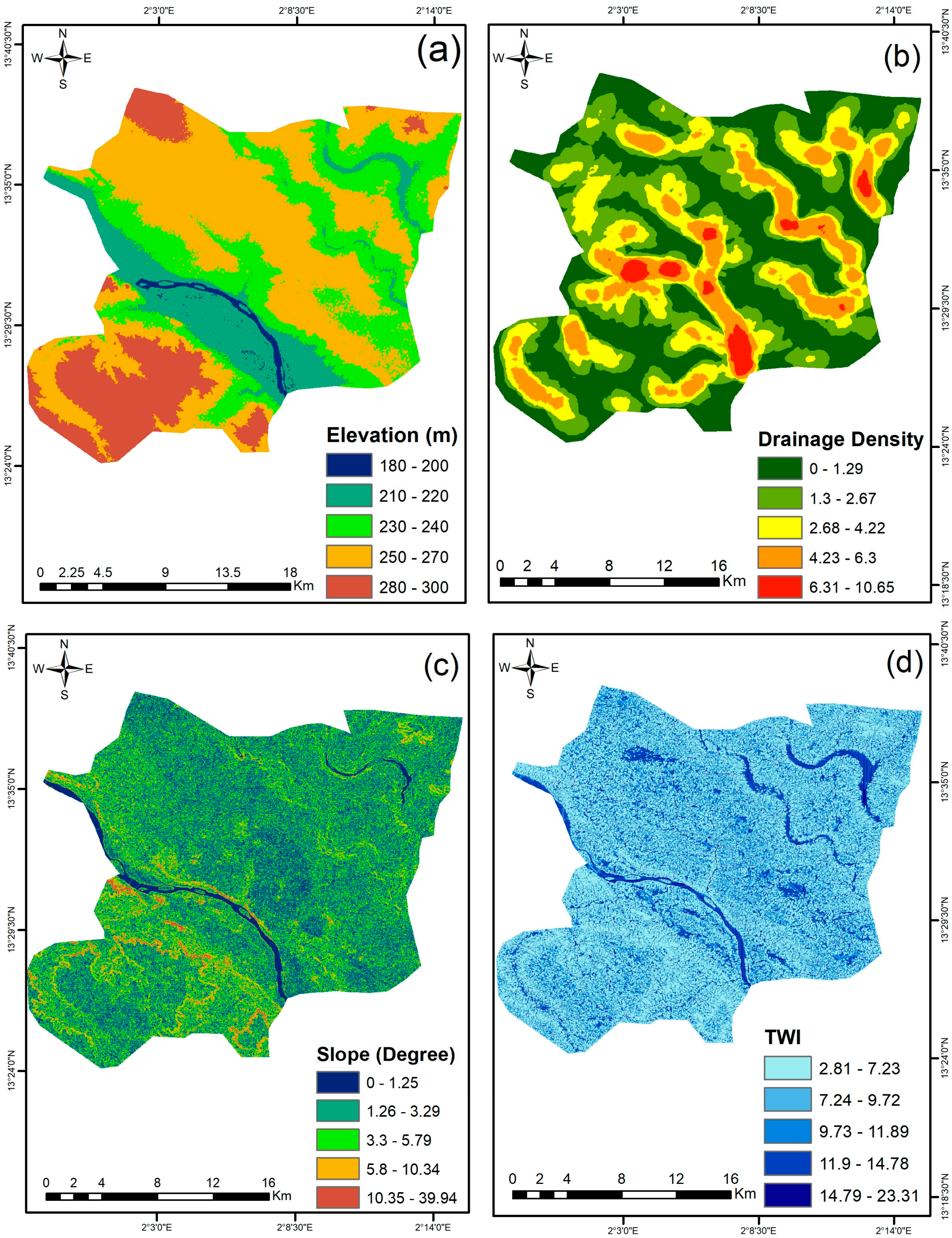

Figure 2. Different thematic layers used for flood susceptibility map in Niamey: (**a**) elevation, (**b**) drainage density, (**c**) slope, (**d**) Topographic Wetness Index (TWI).

Niamey's low-elevation areas are mainly concentrated in the center, particularly in the southeast and east of the city. Lokoja, on the other hand, these low-lying areas are located in the north and extreme southeast of the city. This elevation parameter was weighted at 29% (Table 4) in the AHP model, underlining its importance in assessing flood risk.

As for slope, it varies from 0 to 40 degrees in Niamey, with a breakdown into five categories: very high, high, moderate, low, and very low. Most of the Niamey area falls into the high- to very high-risk classes (80%), favoring increased retention of runoff thus reinforcing the area's vulnerability to flooding. In Lokoja, a similar pattern is observed, where 84% of the territory falls into the very high to high categories. This dominance of steep slopes underlines the high-risk of flooding in this area. The slope factor was weighted at 24%. The TWI ranged from 2.8 to 23 in Niamey and 3.2 to 23 in Lokoja. This index, essential for assessing susceptibility to flooding, was given a weighting of 16% in the overall analysis, demonstrating the importance of topographical conditions in the concentration of moisture in these areas. However, drainage density, which reflects the quantity of watercourses per unit area, ranges from 0 to 11 km/km^2 in Niamey, and from 0 to 2.5 km/km^2 in Lokoja. This parameter was weighted at 9% in the AHP model. Areas with high drainage density represent 15.32% of the surface area in Niamey and 25.54% in Lokoja, indicating a greater runoff capacity in Lokoja. But, in Niamey, the very low-density category predominates (39%), while in Lokoja, it covers 28% of the area. This contrast suggests that the overall drainage density is higher in Lokoja, which could accentuate its flood risk.

