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Flood Risk Assessment and Mapping in the Hadejia River Basin, Nigeria, Using Hydro-Geomorphic Approach and Multi-Criterion Decision-Making Method

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Abstract: Flood risk management is crucial for climate change resilience. The Hadejia River basin is known for severe and frequent floods, which have destroyed houses and farmlands and claimed many lives. This study developed a GIS-based flood risk and vulnerability mapping assessment using the Analytical Hierarchical Process (AHP) to outline scenarios that reduce risk and vulnerability associated with floods in the Hadejia River basin. The risk mapping of the basin integrated seven hydro-geomorphological indicators influencing extreme events (elevation, mean annual rainfall, slope, distance from rivers, soil type, and drainage density) and six socio-economic vulnerability indicators (population density, female population density, literacy rate, land use, employment rate, and road network) using a multi-criterion analysis. The average annual rainfall data of 36 years (1982–2018) were used for flood plain mapping in this study. Combining the flood hazard and socio-economic vulnerability indices of the basin revealed high-to-very high flood risk in the downstream and central upstream portions of the basin, which cover about 43.4% of the basin area. The local areas of Auyo, Guri, Hadejia, Ringim, Kafin Hausa, and Jahun were identified as zones at a very high flood risk. The study also revealed that flood hazard and vulnerability indicators have different influences on flood risk. The validated results resonate with the records of previous flood distribution studies of the basin. This research study is significantly important for developing strategic measures and policy revision through which the government and relief agencies may reduce the negative impact of floods in the Hadejia River basin.

Keywords: flood risk; flood hazard; socio-economic vulnerability; multi-criterion analysis; Analytical Hierarchical Process (AHP)

1. Introduction

Floods are amongst the most catastrophic, frequent, and widespread natural disasters worldwide, causing severe economic and environmental damage with devastating effects on livelihoods [1–11]. About 47% of disasters related to weather are the result of floods [12]. About 34% of worldwide natural disasters from 1960 to 2014 were floods that caused financial losses for over 2.5 billion USD per annum and the death of 1254 persons per year [11,12]. Floods affected 2.8 billion people and killed 540,000 people between 1980 and 2009 across the world [13–15]. According to the IPCC [16], in the future, the African Continent will experience a drastic increase in extreme hydrological events, including floods. Studies showed that West Africa recently experienced precipitation above average during the period of June to September when compared with the past 35 years [17]. In 2013, the Niger River floods in Benin destroyed more than 21,500 ha of crops and about 9200 houses [18]. Furthermore, 20% of the people living in the Mono River basin were displaced by heavy rain, which caused severe floods in the downstream part of the basin in 2008 [19]. Adegboyega et al. [20] and Alfa et al. [5] showed that flooding accounts for the highest losses resulting from extreme hydrological events in Nigeria. In 2018, floods affected more than 1.9 million persons across 12 states in Nigeria, with the displacement of more than 500,000 from their households [21]. The main causes of flooding are related to the inability of river channels to accommodate flood waters beyond carrying capacity [5]. This is the case in most part of the Hadejia–Jama'are river system, where the failure of the river to safely accommodate and discharge its runoff during peak rainy season resulted in the flooding of many hectares of agricultural land and the submergence of several communities along the river system over the last decades [22].

Human settlements are progressively becoming exposed to the risk of disasters. Sustainable development goal (SDG) 11 calls for focus on making ''… cities and human settlements inclusive, safe, resilient and sustainable'' [23]. It is, therefore, imperative to assess and provide management strategies for disasters. According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change, there is a predicted increase of 20% is flooding in West Africa over the next decades relative to the previous decades due to climate change, which may worsen and become severe by 2050 [24].

A Geographic Information System (GIS) is an important tool for mapping flood risk [25–34]. Behazin et al. [18] and Ikirri et al. [34] argued that the integration of remote sensing and GIS techniques coupled with the Analytical Hierarchical Process (AHP) are the best techniques for flood risk and vulnerability assessment, especially in areas with sparse or outdated data. This technique was adopted here for flood risk mapping and vulnerability assessment in the Hadejia River watershed due to limited data. There is no unique way of choosing the criteria used for developing a flood hazard layer [35]. However, several studies used various criteria that contribute to flood hazard, such as slope, land use, distance from streams, distance from drainage line, rainfall intensity, elevation, curvature, the topographic wetness index (TWI), lithological units, and soil [3,7,24,28]. Stefanidis et al. [36] employed a GIS and freely available data obtained from OpenStreetMap to analyse flood extent zones in Greece. Another study by Ikirri et al. [34] utilized a GIS and the AHP to analyse flood plain zones in the Taguenit Wadi watershed, Lakhssas, Morocco, by combining seven parameters influencing extreme phenomena. Moreover, Yi [37] combined FEMA flood maps and the USGS National structure database and assessed the exposure of Critical Infrastructures in the United States using a GIS-based approach.

Several attempts were made by different researchers to analyse floods in the Hadejia River basin, including [20,29,30]. Flood risk assessment in some parts was completed by Ilyasu [22], who used questionnaires to assess the flood impacts on some selected communities in the basin. Floods were simulated using HEC-RAS along some sections of the river in 2013 by Yahaya et al. [38]. The authors reported on the construction of levees in the overflown section to avert the consequence of flooding in the studied section. However, the research study only considered a section of the river without simulating the whole river due to the lack of hydrological data. This paper built on previous work, applying an approach for analysing flood risk and vulnerability using multi-criterion evaluation techniques coupled with a GIS and the AHP to evaluate strategies to manage the risk and vulnerability associated with flooding in the Hadejia River basin. This study aimed to develop a GIS-based framework for flood risk and vulnerability mapping and assessment in the Hadejia River basin. The approach used easily accessible data and less tedious GIS analyses for flood risk and vulnerability assessment. The findings of the research study provide an insight into how high-flood-risk and vulnerability zones can be identified for timely flood risk reduction.

2. Material and Methods

2.1. Study Area

The Hadejia River basin is in the semi-arid northern part of Nigeria (Figure 1). The Hadejia River source is from the Kano highlands, while the Jama'are river system has its source in the Jos plateau. Among the major dams situated in the basin are the Tiga, Watari, and Challawa Gorge dams, while the Kafin Zaki dam has only been proposed [39]. The Hadejia River basin has an area of 30,569 Km^2 and is located between the latitudes of 11°32′08.4″ N and 12°26′24.8″ N and the longitudes 8°07′50.0″ E and 10°01′50.9″ E. It is situated in the semi-arid north-western part of the Federal Republic of Nigeria [40].