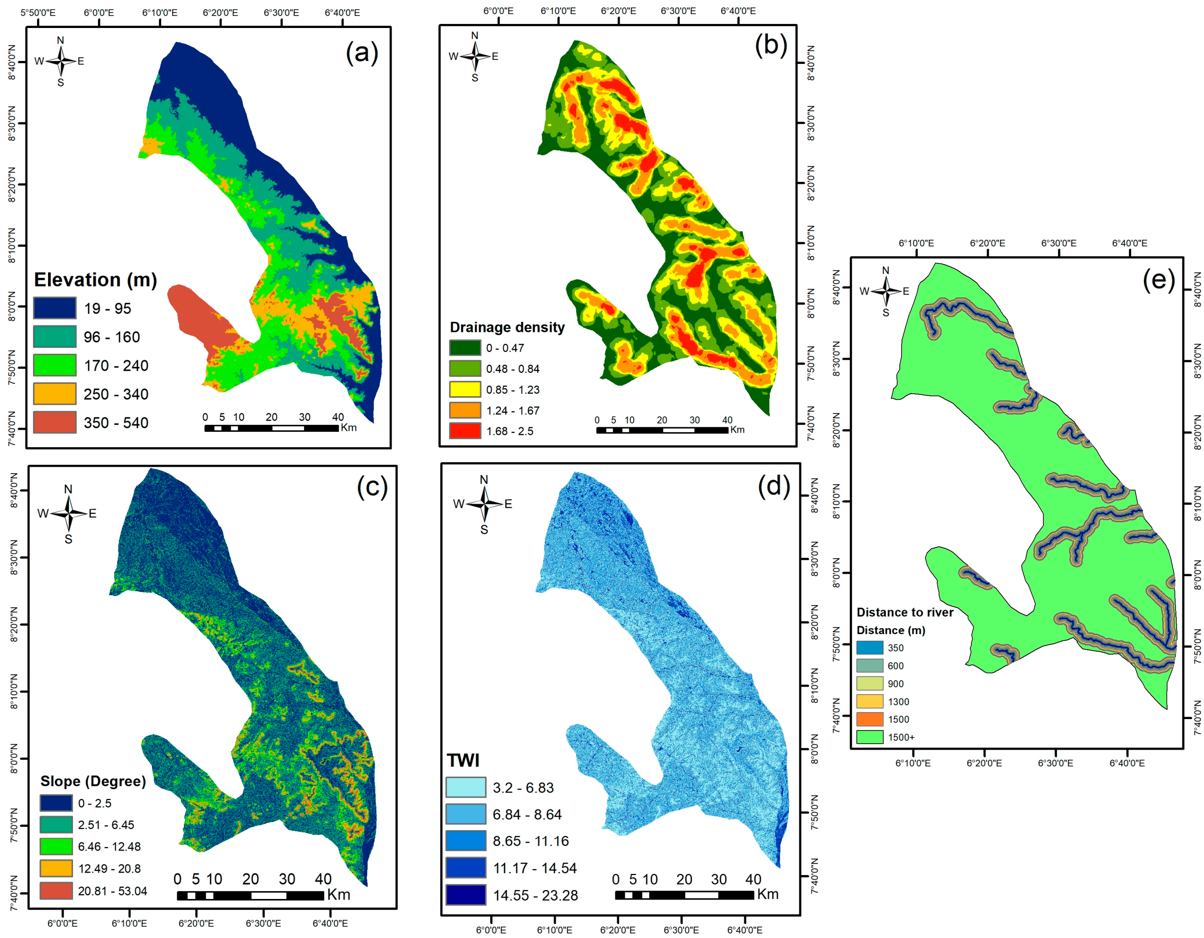

Figure 3. Different thematic layers used for flood susceptibility map in Lokoja: (**a**) elevation, (**b**) drainage density, (**c**) slope, (**d**) Topographic Wetness Index (TWI), (**e**) distance to river.

Precipitation, a key factor in the occurrence of floods, is weighted at 4 % in this study. Precipitation was divided into five classes, very low (7.04 %), low (17.84 %), moderate

(48.49 %), high (22.34 %), and very high (4.3 %), underlining its central role in triggering floods. On the other hand, NDWI, which assesses the presence of water and its link with flood risk, varies between −0.5 and −0.2 in Niamey (Figure 4b) and varies and between −0.43 and 0.17 in Lokoja (Figure 5c). In Niamey, the predominant category is that of very weak zones, while in Lokoja, the weak class is the most represented. This parameter was weighted at 4% in the overall analysis, reflecting the direct impact of the presence of water on susceptibility to flooding.

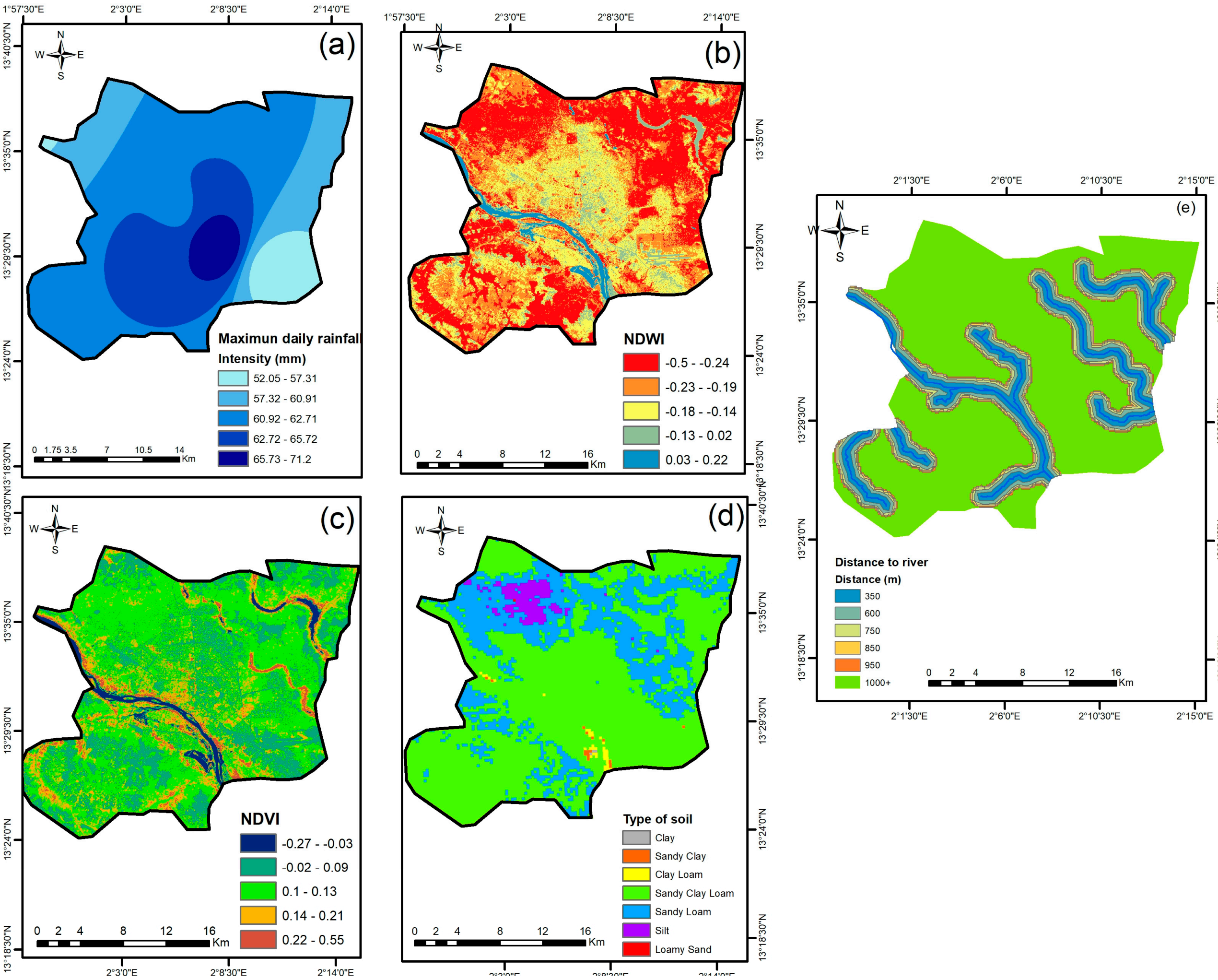

Figure 4. Different thematic layers used for flood susceptibility map in Niamey: (**a**) rainfall, (**b**) NDWI, (**c**) NDVI, (**d**) type of soil, (**e**) distance to river.

Similarly, NDVI, which assesses vegetation cover and its influence on flooding, varies between −0.3 and 0.3 in Niamey and between −0.16 and 0.50 in Lokoja. Negative values of this index indicate increased susceptibility to flooding. NDVI was weighted at 2%, reinforcing the understanding of the role of vegetation in runoff management.

The soil type parameter is presented in Figure 4d 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 5d, 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 %.

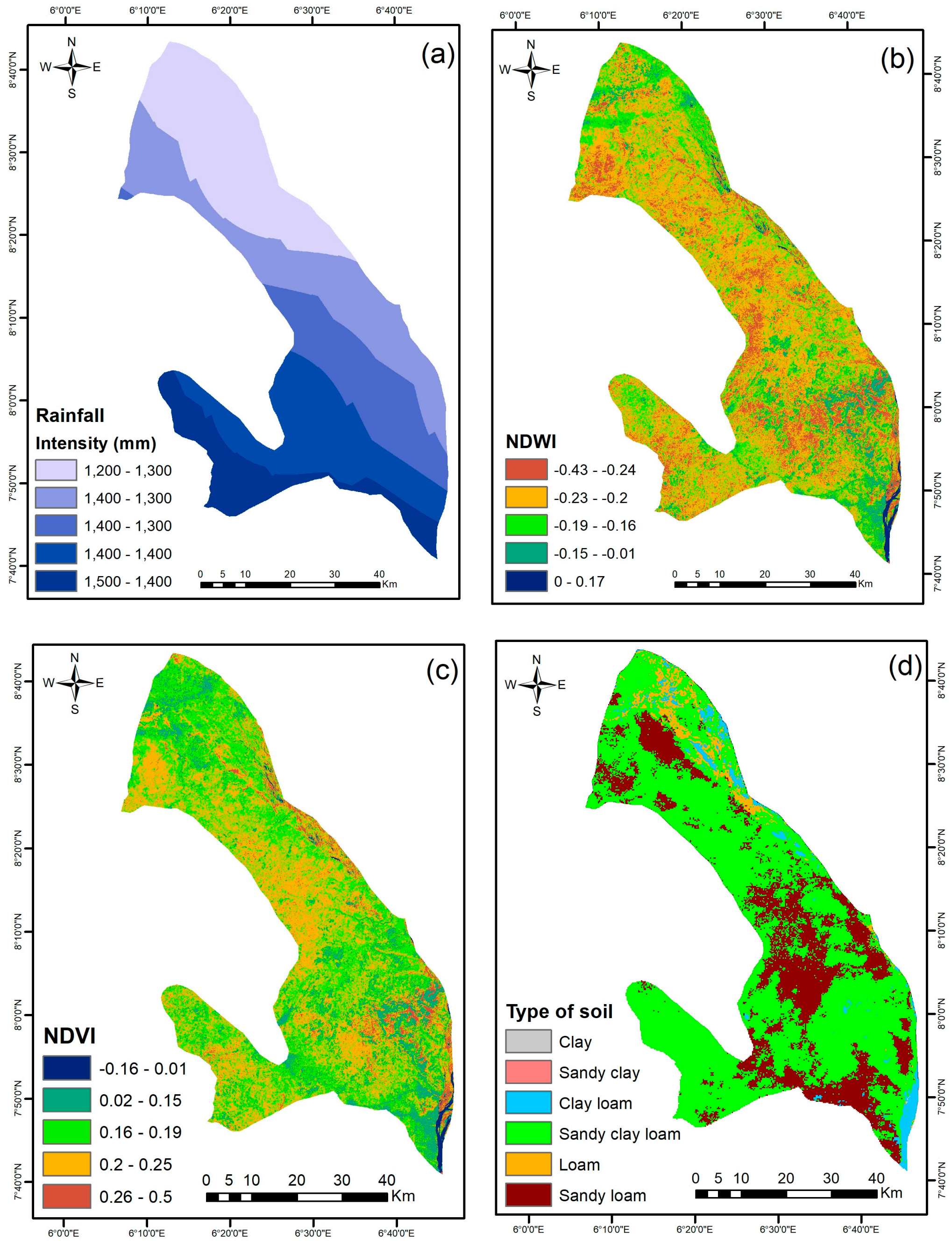

Figure 5. Different thematic layers used for flood susceptibility map in Lokoja: (**a**) rainfall, (**b**) NDWI, (**c**) NDVI, (**d**) type of soil.

4.2. Flood Vulnerability Layers

The vulnerability map provides precise information on areas potentially prone to flash flooding. The parameters influencing vulnerability relate in particular to the socio-economic aspect, including the people and their property likely to be impacted by natural events, in terms of both quantity and quality [1]. In addition, the vulnerability map results from the combination of several factors, in particular the land occupation and use map (LULC), the thematic population map, and the distance from roads. Among these factors, LULC plays a major role in determining runoff and flood behavior. The figure shows the map of land cover classes. Using the reclassification tool, the land use map was reclassified on a scale from 1 (very low vulnerability) to 5 (very high vulnerability). 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. Figures 6a and 7a illustrate LULC for Niamey and Lokoja metropolitans.

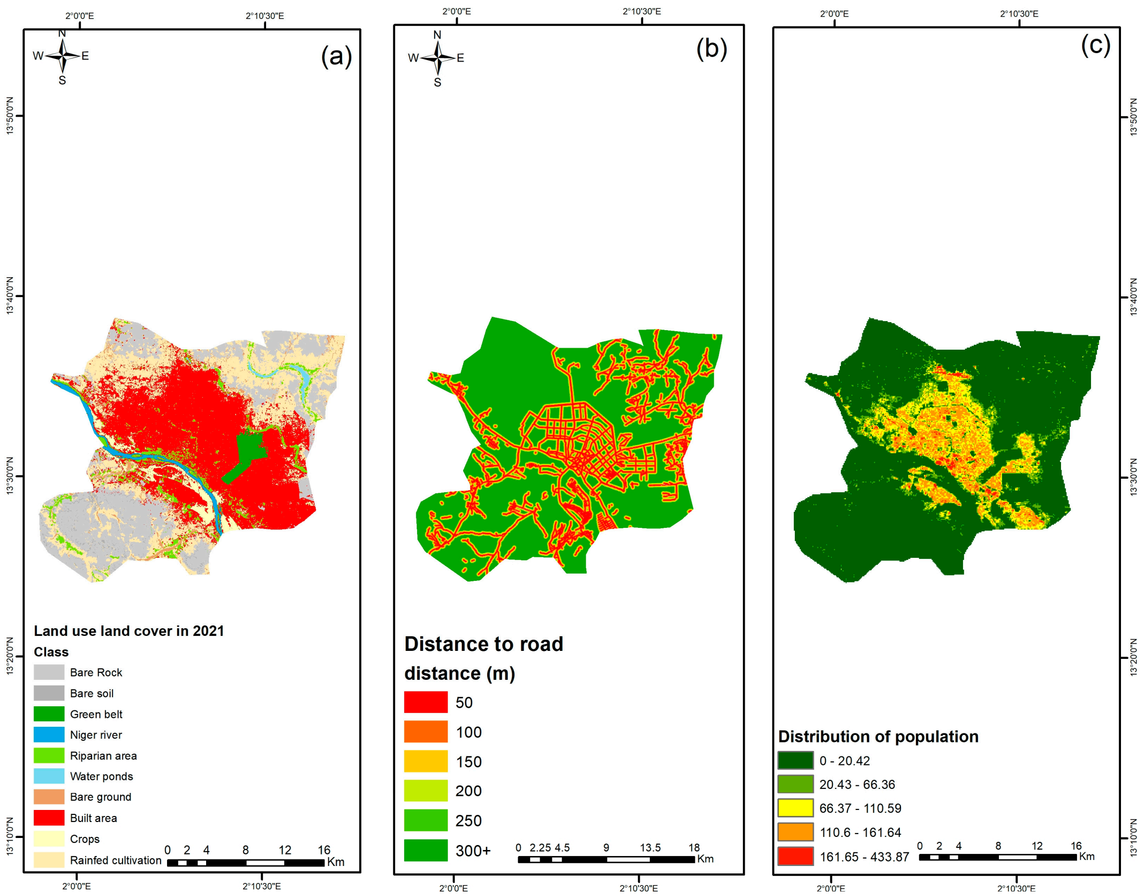

Figure 6. Thematic layer for flood vulnerability: (**a**) LULC in Niamey, (**b**) distance to road, (**c**) distribution of population in Niamey, Niger.