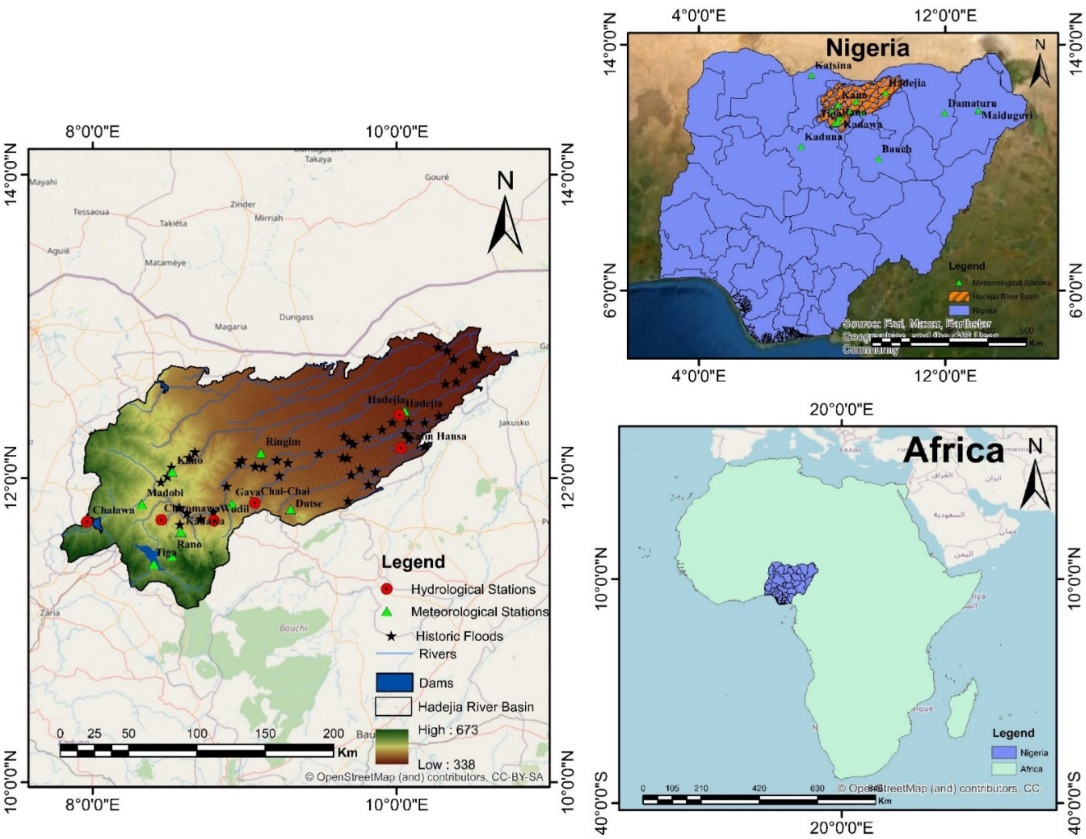

Figure 1. Location map of the study area.

The hydrology of the study area is dendritic in nature [41]. The observed mean annual flow and the peak flow in the basin are 1396 m^3/s to 43 m^3/s and 597 m^3/s to 38 m^3/s, in the wet season and dry season, respectively [40]. The basin includes the Tiga, Challawa Gorge, and Watari dams [42]. Other notable water resource management and irrigation projects in the basin are Kano River Irrigation Project (KRIP) and Hadejia Valley Irrigation Project (HVIP) [43–45].

The climate system in the basin is regulated by two air masses, the south-west (SW) and north-east (NE) trade winds [46]. The temperature of the basin rises to about 40 °C between March and April and 12 °C between December and January [47]. Rainfall in the area is known to vary spatially and temporally with the mean annual rainfall in the north-east, midstream, and the extreme south of the basin, and it has values of about 600 mm, 800 mm, and 1000 mm, respectively [47].

The prominent vegetation found in the study area is savannah vegetation, dominated by grasses and shrubs with scattered tree species [48]. The area has two distinct types of savanna vegetation of Sudan Savanna and Sahel Savanna. The major economic activity in the basin is agriculture [49], with about 80% of its surface area being arable land, supporting about 85% of the total population [34,41].

2.2. Data

Data are fundamental and essential for GIS analyses. The data in this research study included those derived from remote sensing, meteorological stations, population commission, and field surveys and focus group discussions. Thirty-six years of daily rainfall data from 7 stations were obtained from Nigerian Meteorological Agency (NiMet) and Hadejia–Jama'are River Basin Development Authority in Nigeria (HJRBDA). The population census data of 2006 and 2011 were obtained from the official website of National Population Commission (NPC) and National Bureau Statistics (NBS) at the LGA level (https://www.nationalpopulation.gov.ng and https://www.nigerianstat.gov.ng accessed on 25 October 2022) , respectively. Other relevant data, such as the public perception of flood disasters, factors responsible for floods, causes of floods in the study area, and history of previous flood events, were obtained through focus group discussions with the stakeholders, policy makers, and local residents, as well as reconnaissance surveys.

The soil data of the basin were acquired from the Food and Agriculture Organization (FAO) website (https://www.fao.org/geonetwork/srv/en/metadata.show?id=14116 accessed on 25 October 2022), while Landsat 8 OLI (Operational Land Imager) and SRTM DEM (30 × 30) data were obtained from United States Geological Survey (USGS) (https://earthexplorer.usgs.gov accessed on 25 October 2022). The GPS coordinates of locations that previously suffered floods were obtained using GPS equipment.

2.3. Development of Indicators of Flood Risk

According to Ntajal et al. [19], the most common procedures for developing indicators for flood risk assessment using a GIS are those that include inductive or deductive procedures. The deductive procedure was adopted and used to develop indicators. The study considered flood risk as the product and function of flood hazard and socio-economic vulnerability [7,28]. The methodological framework for the development of flood risk maps and their assessment is shown in Figure 2.

2.3.1. Selection of Flood Hazard Indicators

This study included hydro-geomorphic factors, as used by [7,8,50], such as elevation, mean annual rainfall, slope, distance from rivers, soil, flow accumulation, and drainage density, as they influence the flood hazard extent. Soil was used as the geological layer [50], while flow accumulation and drainage density were included among the hydro-geomorphic factors. These indicators were carefully selected based on the physiographic nature of the studied basin. The basin has moderately high rainfall, clay soil type, and steep slopes, among others, which enhances the likelihood of the occurrence of floods. Rainfall and land use were included in few previous studies of mapping flood hazard using multi-criterion analyses [27,50], but given the importance of short, high-intensity rain in Nigeria, the mean annual rainfall was included among the criteria of flood hazard in the study.

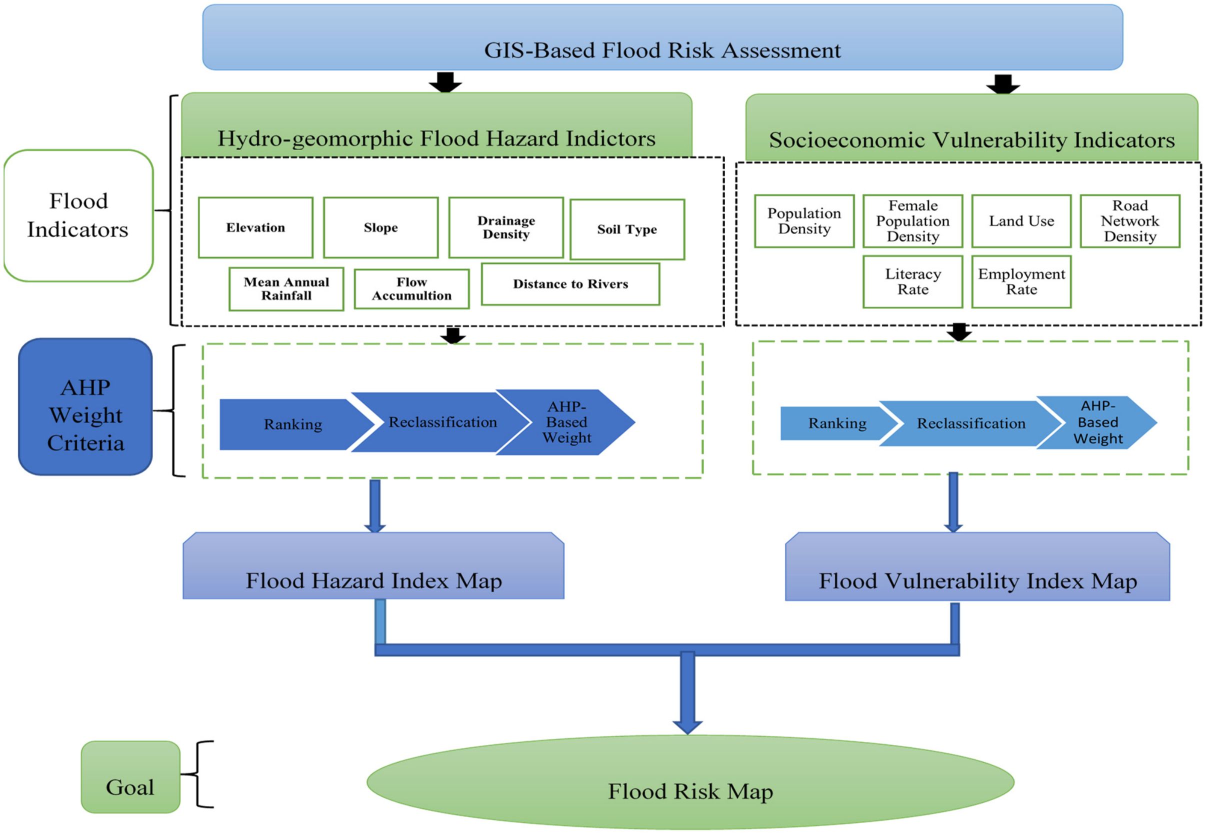

Figure 2. Methodological flow chart of the study.

2.3.2. Selection of Flood Vulnerability Indicators

Generally, flood vulnerability studies are based on the extent of potential harm inflicted under various physical and socio-economic susceptibility and capacity measures in a particular area in a particular time period [51]. This study adopted and modified the socio-economic vulnerability indicators selected by [7,52,53] to suit the conditions of the study area. The socio-economic indicators selected in this study were population density, female population density, literacy rate, land use, employment rate, and road network. These were selected because the study region is known to be among the most populous parts of Nigeria, with more females than males and low literacy and employment rates.

2.4. Normalization of Flood Hazard and Vulnerability Indicators

The normalization of the indicators was completed using the method of UNDP's Human Development Index [19,54]. The functional relationships of the indicator values with flood hazard and vulnerability were identified. Equations (1) and (2) were used for the positive and negative functional relationships with flood hazard and vulnerability, respectively [54].

$$Y = 1 + 9 \times \frac{(X - X_{\min})}{(X_{\max} - X_{\min})} \quad (1)$$

$$Y = 1 + 9 \times \frac{(X_{\max} - X)}{(X_{\max} - X_{\min})} \quad (2)$$

where X represent the raw data; $X_{\max}$ is the maximum value of the data; $X_{\min}$ is the minimum value of the data; and Y is the normalized value.

The indicators were normalized to values of 1 to 10 based on the functional relationships of the variables with the flood hazard and vulnerability components.

2.5. Assigning Weights Using Analytical Hierarchical Process

The Analytical Hierarchy Process (AHP) is a semi-quantitative decision-making value judgment approach in which experts, planners, and policy makers use their expertise experience and knowledge to break a problem into a hierarchy structure in order to solve it [3]. The AHP considers both objective and subjective factors to select the best alternatives. In the present study, AHP Excel Template Version 2018-09-15 created by Klaus D. Goepel (https://bpmsg.com accessed on 25 October 2022) was used for the pair-wise comparisons and calculations of the weights and CRs [28]. In this pairwise comparison matrix, the relative importance value of each factor was assigned by rating each factor against every other factor based on a comparative scale, proposed by [55,56], that ranged between 1 and 9, where 1 is equal importance and 9 is extreme importance (the details are provided in Table 1).

Table 1. Saaty's criterion weight scale.

Relative Importance	Definition
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

A consistency check was performed by computing the consistency ratio (CR), which depicted the quality of the pair-wise comparisons, because in practice, the decision maker's expression involves some fuzziness that may make the matrix have inconsistencies [7]. The judgment or preference is consistent only if the CR is greater than 0.10 [55,57].

The CR is calculated using Equation (3).

$$CR = \frac{CI}{RI} \quad (3)$$

where *CI* is the consistency index, which reflects the consistency of the judgment, and *RI* is the random inconsistency index dependent on the sample size. The consistency index, *CI*, is calculated using Equation (4).

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (4)$$

where n is the number of criteria and $\lambda_{\max}$ is the average of the value of the consistency vector (calculated factor weight).

The random inconsistency index, *RI*, depends on the sample size. *RI* values for respective sample sizes are presented in Table 2.

Table 2. Random index matrix [55].

Number of Criteria	1	2	3	4	5	6	7	8	9	10	11
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

The acceptable judgment range is $0 \leq CR \leq 0.1$, with a value of zero being the most consistent [57]. Any value outside this range would require the assignment of the criterion weight again. A consistency ratio of $CR < 0.10$ indicates a reasonable level of consistency in the pairwise comparison, while a CR value of ≥ 0.10 signifies inconsistent judgment [7].

2.6. Derivation of Flood Hazard and Flood Vulnerability Index

The flood hazard index (*FHI*) and flood vulnerability index (*FVI*) were derived by aggregating the weights and corresponding hazard and vulnerability classes at each level of the hierarchy using Equations (5)–(7), respectively.

$$FHI/FVI = \sum_{i=1}^{n} W_i \times r_i \quad (5)$$

where FHI/FVI is the flood hazard/flood vulnerability index, W_i is the weight of each indicator, r_i is the rating of the indicator in each point, and n is the number of the criteria.

$$FHI = W_{El} \times El + W_{Sp} \times Sp + W_{DD} \times DD + W_{ST} \times ST + W_R \times R + W_F \times F + W_{DR} \times DR \quad (6)$$

where El, Sp, DD, ST, R, F, and DR are elevation, slope, drainage density, soil type, mean annual rainfall, flow accumulation, distance from rivers; and $W_{El,}$ W_{Sp}, W_{DD}, W_{ST}, W_R, W_F, and W_{DR} are their corresponding weights.

$$FVI = W_{Pd} \times Pd + W_{Fd} \times Fd + W_{Lu} \times Lu + W_{Rd} \times Rd + W_{Lr} \times Lr + W_{Er} \times Er \quad (7)$$

where Pd, Fd, Lu, Rd, Lr, and Er are population density, female population density, land use, road network density, literacy rate, and employment rate; and W_{Pd}, W_{Fd}, W_{Lu}, W_{RD}, W_{Lr}, and W_{Er} are their corresponding weights.

Flood Risk Indicators and Flood Risk Index

Flood risk is defined as the product of "hazard" and the "total vulnerability" [1,29,58,59]. The flood disaster risk indicator, F_{RI}, of the study area was generated via the spatial layer overlay operation between the flood hazard and total vulnerability (socio-economic vulnerability), i.e., hazard indicator F_{HI} and total vulnerability indicator F_{VI}. The flood risk map based on flood hazard and total vulnerability is derived from Equation (8).

$$F_{RI} = F_{HI} \times F_{VI} \quad (8)$$

where F_{RI} is the flood risk index, F_{HI} is the flood hazard index, and F_{VI} is the flood vulnerability index.

2.7. Validation of Flood Risk Map

Qualitative validation methods used in previous studies [7,60,61] were adopted to verify the spatial risk maps. The methods involved extensive field survey and document review to assess the accuracy of the spatially generated hazard, vulnerability, and risk maps. The coordinates of the locations of various previous floods, such as inundated towns, farmlands, and dilapidated infrastructure that suffered floods, and other prominent features, such as bridges, dams, and irrigation farms, were collected using GPS equipment [7]. The visit included an in-depth field observation and discussion with local people, experts, and policymakers to obtain their views about the produced maps. The history of previous flood effects, and their severity and extents were also explored through a literature review and discussions with the stakeholders and residents. The flood risk map was validated using the data obtained from fieldwork throughout the entire study area. Fieldwork was conducted in July 2020 by the lead author and field assistants. Various previously flood-inundated areas, such as towns, villages, and farmlands, were visited, and the GPS coordinates of these locations were recorded. These coordinates were plotted on the generated flood risk map of the basin in order to compare the field results and the spatially generated flood risk map.