On the other hand, the spatial distribution of the population has made it possible to define the socio-economic aspect by distinguishing areas of high population concentration where pressure on natural resources and infrastructure is more intense. The distribution map is produced using the data from the Global Human Settlement that are available for open access (https://human-settlement.emergency.copernicus.eu/download.php?ds=pop (accessed on 15 October 2024)) and found that it ranges from 0 to 433.9 for Niamey and from 0 to 410.9 for Lokoja, as depicted in Figures 6b and 7b. After that, the map layers were reclassified (very low, low, medium, high, and very high) with the percentage of the total city area, as illustrated in Appendix A (Tables A3 and A4 respectively for Niamey and Lokoja). There is a direct relationship between high population density and extreme vulnerability [45]. Therefore, areas with very high concentrations were classified as very vulnerable in this study. The distribution of distances to roads in the study area was mapped by buffering around the main roads. Figures 6b and 7b show the different classes of proximity to roads. Five classes were established based on the accessibility of the road network. These classes are as follows: very low, low, medium, high, and very high. In this way, the study can support municipal planners identify the area's most likely to be vulnerable to risk, enabling a more effective allocation of resources for crisis prevention and management. By classifying levels of vulnerability, it provides a valuable tool for prioritizing interventions, reinforcing infrastructure in high-risk areas and devising adaptation strategies tailored to local circumstances. It also helps communities to become more resilient in the face of extreme events, by including risk reduction measures in urban planning schemes. The weighting coefficients and eigenvectors were calculated for all the vulnerability criteria; Table 5 provides the values. The weights for LULC, population distribution, and the distance to the road are 61%, 27%, and 12%, respectively. Table 6 gives consistency ratio, and consistency index of the vulnerability map, given that CR is approximately 6%.

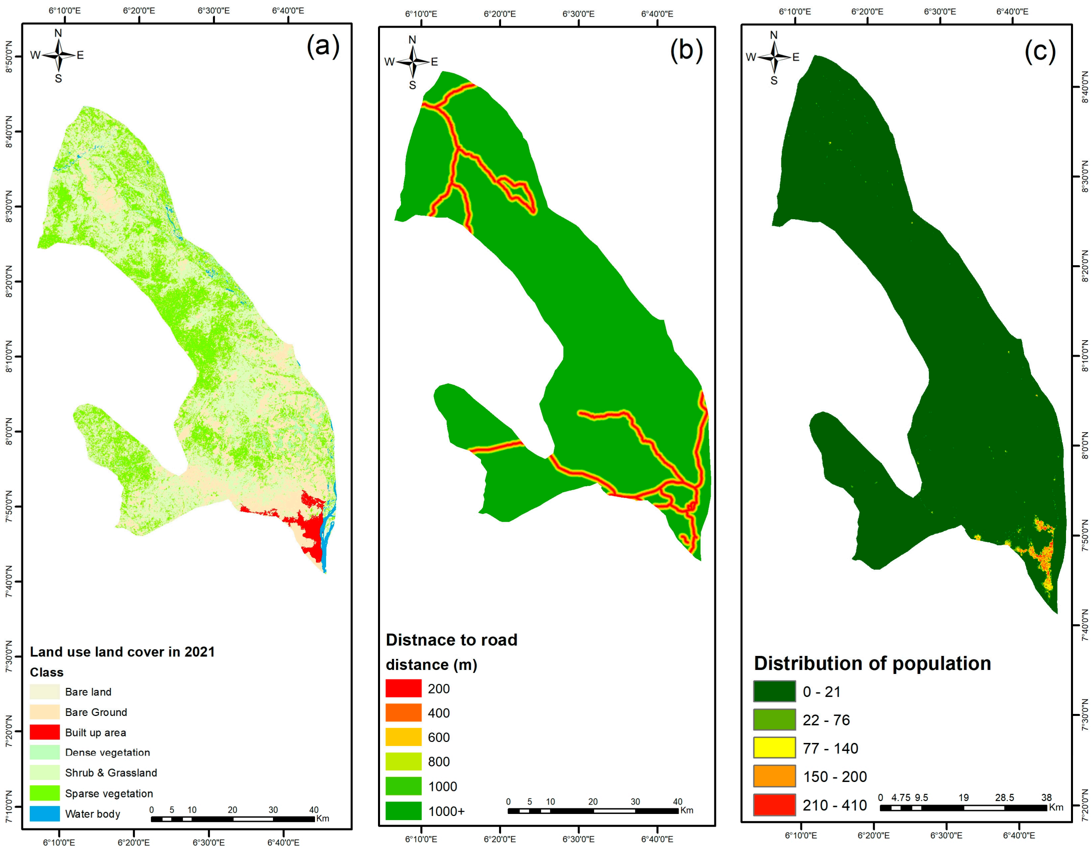

Figure 7. Thematic layer for flood vulnerability: (**a**) LULC for Lokoja, (**b**) distance to road, (**c**) distribution of population in Lokoja, Nigeria.

Table 5. Pairwise comparison matrix for flood vulnerability.

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

Table 6. Consistency check for flood vulnerability.

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

Based on the findings, it was demonstrated that most of Niamey's surface area falls within moderate (25%) and high vulnerability levels (9%), with 9% of the area classified as very highly vulnerable. On the other hand Lokoja, very low (66%) and low (29%) vulnerability levels dominate, while highly vulnerable areas account for 2%, and very highly vulnerable areas represent only 1% of the surface.

4.3. Flood Susceptibility

The consistency ratio demonstrated satisfactory coherence between the layers, with a value of 0.08 (below 0.10), as indicated in Table 7. 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 (Figures 8 and 9). In this analysis, the highest weight was assigned to elevation (29%), followed by slope (24%), topographic wetness index (16%), drainage density (9%), distance to the river (9%), precipitation (5%), NDWI (4%), NDVI (2%), and soil type (2%)

Table 7. Main results of consistency check for flood susceptibility.