3. Results

3.1. Flood Hazard Indicators

The different flood hazard indicators selected for this study were based on geomorphological and hydrological attributes, namely, elevation, slope, soil type, flow accumulation, mean annual rainfall, drainage density, and distance from rivers (Table 3).

Table 3. Comparison matrix for flood hazard indicators.

Flood Hazard Indicators	Elevation	Slope	Drainage Density	Soil Type	Mean Annual Rainfall	Flow Accumulation	Distance from Rivers
Elevation	1	2	3	3	4	5	7
Slope	0.5	1	2	2	3	6	7
Drainage Density	0.33	0.5	1	2	3	3	6
Soil Type	0.33	0.5	0.5	1	2	3	4
Mean Annual Rainfall	0.25	0.33	0.33	0.5	1	2	3
Flow Accumulation	0.20	0.17	0.33	0.33	0.5	1	2
Distance from Rivers	0.14	0.14	0.17	0.25	0.33	0.5	1
Total	2.76	4.64	7.33	9.08	13.83	20.5	30

3.1.1. Elevation

Elevation is an important factor that contributes to flood hazard in a particular watershed [6,9]. Floods of low magnitude normally inundate low-lying areas. The elevation of the study area ranges from a maximum of 673 m to a minimum of 338 m above the mean sea level. The lowest elevation corresponds to the very high flood hazard class, whereas the highest elevation corresponds to the very low flood hazard class. Figure 3a shows that lower elevations dominate the north-eastern part of the basin, which renders it more prone to flooding. The elevation of 338–383 m represents a very-high-flood-hazard area, while the elevation of 539–673 m is considered as a low flood hazard class (Figure 3a).

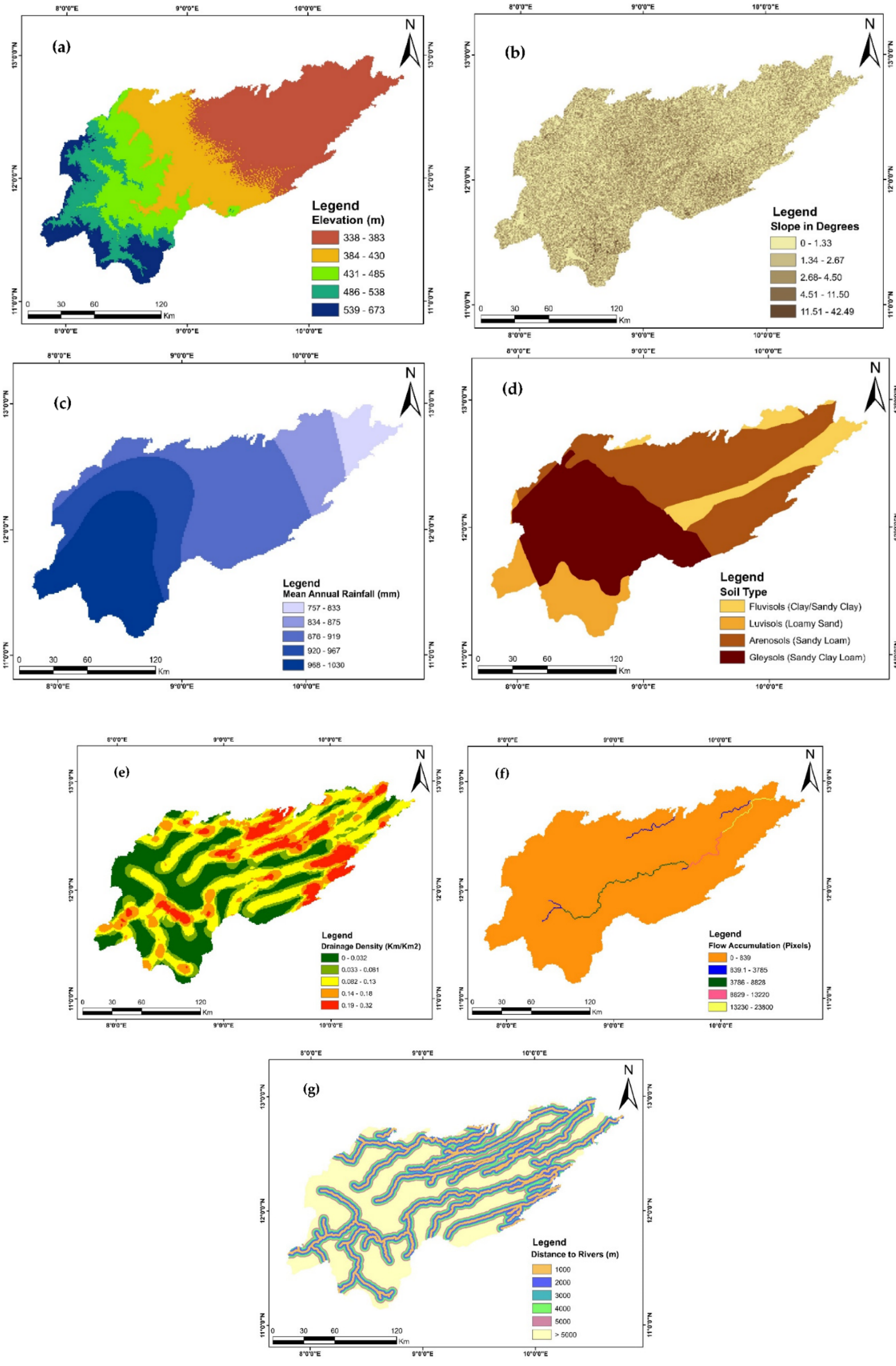

Figure 3. Flood hazard indicators. (**a**) Elevation. (**b**) Slope. (**c**) Mean annual rainfall. (**d**) Soil type. (**e**) Drainage density. (**f**) Flow accumulation. (**g**) Distance from rivers.

3.1.2. Slope

Flood inundation depends on the length and steepness of the slope in a particular area [7]. Relatively flat and moderate slopes suffer prolonged inundation, while steep and high slopes pass flood waters downstream [3]. The slope of the Hadejia River basin ranges from 0° to 42.5°. Figure 3b shows the slope map of the study basin classified into five slope classes, from very low (0.00°–1.33°) to very high (11.6°–42.5°). It is worth noting that the north-eastern part of the basin has a relatively flat slope, which renders it more prone to flooding events, while higher slopes dominate the central and north-western parts of the basin. This could be the sole reason why the north-western part of the watershed is less prone to flooding events.

3.1.3. Mean Annual Rainfall

The mean annual rainfall in the basin ranges from 757 to 1030 mm. Rainfall falls from the north-western to north-eastern portions of the study area. The flood hazard increases with the increase in rainfall. Figure 3c shows the mean annual rainfall classes in the study region, which are very low (757–833 mm), low (834–875 mm), medium (876–919 mm), high (920–967 mm), and very high (968–1030 mm). It is worth noting that the north-western and central parts of the watershed receive the highest mean annual rainfall. Rainfall values of 968–1030 mm and 876–919 mm are concentrated in Kano State, adjacent to the LGAs of Jigawa State, which increases the chance of severe flood events in the region. However, the region is characterized by high slope angle and elevation. As such, all flood waters easily flow downstream to many parts of Jigawa and Yobe States, putting a large portion of the states at a high risk of floods. Despite the fact that the upstream rainfall amount is slightly higher than that in the central part of the watershed, the central and the downstream areas have a relatively flat topography, an extremely flat slope, and poor drainage conditions. As such, the influence of rainfall on flood hazard is overshadowed by these geomorphic characteristics.

3.1.4. Soil Type

The soil map of the study area is presented in Figure 3d, showing four distinct soil types. Aerosol soil covers 39.7% of the basin (a sandy loam soil characterized by low permeability); therefore, it represents a high flood hazard because of its low infiltration rate. Fluvisol covers 13.5% of the basin. This soil has a low infiltration rate because of its high clay content; therefore, it represents a very high flood hazard. Gleysol covers about 35.2% of the basin and is sandy clay loam. Moreover, the soil is classified to represent a high flood hazard due to its low infiltration rate. Lastly, Luvisol soil is present in the study area and covers about 11.6% of the watershed; it has high permeability and thus a high rate of infiltration, which renders the soil a low flooding hazard. The soil-type map indicates that clay and clay loam soils are dominant in the lower portion of the study area, which has a low infiltration rate. This renders the region more susceptible to flooding; hence, it represents the highest flood hazard.

3.1.5. Drainage Density

High drainage density signifies high surface runoff and thus high flooding likelihood [61]. High drainage densities mean greater runoff rates and hence high flooding susceptibility [62]. Figure 3e shows the drainage density map of the study area. The drainage density map is classified into five density classes, namely, very high, high, medium, low, and very low. Very high drainage densities can be found in urban areas, main roads, and agricultural lands, while very low drainage densities can be found in bare land and areas that lack vegetation in the basin. The very high drainage density class ranges from 0.190 to 0.310 km/km^2, representing a very high flood hazard; the other classes are high (0.140–0.180 km/km^2), moderate (0.082–0.130 km/km^2), low (0.033–0.081 km/km^2), and very low (0–0.032 km/km^2) drainage density classes.

3.1.6. Flow Accumulation

Flow accumulation is considered a contributing indicator of flood hazard in the Hadejia River basin [61]. The flow accumulation map was developed using the GIS analysis of the digital elevation model with the spatial analyst tool in ArcGIS (Figure 3f). In the figure, the black and the blue pixels represent high flow accumulation, while the green and light-green pixels and the back-surrounding grey pixels represent moderate and low flow accumulation. Flow accumulation ranges from 0 to 23,800 pixels. Flow accumulation layers are classified into five classes from the very low class (0–829 pixels) to the very high class (13,230–23,800 pixels). Figure 3f shows that the study area is dominated by areas of high flow accumulation, mostly in the north-eastern part of the basin.

3.1.7. Distance from Rivers

Proximity to a river is an important indicator of flood hazard because areas close to rivers experience more frequent flooding than areas further away from rivers [61]. Figure 3g shows a map of the distance from rivers in the study area. Areas that are within 1000 m from rivers represent a very high hazard of floods, whereas areas within distances of 2000, 3000, 4000, and 5000 m from rivers are considered to represent high, moderate, low, and very low flood hazard, respectively.

3.2. Socio-economic Flood Vulnerability Indicators

Six different indicators of flood vulnerability were selected for flood vulnerability, namely, population density, female population density, literacy rate, land-use, employment rate, and road network density (Table 4).

Table 4. Comparison matrix for flood vulnerability indicators.

Flood Vulnerability Indicators	Population Density	Female Population Density	Land Use	Road Network Density	Literacy Rate	Employment Rate
Population Density	1	2	3	3	4	6
Female Population Density	0.5	1	2	3	3	6
Land Use	0.33	0.5	1	2	2	4
Road Network Density	0.33	0.33	0.5	1	2	3
Literacy Rate	0.25	0.33	0.5	0.5	1	2
Employment Rate	0.17	0.17	0.25	0.33	0.5	1
Total	2.58	4.33	7.25	9.83	12.5	22

3.2.1. Population Density

The population density distribution is one of the instrumental components of vulnerability to flash floods [62]. The higher the population density is, the higher the likelihood of life and economic losses is [7]. Population density was given the highest weight (Table 4). Figure 4a shows the population density map of the study area. The population density is categorized into the five density classes of very low, low, medium, high, and very high population densities. The most densely populated area in the basin has a population range of 778–31,504 persons per square kilometre and is situated in the central part of Kano State, while the lowest populated zone has a population density of 78–210 persons per square kilometre.

Other areas with a very high population density are Hadejia town and Itas/Gadau LGA of Jigawa State. Figure 4a reveals that seventeen local government areas were found to have a very low population density, and most of them are situated in Jigawa State. These very low and low population densities render them less vulnerable to flood disasters.

3.2.2. Female Population Density

The female population density of an area determines the area vulnerability to natural disasters such as floods [7]. Women are perceived to be at a high risk amongst the vulnerable population. Figure 4b presents the female population density map of the study area. It is worth noting from the figure that seventeen local government areas (LGAs) have a very low female population density, 40–105 females/square kilometre. A very high female population density can be found in the central part of Kano State and some parts of Jigawa State. A moderate female population density can be found in the north-western fringe of the study area.

3.2.3. Literacy Rate

The percentage of literate people in an area is expressed in terms of the literacy rate. A literate population can easily understand the severity and nature of a disaster and be able to respond more quickly [7]. The literacy rate map of the study area is presented in Figure 4c and shows how literacy rate varies significantly from state to state. Very low and low literacy rates (0–39.8%) can be found in the north-western part of the study area. A moderate literacy rate (39.9–53.6%) covers the LGAs of Jigawa State. This population likely has a moderate vulnerability to floods. Furthermore, a high literacy rate (58.2–58.3%) is concentrated in the LGAs of Yobe State. The higher value of literacy rate in this region aids the inhabitants to understand written information (newspapers, etc.) that provides details of the severity and nature of natural hazards and how quickly they can expect to adapt and recover.

3.2.4. Land Use

Land use/land cover plays an important role in identifying zones vulnerable to flooding [3]. Impervious surfaces such as residential areas and roads increase storm runoff generation. Bare lands tend to increase the erosion of soils and high runoff flow downstream of the watershed, whereas areas with high vegetation density generally have low potential for flooding, as vegetation enhances infiltration and decreases runoff generation [7]. Figure 4d presents the land use map of the study area, which was classified into eight classes: wood and grasses, irrigated cropland, bare land, forest, shrubland, vegetation, built-up areas, and water bodies. The land use map shows that rain-fed cropland, grassland, wood and grasses, irrigated cropland, built-up, and shrub cover 54.06%, 27.25%, 13.57%, 2.61%, 1.16% and 1.03%, 0.27%, and 0.06% of the area, respectively.

3.2.5. Road Network Density

Road networks play an important role during flooding, especially in relief and rescue operations. They also serve as flood shelters [7,12]. The availability of roads, namely, federal highways, state highways, and local government roads, defines how an area is expected to quickly recover from flood impacts. The road network density of the study area is presented in Figure 4e. The very high road density class (0.240–0.640) is represented by