Lambda Max	N	Consistency Index (CI)	Consistency Ratio (CR)
9.97	9	0.12	0.08

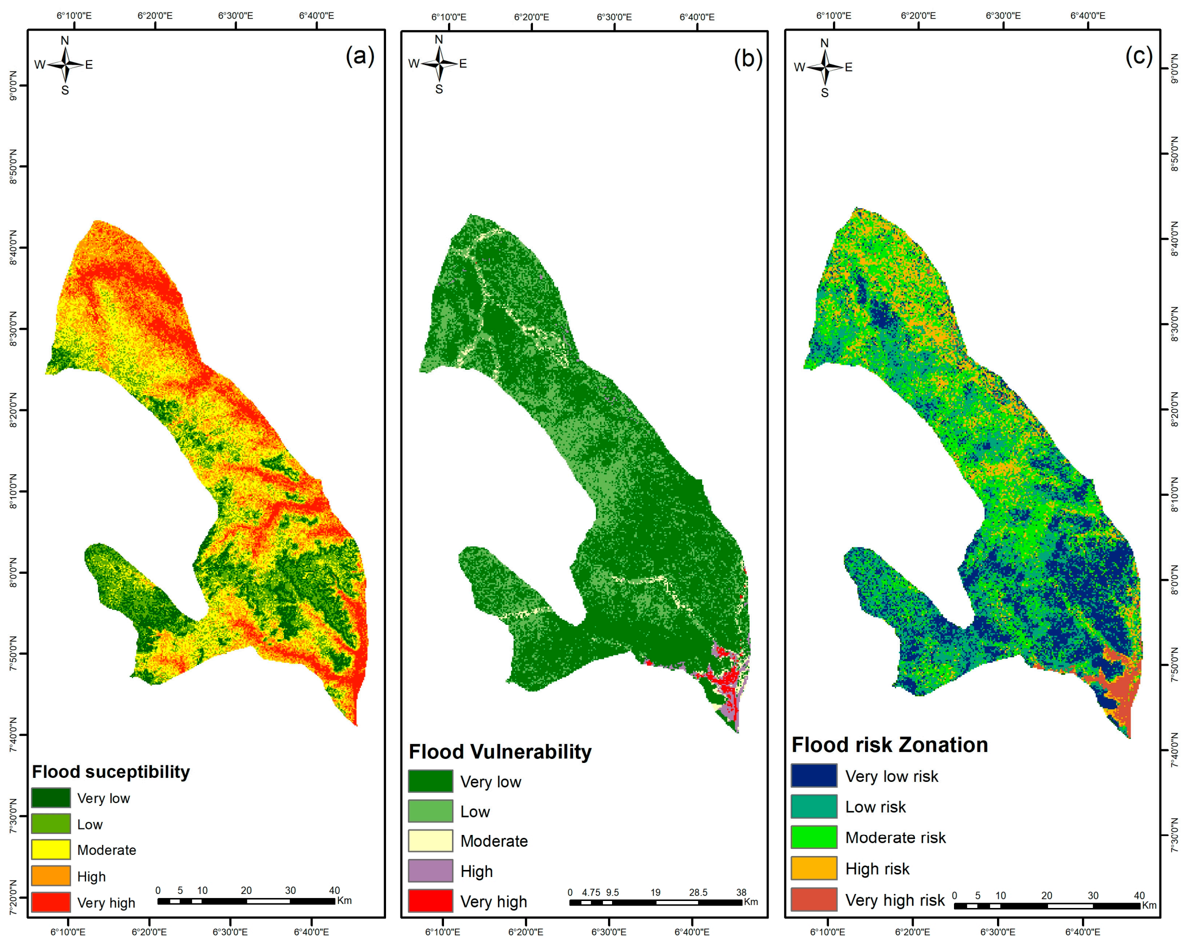

Figure 8. Areas of flood susceptibility (**a**), flood vulnerability (**b**), and flood risk zonation (**c**) of Lokoja (Nigeria).

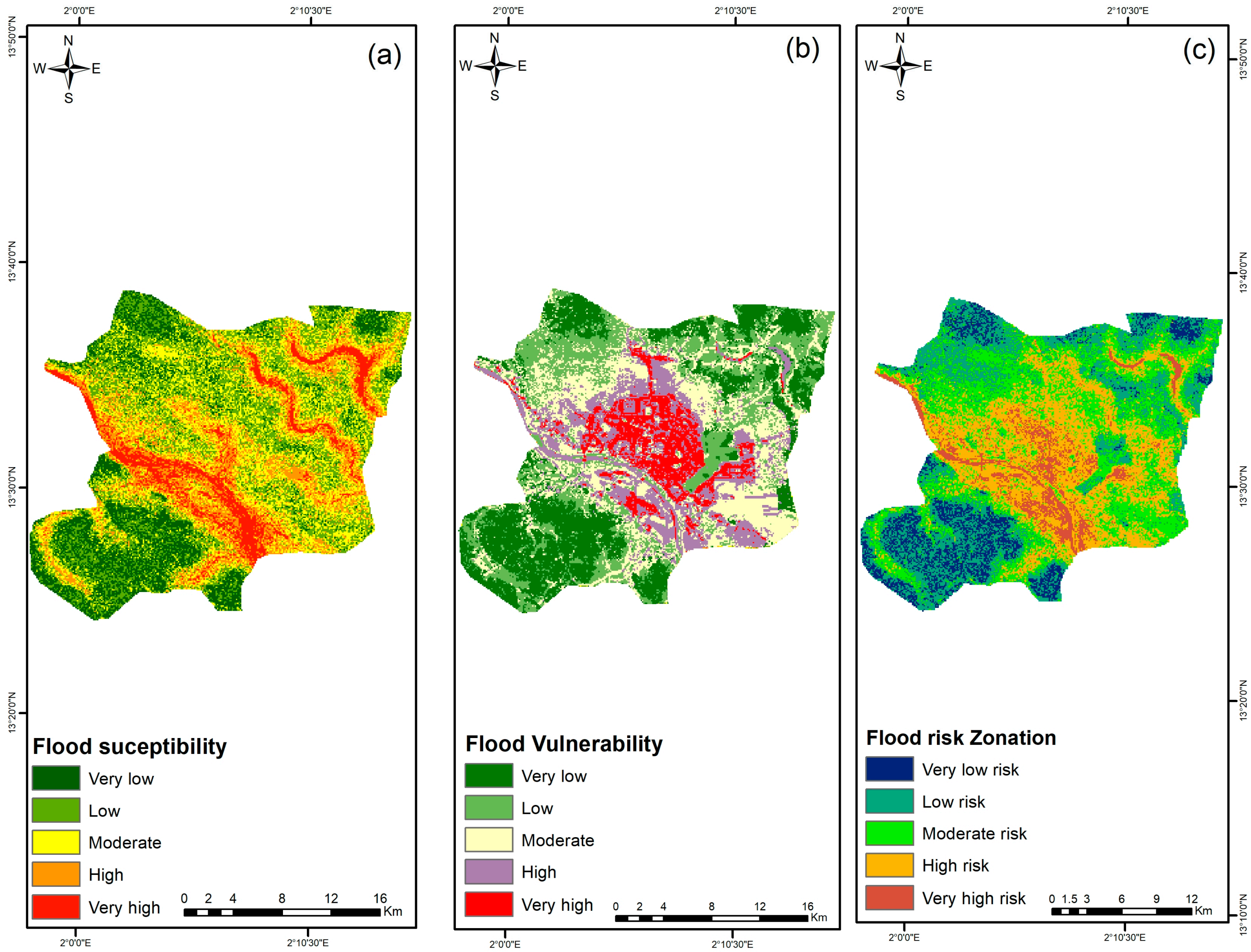

Figure 9. Areas of flood susceptibility (**a**), flood vulnerability (**b**), and flood risk zonation (**c**) of Niamey (Niger).

As a result of computation, the transboundary area is characterized by the hydrologic evolution of the Niger river. These floods generally occur along the riverine areas. The "high" and "very high" flood susceptibility classes are predominantly observed in these areas. 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 susceptibility distribution for Niamey is as follows: very low (17%), low (30%), moderate (30%), high (17%), and very high (9%). For Lokoja, the percentages are as follows: very low (11%), low (21%), moderate (27%), high (25%), and very high (16%). The largest part of the area experiences significant pluvial and fluvial flooding, particularly due to intense heavy seasonal rainfall and overflowing rivers, which are exacerbated by the hydrological dynamics of the River Niger Basin. These characteristics suggest that flood mitigation efforts in Niamey and Lokoja should prioritize high-risk areas along riverbanks and areas with low infiltration capacity in order to reduce the impacts of seasonal flooding that threaten infrastructure, agriculture, and communities.