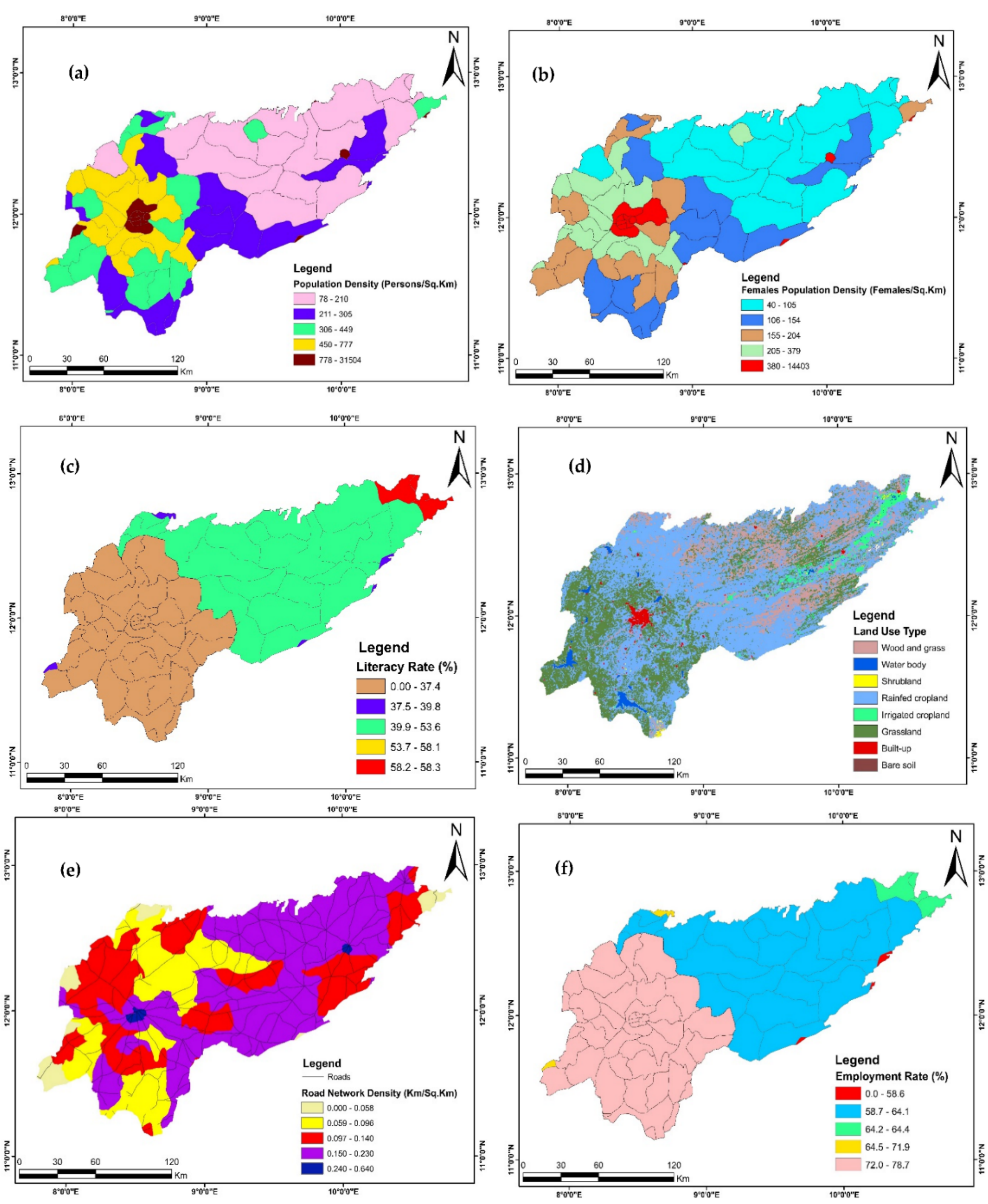

Figure 4. Flood vulnerability indicators. (**a**) Population density. (**b**) Female population density. (**c**) Literacy rate. (**d**) Land use type. (**e**) Road network density. (**f**) Employment rate.

Kano central and Hadjia LGA of Jigawa state. The high road network density class (0.150–0.230) covers about 50% of the study area in the north-eastern part of the basin. Other portions of the study area are in the moderate class (0.097–0.140), low class (0.059–0.096), and very low class (0.00–0.058) of road network densities.

3.2.6. Employment Rate

The employment rate map of the study area is presented in Figure 4f. The rate of employment of the study area varies significantly from state to state. The very low and low employment rate classes (0–58.6% and 58.7–64.1%) define the north-eastern part of the study area, that is, Jigawa and some part of Bauchi State, while the extreme north-eastern part of the study area is in the moderate employment rate class (64.2–64.4%). Furthermore, the very high employment rate class (64.5–78.7%) includes the LGAs of Kano State. The high employment rate of this region plays a vital role in making the region safe from socio-economic vulnerability to flooding.

3.3. Normalized Flood Hazard and Vulnerability Indicators

For comparison purposes, all the indicators were made dimensionless by assigning quantitative values to the qualitative data, such as the sub-indicators of soil type and land use, based on their influence and contribution to flood hazard and vulnerability. The assigned values for soil type and land use are presented in Tables 5 and 6, respectively.

Table 5. Classes of flood hazard indicators, and their weight and ranking.

Indicator	Relative Weight	Reclassified Indicator	Ranking	Hazard
Elevation (m)	33%	539–673	1	Very low
		486–538	2	Low
		431–485	3	Moderate
		384–430	4	High
		338–383	5	Very high
Slope (°)	23%	11.6–42.5	1	Very low
		4.51–11.5	2	Low
		2.68–4.50	3	Moderate
		1.34–2.67	4	High
		0.00–1.33	5	Very high
Drainage density (Km/Km^2)	16%	0.00–0.032	1	Very low
		0.033–0.081	2	Low
		0.082–0.130	3	Moderate
		0.140–0.180	4	High
		0.190–0.310	5	Very high
Soil type	12%	Luvisol (loamy sand)	1	Very low
		Gleysol (sandy clay loam)	4	High
		Arenosol (sandy loam)	4	High
		Fluvisol (clay/sandy clay)	5	Very high
Mean annual rainfall (mm)	8%	757–833	1	Very low
		834–875	2	Low
		876–919	3	Moderate
		920–967	4	High
		968–1030	5	Very high
Flow accumulation (px)	5%	0–839	1	Very low
		839.1–3785	2	Low
		3786–8828	3	Moderate
		8829–13,220	4	High
		13,230–23,800	5	Very high
Distance from Rivers (m)	3%	>5000	1	Very low
		4000–5000	2	Low
		3000–4000	3	Moderate
		2000–3000	4	High
		<1000	5	Very high

Table 6. Classes of flood vulnerability indicators, and their weight and ranking.

Indicator	Relative Weight	Reclassified Indicator	Ranking	Hazard
Population density (persons/square kilometre)	36%	78–210	1	Very low
		211–305	2	Low
		306–449	3	Moderate
		450–777	4	High
		778–31,504	5	Very high
Female population density (females/square kilometre)	25%	40–105	1	Very low
		106–154	2	Low
		155–204	3	Moderate
		205–379	4	High
		340–14,403	5	Very high
Land use	15%	Water Bodies	1	Very low
		Wood and Grass	1	Very low
		Grassland	1	Very low
		Shrubland	2	Low
		Bare soil	3	Moderate
		Irrigated Cropland	4	High
		Rainfed Cropland	5	Very high
		Built-up	5	Very high
Road network density (Km/Km^2)	11%	0.240–0.640	1	Very low
		0.150–0.230	2	Low
		0.097–0.140	3	Moderate
		0.059–0.096	4	High
		0.000–0.058	5	Very high
Literacy rate (%)	8%	58.2–58.3	1	Very low
		53.7–58.1	2	Low
		39.9–53.6	3	Moderate
		37.5–39.8	4	High
		0.00–37.4	5	Very high
Employment rate (%)	4%	72.0–78.7	1	Very low
		64.5–71.9	2	Low
		64.2–64.4	3	Moderate
		58.7–64.1	4	High
		0.00–58.6	5	Very high

3.4. Weight Assignment Using GIS-Based AHP

The pair-wise matrices of all flood hazard- and vulnerability-related factors are shown in Tables 3 and 4. The CR values of flood hazard and vulnerability were found to be 2.3% and 2.1%, respectively, i.e., less than 10%, signifying an acceptable consistency level [55]. The overall weight and ranking of each factor for both hazard and vulnerability are presented in Tables 5 and 6, respectively. The derived weights of the flood hazard indicators were found to be: elevation, 33%; slope, 24%; drainage density, 16%; soil type, 12%; mean annual rainfall, 8%; flow accumulation, 5%; and distance from rivers, 3%. This implies that the elevation and the slope have the highest geomorphic influence on and contribution to flooding events in the study area. However, the derived weights of the socio-economic vulnerability indicators were found to be: population density, 36%; female population density, 25%; land use, 15%; road network density, 11%; literacy rate, 8%; and employment rate, 4%. This implies that population density has the highest socio-economic contribution to flood vulnerability in the study area, which is in line with previous studies [6,7].

3.5. Flood Hazard Map

The flood hazard map of the study area is presented in Figure 5a and illustrates the potential areas at risk of flooding. It highlights five flood hazard classes ranging from very low to very high. The very high and high classes constitute 10.4% and 17.2% of the study area and are distributed in Jigawa State and some parts of Kano and Yobe States. These areas are essentially known to have relatively flat slopes, low elevation, and a low amount of rainfall compared with the upstream part of the watershed. High and very high hazards are evident in agricultural land and urban built-up areas of the watershed, as can be viewed in Figure 5a. The high hazard nature of these regions subjects them to a high risk of flooding. In a nutshell, a high flood hazard indicates a high flood risk [60].

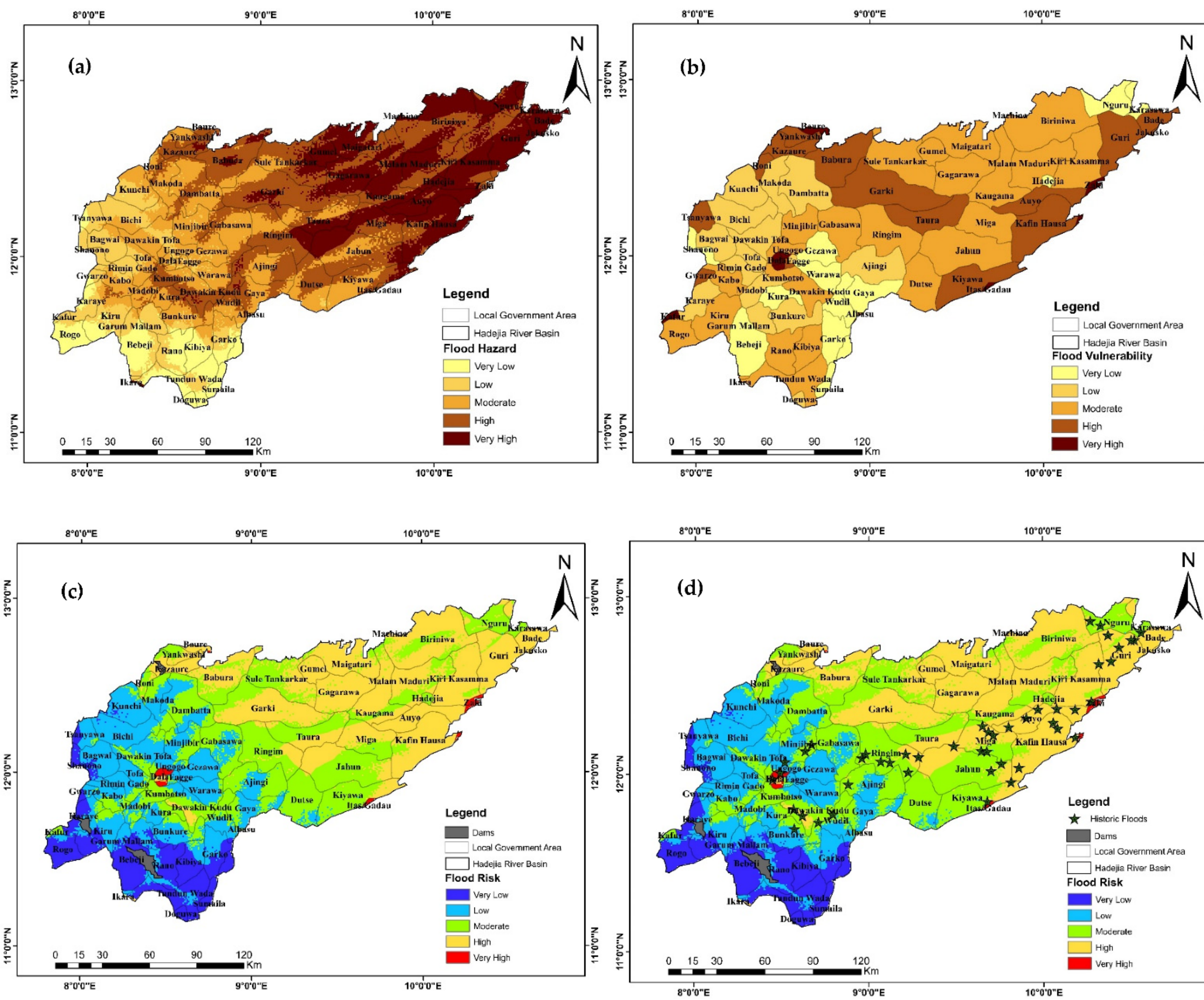

Figure 5. (**a**) Flood hazard layer. (**b**) Flood vulnerability layer. (**c**) Flood risk map after AHP analysis. (**d**) Validated flood risk map of Hadejia River basin.

Furthermore, the moderate flood hazard class covers about 49.4% of the basin, which includes a small part of Jigawa State and a large section of Kano State. In contrast with the north-eastern part of the study area, the extreme upstream part is dominated by low and very low hazard classes, which cover about 18.3% and 4.5% of the study area, respectively. These areas are characterized by high elevation, steep slopes, rocky and sandy soils, moderate rainfall, and relatively low drainage density. These findings are in accordance with other studies [6,19], where areas located at high elevation, steep slopes, and rocky and sandy lithological setting were found to be less prone to flooding events.

3.6. Flood Vulnerability Map

The flood vulnerability map of the study area is presented in Figure 5b, which highlights five areas of vulnerability classes ranging from very low to very high vulnerability. The very high and high vulnerability classes constitute about 2.3% and 21.8% of the study area, respectively; areas characterized by the urban built-up and bare soil classes of land use, high population and female population densities, low literacy and employment rates, and very poor road network systems are in these vulnerability classes. The medium vulnerability class covers 53.6% of the basin and constitutes about 24 local government areas of Kano and Jigawa States. The low and very low vulnerability classes cover 13.4% and 8.9% of the study area, respectively. These are areas of agricultural lands, vegetation, low population density, a high literacy rate, high economic activities, good drainage system, and highly residential areas. This is in agreement with the previous findings [7]. In general, high flood vulnerability may lead to high flood risk.

3.7. Flood Risk Map

The flood risk maps of the study area are presented in Figure 5c. The flood risk is divided into five levels of risk ranging from very low to very high risk. The respective percentages of areas at very high, high, moderate, low, and very low risk are 1.8%, 41.6%, 24.8%, 20.3%, and 11.5%. The high- and very-high-flood-risk zones are characterized by low slopes and elevations, high drainage density, low permeable soil, high population density, a low literacy rate, slightly high annual rainfall, and the urban built-up and bare land types of land uses. The overall area at high and very high flood risk in the basin constitutes about 43.4% of the entire watershed. Communities identified to be at high and very high risk of flooding within the study area are Guri, Dabi, Auyo, Kano Municipal, Fage, Jahun, Maigatari, Gumel, Gagarawa, and Hadejia LGAs. A careful analysis of the flood risk map revealed that urban built-up, clay soil types, and low slope and elevation increase the risk of flooding in these regions.