4.4. Flood Risk Map

The primary outcome of this study is the development of a flood risk zoning map, created by combining susceptibility maps with land use data. The resulting risk map is classified into five zones, very low, low, moderate, high, and very high, as shown in the figure. 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 (Table 8).

Table 8. Spatial distribution. Areas of flood susceptibility, flood vulnerability, and flood risk zonation for Niamey and Lokoja metropolitans.

Study Zone	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

The very low, low, and moderate flood risk classes represent 10%, 26%, and 31% of the area in Niamey, and 23%, 33%, and 28% 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 characterized by low elevation, gentle slopes, and high drainage density. The figure illustrates the blocks most affected by high flood risk.

4.5. Implications of Findings for Sustainable Environmental Management

The results of this study highlight significant differences in flood susceptibility, vulnerability, and risk between Niamey and Lokoja due to their distinct topographic, hydrological, and socio-economic characteristics. Using GIS combined with the MCE method and AHP, a selection of nine specific mapping parameters was made for the assessment of flood susceptibility and three for the assessment of flood risk vulnerability in Niamey and Lokoja. This choice is based on the selection of criteria that directly influence the conditions of vulnerability and susceptibility to flooding in these regions [18,26,37]. However, the weighting obtained through AHP may be subject to a degree of uncertainty, influenced by the judgements of the experts involved in the study. To assess the consistency of these judgements, a Consistency Ratio (CR) was calculated, resulting in 0.08 for flood susceptibility and 0.06 (Table 7) and for vulnerability (Table 6), indicating a reasonable level of reliability. Thus, the weights assigned are considered acceptable for flood risk analysis in these areas. The elevation factor was given a weighting of 29% in the AHP analysis due to its decisive role in the areas at risk. Niamey, with its flatter topography and moderate slopes, favors the accumulation of runoff water, while the steep slopes in Lokoja amplify water runoff, increasing the risk of pluvial flooding. The analyses show that Niamey and Lokoja have similar distributions in terms of susceptibility classes, but with notable variations, particularly in the spatial distribution of risks. Niamey is characterized by a high proportion of low-susceptibility areas (47% combined for the very low and low classes), while Lokoja has a higher proportion of high-risk areas (41% combined for the high and very high classes). These differences can be explained by the generally higher altitude of Lokoja, but with marked variations due to the local topography. In terms of vulnerability, Niamey has a more even distribution of vulnerability levels, with moderate to high classes dominating (43% of the total area). In contrast, Lokoja shows a predominance of very low to low classes (95% combined), suggesting greater structural resilience in most areas, probably due to a lower population density in high-risk areas. Socio-economic factors, notably population distribution and LULC, also played a major role, with a combined weight of 88% in the vulnerability analysis. In Niamey, densely populated areas, often combined with inadequate infrastructure, increase vulnerability to the impacts of flooding. In addition, the analysis of distances to roads shows that some vulnerable areas also suffer from limited access, which complicates relief efforts. The combination of susceptibility and vulnerability maps has produced flood risk zoning maps. The results show that areas of high- and very high-risk are concentrated mainly along river corridors in both regions, but with differences in their spatial extent. Niamey has 32% of its total surface area in these categories, compared with only 15% for Lokoja. These results are consistent with the hydrological and topographical characteristics of the two regions, where alluvial plains and low altitudes are the most vulnerable. The risk class analysis shows that Lokoja has a higher proportion of very low and low-risk areas, largely due to better stormwater management and higher altitudes. In contrast, very high-risk areas in Niamey are exacerbated by poor infrastructure, low vegetation cover, and lower drainage density, contributing to inefficient surface water management. These results demonstrate the importance of an integrated approach to flood management, combining land use strategies, mitigation measures based on green infrastructure, and planning adapted to local dynamics. In Niamey, priorities should include improving drainage infrastructure, managing heavily populated areas, and reforestation to reduce runoff. In Lokoja, although the areas at risk are less extensive, it is crucial to strengthen protection measures in low-lying and riparian areas. These results also illustrate the need for cross-border cooperation to manage the impacts of flooding in the River Niger Basin, particularly with regard to extreme events linked to climate change. The risk maps generated are an essential tool for urban planning and resource allocation, enabling the social and economic impacts of recurrent flooding to be mitigated.

The lack of high-resolution capabilities had a significant influence on the production of the maps in this study. In addition, very low-resolution Digital Elevation Model (DEM) data were used to extract the various factors influencing susceptibility to flooding. One of the limitations of our study is that the resolution and accuracy of the DEM data can have an impact on the accuracy of the derived terrain data, such as elevation, slope, and drainage density, as well as that derived from it. Another major problem in determining susceptibility using the multi-criteria decision analysis (MCDA) approach is the selection of flood conditioning factors. In this study, nine factors were selected for flood susceptibility, which is similar to other studies conducted by Gaurav et al. [45] and Mokhtari et al. [26], as well as Nsangou et al. [46] and Vilasan et al. [37], with the latter two using ten factors. In addition, Belazreg et al. [17] used six factors. This variability in the number of criteria demonstrates the importance of selecting those that best correspond to the geomorphological and geological conditions of the study region while ensuring that no single factor dominates the overall weighting. In addition, one of the main drawbacks of this methodology is that it relies heavily on expert opinion to assign weight to the various criteria. This reliance can introduce bias, as experts may have different views on the importance of certain factors. Furthermore, while this approach is suitable for regional assessments, its transposition to a global scale may present difficulties. Despite these limitations, the weaknesses identified in our analysis are mitigated by the use of a consistency ratio test for judgements. According to [32], the consistency ratio threshold must be less than 10% to guarantee the consistency of judgements. In this study, the consistency ratio was 8% and 6%, respectively, for flood susceptibility and vulnerability susceptibility, which indicates that our judgements can be considered consistent.

5. Conclusions

This comparative study of Niamey and Lokoja employed an integrated multi-criteria approach, combining the AHP, GIS, and diverse environmental indicators to map and analyze flood-prone areas. By superimposing a flood susceptibility map, derived from factors such as elevation, slope, drainage density, and proximity to rivers, with a vulnerability map based on land use, the study revealed distinct flood risk patterns in each city.

The analysis successfully identified areas prone to flooding and facilitated an assessment of their potential consequences. Niamey exhibited a greater overall extent of flood-prone areas, while Lokoja presented a higher concentration of high-risk zones, particularly near watercourses. This disparity underscores the influence of topographical factors in shaping flood risk, with low-lying areas in Niamey and proximity to the confluence of major rivers in Lokoja contributing significantly to vulnerability.

Flooding in both cities is driven by a complex interplay of factors, including topography, rainfall intensity and frequency, and the adequacy of drainage infrastructure. Furthermore, land use changes, such as urban expansion and deforestation, coupled with the impacts of climate change on rainfall patterns, exacerbate flood risk by altering water absorption and runoff dynamics.

The spatial distribution of flood risk also differed significantly between the two cities. Niamey displayed a concentration of low-risk areas in its northern and southern fringes, with moderate to high vulnerability prevalent in the central region. Conversely, Lokoja exhibited a more widespread moderate risk, punctuated by pockets of very low-risk in the north and a concentration of high-risk in the south, particularly in the city center.

These findings underscore the necessity of city-specific adaptation measures for effective flood risk management. In Niamey, prioritizing stormwater management in moderate risk areas is crucial, while in Lokoja, the focus should be on mitigating flood risk in low-lying areas with high drainage density. Ultimately, this study emphasizes the critical importance of proactive and contextually appropriate urban and environmental planning, incorporating nature-based solutions, to effectively mitigate flood risk and enhance resilience in these rapidly urbanising West African cities.