The medium risk class covers 24.8% of the study area while the low- and very-low-flood-risk zones covers 31.8% of the study area. These risk classes are concentrated in the upstream part of the watershed, and the zones are characterized by steeper slopes, high elevation, permeable soil, vegetation, the forest type of land use, very low population density, and very high literacy and income rates. Another reason for their low and very low risk of flooding is the presence of the Tiga and Challawa Gorge dams at Tiga and Kiru LGAs of Kano State (Figure 5c). These hydraulic structures impound large quantity of runoff water coming from upstream locations that may cause flooding downstream, which puts the area at a low flood risks. This hydro-geomorphic and socio-economic nature of the area plays a vital role in defining low and very low flood risk.

3.8. Validation of Flood Risk Map

The flood risk map and the associated validation points in the Hadejia River basin are presented in Figure 5d. The results of the verification revealed good agreement between the flood risk map and the previous flood records [63,64]. This shows that the proposed methodology can be applied in other study areas to develop flood risk maps, as it is flexible and easy to use, is of acceptable accuracy, and requires few data. Figure 5d shows that high and very high flood risk is ascribed to areas that have previously encountered flood hazard, while low and very low flood risk is concentrated in the upstream part of the basin, particularly in areas near the Tiga and Challawa Gorge dams, and the irrigation scheme at Kura LGA. An example is the flood event of Guri and Auyo that occurred in August 2018, which led to the destruction of vast agricultural lands, the collapse of infrastructure, and more than a dozen deaths. Twenty-nine out of the forty-nine previous flood events occurred within the high- and very-high-flood-risk regions. Furthermore, only 16 previous flood events were recorded in moderate-flood-risk zones, while 2 previous flood events were in low-flood-risk regions, and 2 surveyed coordinates of Challawa Gorge and Tiga dams were also found to be in low-risk zones except for the Watari dam of Kazaure LGAs, which are based in moderate-to-high-flood-risk regions.

4. Discussion

This paper presents flood risk assessment and mapping using an integrated approach combining the AHP and GIS analyses through the utilization of the MCA. Flood hazard and vulnerability have CR values of 2.3% and 2.1%, respectively, less than 10%, signifying an acceptable consistency level [55,57]. Agricultural land and urban built-up areas show to be high-to-very-high-flood-hazard zones, which resonates with previous studies [6,7,19]. These hazard zones cover about 27.6% of the basin. Moreover, 49.4% of the study basin is in the moderate class, including Jigawa and a large part of Kano State. The high vulnerability classes cover about 23.1% of the study region, including the urban built-up and bare soil classes of land use and areas with very poor road network systems. The high- and very-high-flood-risk zones cover 43.4% of the basin. These include the communities of Guri, Dabi, Auyo, Kano Municical, Fage, Jahun, Maigatari, Gumel, Gagarawa, and Hadejia LGAs. This may be due to the urban built-up dominance, clay soil types, and low slope and elevation in these regions. This is in agreement with the findings in [7,9,52]. These findings also relate to the outcome in [33] in Costa Rica indicating that higher flood risk values occur in flatland (low slope) and borderland areas. Different regions in the study area are identified to have different hazard, vulnerability, and risk classes based on the analysis of the result of the flood hazard, risk, and vulnerability in the study area; the literature review; and a rigorous field study. This indicates the need to explore sustainable flood reduction and mitigation measures that suit the conditions of the study area. As such, various structural and non-structural measures are explored for the study area.

The structural measures for flood control employ the techniques of storing, diverting, and confining flood water [7]. This measure can be achieved through the installation of facilities that prevent flood disasters [65]. Due to sand mining, embankment construction, and the impastation of aquatic grasses in Hadejia River, many changes in the water course and channel morphology occurred over the last decades, leading to the submergence of large portions of farmlands, villages, and roads and the dilapidation of electric poles and culverts. There is a need to develop policy to restore the natural conditions of the channel through riverbed dredging and the construction of backflow preventers. Furthermore, the Hadejia River embankment is not monitored and evaluated properly, and a large population of the basin lives near flood-prone rivers due to ineffectual policies. There is a need for more frequent monitoring and evaluation by the government and local residents, particularly in the most vulnerable areas identified. Moreover, Sustainable Urban Drainage (SUD) or Managed Aquifer Recharge (MAR) may be practiced in the cities of Kano State (Kano Municipal, Dala, Fage) in order to reduce the impact of urban development on flooding and the pollution of waterways. The drainage density and road network density maps (Figures 3e and 4e) of the Hadejia River basin show a high degree of congestion and roads in some areas, such as Kano Municipal, Fage, Guri, Auyo, Ungogo, and Hadejia, that do not have appropriate water runoff management. It is imperative to identify these places that do require interventions to carry out the evacuation of debris for the safe discharge of flood waters.

Non-structural measures are designed to keep infrastructures, agricultural land, and other structures away from waterways. These measures allow individuals or the community to cope with flood disaster risk more effectively [66]. It is suggested that architectural approaches of flood control measures, such as structure elevation (building structures above the flood level), prevention using watertight emulsion for the exterior walls of buildings, and establishing flood-resilient building codes with regards to occupancy and the use of buildings in areas with low-lying elevations and high-flood-risk areas (such as Auyo, Guri, Jahun, Miga, Nguru, and Jakusko (Figure 5b)), could be implemented to reduce the flood risk of these locations. Moreover, land use planning, when coupled with land use restriction policies, provides an effective measure of risk reduction in a particular area [7]. Figure 5c shows places such as Auyo, Guri, and Jahun, which are at a high flood risk and should be designated to have low occupancy uses, whereas the moderate- and lower-risk zones should be designated for high occupancy uses for improving the drainage network and the reduction in less pervious surfaces. Proper land use planning and zoning signifies lower flood disaster risk [7]. Furthermore, flood insurance is considered a mitigation technique because it does not reduce damage but compensates the affected individual or societies for their losses [7,65]. In the areas of Auyo, Guri, Kano Municipal, Fage, Jahun, and Miga LGAs in the study area with high to very high flood risk and vulnerability, the government should implement a flood insurance system for the inhabitants living in these regions that covers life and economic damages due to floods. Capacity for flood resilience is a measure used to reduce the physical vulnerability of people to floods [7,66]. This could be implemented in the basin and achieved through sensitization workshops and the training of the residents of the local communities on flood risk reduction. The communities with high-to-very high vulnerability in the study area, however, have a low literacy rate and need to be educated on the techniques of flood risk reduction and mitigation.

5. Conclusions

This study developed a spatial flood risk assessment map of the Hadejia River basin. The spatial distribution of the flood-risk zones of the Hadejia River basin was mapped using the Analytic Hierarchy Process (AHP) method integrated with a Geographical Information System (GIS) in order to reduce risk and vulnerability associated with floods. The study was the first in the basin to combine a hydro-geomorphic hazard analysis and a socio-economic vulnerability assessment for identifying flood disaster risk zones. The results of the present study are useful for improving flood mitigation and vulnerability management strategies.

The proposed methodology showed that very-high- and high-flood-hazard zones can be mainly identified in the north-eastern and south-eastern parts of the watershed. This methodology could serve as the basis for an integrated flood risk and vulnerability assessment. Moreover, the methodology is simple, requires few data, and is transferable, as it relies on remotely sensed data. The study revealed that high and very high vulnerability classes primarily cover the south-eastern, central, and extreme upstream parts of the study area. In contrast with the south-eastern and extreme parts of the watershed, the north-eastern and south-western portions of the study area are characterized by moderate, low, and very low vulnerability classes. This is due to the devastating effects of the selected socio-economic vulnerability indicators. The study also revealed that flood hazard and vulnerability indicators have different influences on flood risk. High flood hazard does not signify high flood risk when vulnerability is low and vice versa. The results of flood risk and vulnerability assessment and mapping are crucial for the strategic management of flood disaster risk. This can help the government, policy makers, and planning and relief agencies to come up with effective flood reduction and migration measures.

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