Based on these findings, the study underscores the need for localized and collaborative flood risk management strategies. Integrating flood risk zoning into urban planning is vital to prevent further development in high-risk areas, while regional cooperation between Niger and Nigeria is essential for addressing shared risks in the Niger River Basin. Nature-based solutions, such as reforestation, wetland restoration, and green infrastructure, should be piloted in both cities to reduce runoff and enhance drainage capacity. Stakeholder engagement, particularly involving local communities, is critical for ensuring the effectiveness of flood mitigation measures. Public awareness campaigns can improve preparedness and response to flood events, while higher-resolution datasets and real-time monitoring systems are necessary for enhancing the accuracy of future assessments. Lastly, integrating flood risk management into broader climate change adaptation plans will ensure long-term resilience to the increasing frequency and intensity of flooding events in the region.

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Data Availability Statement: The original contributions presented in the study are included in in the Appendix A. Additionally, some data are open access and can be made available upon receipt of an official request to, a corresponding author. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Selected Criteria and Associated Weighting of Each Factor Used in Developing Flood Susceptibility Map in Niamey.

Factor	AHP Weight for Each Factor	Reclass Class	Flood Susceptibility Level	Area in km^2	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 High	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	High	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 A2. 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 km^2	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 A3. 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 km^2	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
TP	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 A4. 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 km^2	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
TP	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

References

1. Farid, M.; Sihombing, Y.I.; Kuntoro, A.A.; Adityawan, M.B.; Syuhada, M.M.; Januriyadi, N.F.; Moe, I.R.; Nurhakim, A. Development of flood hazard index under climate change scenarios in Java Island. *Prog. Disaster Sci.* **2023**, *20*, 100302. [CrossRef]
2. de Corcuera, L.N.; del Mar Barbero-Barrera, M.; Hidalgo, A.C.; Martínez, J.R. Assessment of the adequacy of mobile applications for disaster reduction. *Environ. Dev. Sustain.* **2022**, *24*, 6197–6223. [CrossRef]
3. United Nations OCHA. *Overview of Flooding in West and Central Africa in 2021*; United Nations OCHA: New York, NY, USA, 2022.
4. IPCC. *Changements Climatiques 2007 R a pp ort de s y n t h è se*; IPCC: Geneva, Switzerland, 2007.
5. Tarchiani, V.; Tiepolo, M. *Risque et Adaptation Climatique dans la Région Tillabéri, Niger*; L'Harmattan: Paris, France, 2016.
6. Fiorillo, E.; Crisci, A.; Issa, H.; Maracchi, G.; Morabito, M.; Tarchiani, V. Recent changes of floods and related impacts in Niger based on the ANADIA Niger flood database. *Climate* **2018**, *6*, 59. [CrossRef]
7. Amogu, O.; Descroix, L.; Yéro, K.S.; Le Breton, E.; Mamadou, I.; Ali, A.; Vischel, T.; Bader, J.C.; Moussa, I.B.; Gautier, E.; et al. Increasing river flows in the Sahel? *Water* **2010**, *2*, 170–199. [CrossRef]

8. Nka, B.N.; Oudin, L.; Karambiri, H.; Paturel, J.E.; Ribstein, P. Trends in floods in West Africa: Analysis based on 11 catchments in the region. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 4707–4719. [CrossRef]
9. Aich, V.; Koné, B.; Hattermann, F.F.; Paton, E.N. Time Series Analysis of Floods across the Niger River Basin. *Water* **2016**, *8*, 165. [CrossRef]
10. Mahe, G.; Olivry, J.C.; Servat, E. Sensibilité des cours d'eau ouest-africains aux changements climatiques et environnementaux: Extrêmes et paradoxes. *IAHS-AISH Publ.* **2005**, *296*, 169–177.
11. Leblanc, M.J.; Favreau, G.; Massuel, S.; Tweed, S.O.; Loireau, M.; Cappelaere, B. Land clearance and hydrological change in the Sahel: SW Niger. *Glob. Planet. Chang.* **2008**, *61*, 135–150. [CrossRef]
12. Di Baldassarre, G.; Montanari, A. Uncertainty in river discharge observations: A quantitative analysis. *Hydrol. Earth Syst. Sci.* **2009**, *13*, 913–921. [CrossRef]
13. Tarchiani, V.; Fiorillo, E.; Issa, H.; Lawan, K.G.; Tiepolo, M.; Sitta, A.A.; Nieino, M.D.; Ibrahim, M.H.; Tankari, A.M.; Diallo, A.L. Les Inondations au Niger 1998–2020. 2021. [CrossRef]
14. Rincón, D.; Khan, U.T.; Armenakis, C. Flood risk mapping using GIS and multi-criteria analysis: A greater toronto area case study. *Geosciences* **2018**, *8*, 275. [CrossRef]
15. Cai, S.; Fan, J.; Yang, W. Flooding risk assessment and analysis based on gis and the tfn-ahp method: A case study of Chongqing, China. *Atmosphere* **2021**, *12*, 623. [CrossRef]
16. Choudhury, S.; Basak, A.; Biswas, S.; Das, J. *Flash Flood Susceptibility Mapping Using GIS-Based AHP Method*; Springer International Publishing: Cham, Switzerland, 2022; pp. 119–142.
17. Belazreg, N.E.H.; Hasbaia, M.; Şen, Z.; Ferhati, A. Flood risk mapping using multi-criteria analysis (MCA) through AHP method case of El-Ham wadi watershed of Hodna basin (Algeria). *Nat. Hazards* **2024**, *120*, 1023–1039. [CrossRef]
18. Mitra, R.; Saha, P.; Das, J. Assessment of the performance of GIS-based analytical hierarchical process (AHP) approach for flood modelling in Uttar Dinajpur district of West. *Geomat. Nat. Hazards Risk* **2022**, *13*, 2183–2226. [CrossRef]
19. Salamatou, A.I.; Abdoulaye, D.; Boubacar, M.M.; Soufianou, S.A.; Ali, M.; Mahamane, S. Dynamics of a third world city: Case of Niamey, Niger. *J. Geogr. Reg. Plan.* **2015**, *8*, 120–130. [CrossRef]
20. Descroix, L.; Genthon, P.; Amogu, O.; Rajot, J.L.; Sighomnou, D.; Vauclin, M. Change in Sahelian Rivers hydrograph: The case of recent red floods of the Niger River in the Niamey region. *Glob. Planet. Chang.* **2012**, *98–99*, 18–30. [CrossRef]
21. Ocha, U.N. 2013 Rainy Season Overview West and Central Africa Rainfall Patterns. 2013, pp. 1–7. Available online: https://reliefweb.int/sites/reliefweb.int/files/resources/Rains%20Report%202013%20FINAL%2011092013.pdf (accessed on 29 December 2024).
22. Massazza, G.; Bacci, M.; Descroix, L.; Ibrahim, M.H.; Fiorillo, E.; Katiellou, G.L.; Panthou, G.; Pezzoli, A.; Rosso, M.; Sauzedde, E.; et al. Recent changes in hydroclimatic patterns over medium Niger river basins at the origin of the 2020 flood in Niamey (Niger). *Water* **2021**, *13*, 1659. [CrossRef]
23. Ayuba, R.; Tijani, M.N. Hydrochemical characterization of groundwater in Lokoja, North-Central Nigeria. *Sustain. Water Resour. Manag.* **2021**, *7*, 61. [CrossRef]
24. Dahri, N.; Abida, H. Monte Carlo simulation-aided analytical hierarchy process (AHP) for flood susceptibility mapping in Gabes Basin (southeastern Tunisia). *Environ. Earth Sci.* **2017**, *76*, 302. [CrossRef]
25. Bansal, N.; Mukherjee, M.; Gairola, A. GIS-based multi-criteria decision analysis for mapping flood-prone areas in Dehradun city, India. *Arab. J. Geosci.* **2023**, *16*, 501. [CrossRef]
26. Mokhtari, E.; Engel, B. Flood risk assessment using analytical hierarchy process: A case study from the Cheliff-Ghrib watershed, Algeria. *J. Water Clim. Chang.* **2023**, *14*, 694–711. [CrossRef]
27. Islam, M.R.; Aziz, M.T.; Alauddin, M.; Kader, Z.; Islam, M.R. Site suitability assessment for solar power plants in Bangladesh: A GIS-based analytical hierarchy process (AHP) and multi-criteria decision analysis (MCDA) approach. *Renew. Energy* **2024**, *220*, 119595. [CrossRef]
28. Danumah, J.H.; Odai, S.N.; Saley, B.M.; Szarzynski, J.; Thiel, M.; Kwaku, A.; Kouame, F.K.; Akpa, L.Y. Flood risk assessment and mapping in Abidjan district using multi-criteria analysis (AHP) model and geoinformation techniques, (Cote d'Ivoire). *Geoenviron. Disasters* **2016**, *3*, 10. [CrossRef]
29. Ogato, G.S.; Bantider, A.; Abebe, K.; Geneletti, D. Geographic information system (GIS)-Based multicriteria analysis of flooding hazard and risk in Ambo Town and its watershed, West shoa zone, oromia regional State, Ethiopia. *J. Hydrol. Reg. Stud.* **2020**, *27*, 100659. [CrossRef]
30. Vignesh, K.S.; Anandakumar, I.; Ranjan, R.; Borah, D. Flood vulnerability assessment using an integrated approach of multi-criteria decision-making model and geospatial techniques. *Model. Earth Syst. Environ.* **2021**, *7*, 767–781. [CrossRef]
31. Boultif, M.; Kheloufi, B.; Hachemi, A.; Mimeche, L. GIS-Based Multi-criteria Decision-Making Techniques and Analytical Hierarchical Process for Flash Flood Risk Assessment Due to a Possible Dam Break in Urban Arid Environment: Case Study of Biskra City, Southern Algeria. *J. Indian Soc. Remote Sens.* **2024**, *52*, 1085–1097. [CrossRef]
32. Saaty, T.L. How to make a decision: The Analytic Hierarchy Process. *Eur. J. Oper. Res.* **1990**, *48*, 9–26. [CrossRef]

33. Hussain, M.; Tayyab, M.; Zhang, J.; Shah, A.A.; Ullah, K.; Mehmood, U.; Al-Shaibah, B. Gis-based multi-criteria approach for flood vulnerability assessment and mapping in district Shangla: Khyber Pakhtunkhwa, Pakistan. *Sustainability* **2014**, *13*, 3126. [CrossRef]
34. Rojas-briceño, N.B.; Meza-mori, G.; Auquiñiv, E. Multicriteria Analysis in Apiculture: A Sustainable Tool for Northwest Peru. *Land* **2023**, *12*, 1900.
35. Barros, V.R.; Field, C.B.; Dokken, D.J.; Mastrandrea, M.D.; Mach, K.J.; Bilir, T.E.; Chatterjee, M.; Ebi, K.L.; Estrada, Y.O.; Genova, R.C.; et al. *Climate Change 2014 Impacts, Adaptation, and Vulnerability Part B: Regional Aspects: Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2014.
36. Rahmati, O.; Kalantari, Z.; Samadi, M.; Uuemaa, E.; Moghaddam, D.D.; Nalivan, O.A.; Destouni, G.; Tien Bui, D. GIS-based site selection for check dams in watersheds: Considering geomorphometric and topo-hydrological factors. *Sustainability* **2019**, *11*, 5639. [CrossRef]
37. Zhran, M.; Ghanem, K.; Tariq, A.; Alshehri, F.; Jin, S.; Das, J. Exploring a GIS—Based analytic hierarchy process for spatial flood risk assessment in Egypt: A case study of the Damietta branch. *Environ. Sci. Eur.* **2024**, *36*, 184. [CrossRef]
38. Ouma, Y.O.; Tateishi, R. Urban flood vulnerability and risk mapping using integrated multi-parametric AHP and GIS: Methodological overview and case study assessment. *Water* **2014**, *6*, 1515–1545. [CrossRef]
39. Samanta, S.; Pal, D.K.; Palsamanta, B. Flood susceptibility analysis through remote sensing, GIS and frequency ratio model. *Appl. Water Sci.* **2018**, *8*, 66. [CrossRef]
40. Antzoulatos, G.; Kouloglou, I.O.; Bakratsas, M.; Moumtzidou, A.; Gialampoukidis, I.; Karakostas, A.; Lombardo, F.; Fiorin, R.; Norbiato, D.; Ferri, M.; et al. Flood Hazard and Risk Mapping by Applying an Explainable Machine Learning Framework Using Satellite Imagery and GIS Data. *Sustainability* **2022**, *14*, 3251. [CrossRef]
41. Ali, S.A.; Parvin, F.; Pham, Q.B.; Vojtek, M.; Vojteková, J.; Costache, R.; Linh, N.T.T.; Nguyen, H.Q.; Ahmad, A.; Ghorbani, M.A. GIS-based comparative assessment of flood susceptibility mapping using hybrid multi-criteria decision-making approach, naïve Bayes tree, bivariate statistics and logistic regression: A case of Topl'a basin, Slovakia. *Ecol. Indic.* **2020**, *117*, 106620. [CrossRef]
42. Penki, R.; Basina, S.S.; Tanniru, S.R. Application of geographical information system-based analytical hierarchy process modeling for flood susceptibility mapping of Krishna District in Andhra Pradesh. *Environ. Sci. Pollut. Res.* **2023**, *30*, 99062–99075. [CrossRef]
43. Bera, R.; Maiti, R. Multi hazards risk assessment of Indian Sundarbans using GIS based Analytic Hierarchy Process (AHP). *Reg. Stud. Mar. Sci.* **2021**, *44*, 101766. [CrossRef]
44. Radwan, F.; Alazba, A.A.; Mossad, A. Flood risk assessment and mapping using AHP in arid and semiarid regions. *Acta Geophys.* **2019**, *67*, 215–229. [CrossRef]
45. Parajuli, G.; Neupane, S.; Kunwar, S.; Adhikari, R.; Acharya, T.D. GIS-Based Evacuation Route Planning in Flood-Susceptible Area of Siraha Municipality, Nepal. *ISPRS Int. J. Geo-Inf.* **2023**, *12*, 286. [CrossRef]
46. Nsangou, D.; Kpoumié, A.; Mfonka., Z.; Ngouh, A.N.; Fossi, D.H.; Mbele H, J.C.; Mouncherou, O.F.; Vandervaere, J.P.; Ndam, N.J.R. Urban flood susceptibility modelling using AHP and GIS approach: Case of the Mfoundi watershed at Yaoundé in the South-Cameroon plateau. *Sci. African* **2022**, *15*, e01043. [CrossRef]