



Research Paper

# Geospatial Mapping for Flood Vulnerability Zones and Risk Knowledge in Northern Bauchi State, Nigeria

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## Abstract

Flooding remains a recurring environmental hazard in the North-Eastern Nigeria, often exacerbating the spread of infectious diseases and threatening livelihoods in communities it occurs. This study, "Geospatial Mapping of Flood Vulnerability Zones and Flood Risk Knowledge", aims to delineate and categorise flood-prone areas to provide decision-makers with spatially explicit information for disaster risk reduction, resources allocation and proffer lasting solutions to the frequent destruction of livelihoods in the area. Optical and radar remotely sensed data were processed and utilized to delineate flood vulnerable zones in the area. Major nine (9) flood causative factors (Landuse/landcover, Normalised difference vegetation index, elevation, slope, rainfall, river/drainage density, distance to the rivers, soil type, and topographic wetness index) were identified and combined in Analytical Hierarchy Process (AHP). These factors were weighted and hierarchically structured in the AHP (within Multi-criteria Decision Analysis) based on their relative influence to flooding in the study area. The results from multi-criteria evaluation generated flood vulnerability map, flood risk categories, and areal extent of each. The study has given concrete knowledge of the flood vulnerability zones in the area. It revealed that 42.1% of the total area falls within the high flood vulnerable zones – found in the middle and northern part of the area; while 27.3% and 30.6% fall within the moderate and low flood vulnerable zones respectively. The findings are expected to support interventions, optimize resource allocation to the identified communities and strengthen resilience strategies against the recurrent adverse effects of flooding in the region.

**Key Words:** AHP; Geospatial Mapping; Flood Vulnerability Zones; Flood Risk Knowledge;

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## I. Background

Floods are recurring seasonal phenomena in Nigeria, occurring mostly during the rainy season. The major causes of floods in Nigeria include heavy rainfall (torrential rains), soil becoming saturated after several episodes of rainfall, when dams collapse, and when excess waters are released from dams or overflowing of major rivers Alimi, *et al.*, (2022). Two major types of floods are dominant in the most part of Nigeria. They are river flooding and urban flash floods. Flash floods also do occur in the rural areas of the country (Olaniran, 1983).

Floods are perhaps the most important natural disasters bedeviling Nigeria, most especially in states in the northern States, numerous villages and extensive farmlands were ravaged by flooding (African Research Bulletin, 2010). Floods lead to widespread disruption of livelihoods activities in so many ways in the communities affected by them, both urban and rural. For example, flooding can cause the collapse of buildings, abutment of bridges and culverts, washing away roads and embankments, submergence of farmlands (leading to destruction of crops, with serious implications on yields, nutritional status and health), market places, schools, hospitals and other healthcare facilities and houses etc.

Floods generally exhibit some life-threatening characteristics when they occur: without early warning, flooding occurring rapidly with a short time-lag, floodwaters flowing with high velocity, floods lasting for a long time, floods having multiple peaks, floodwater being deep (more than one meter deep), floodwater carrying debris

loads and the characteristic accompanying weather. When flood exhibits any of these characteristics, it becomes more dangerous. And floods seldom exhibit only one of these life-threatening characteristics.

It is the intertwined relationship between flood incidence and humanitarian challenges that formed the key attraction for this research proposal. Floods on their own are major natural disasters that wreck serious destructions and cause so many losses of lives, properties and physical injuries. They also pose serious security and humanitarian challenges wherever they occur. Infectious diseases can also manifest as catastrophic biological disasters even without flooding. When these two major natural hazards co-exist or occur at the same time or in quick succession, their combined disastrous forces can lead to a complex emergency situation with tremendous damaging impacts to man and his interests.

The northern part of Bauchi State is traversed by numerous rivers and streams whose carrying capacities are frequently exceeded during the rainy season, resulting in recurrent annual flooding. In response, this study employs geospatial mapping techniques to delineate and assess the spatial extent and magnitude of flood vulnerability zones in the northern region of the State. Specifically, the study identifies and classifies flood-prone areas into distinct risk categories to enhance risk knowledge and support evidence-based decision-making. By clearly mapping the location and severity of flood risk zones, the research provides a framework for targeted mitigation and adaptation strategies. The findings are expected to support effective regional planning, disaster risk reduction intervention measures, and sustainable flood management in affected communities.

### **1.1 Justification of the Study**

Flood prediction in Nigeria is primarily undertaken by the Nigeria Meteorological Agency (NiMET) and the Nigeria Hydrological Services Agency (NIHSA). Since 2020, these agencies have consistently reported forecasts of strong winds and moderate to heavy rainfall, warning that according to NiMet (2024), such conditions are likely to cause flash flooding in vulnerable plains and terrains. Annual flood outlooks have repeatedly identified 12 Northern States as High-risk, with Northern Bauchi State prominently among them. In addition, the National Emergency Management Agency (NEMA) regularly issues alerts over imminent flood threats in North-Eastern Nigeria.

A recent International Organization for Migration (IOM, 2018) assessment in Northern Bauchi State reported that 2,185 individuals were affected by flooding triggered by heavy rainfall and strong winds, with approximately 90% of them displaced across almost all Local Government Areas (LGAs) in the northern part of the state. The LGAs most frequently impacted include Zaki, Gamawa, Dambam, Katagum, Itas/Gadau, Jama'are, Giade, and Misau, with Darazo, Ganjuwa, Warji, and Ningi also identified as flood-prone areas.

While moderate to heavy rainfall remains a key driver of flooding in the region, it is not the sole influencing factor. Other hydrological, topographic, and environmental parameters – such as drainage patterns, slope, soil type, and proximity to rivers – play critical roles but are often overlooked in most flood risk studies. Many existing assessments (Pradhan & Youssef, 2011; Alimi, *et al.*, 2022) failed to integrate these factors into a holistic, spatially explicit model for flood vulnerability zoning, risk knowledge and assessment.

This study therefore, seeks to address this gap by identifying and quantifying unique flood hazard parameters in Northern Bauchi State and assigning their proportional contributions to flood within an Analytical Hierarchy Process (AHP) framework. Using satellite Earth Observation (EO) data in combination with in-situ measurements, the study will produce a comprehensive, multi-factor flood vulnerability assessment to support more accurate methodology and informed decision-making for flood mitigation in the region.

### **1.1 The Study Area**

Geographically, Bauchi State is lying between Latitudes 9°30'30"N and 12°31'23"N, and Longitudes 8°43'35"E to 11°01'30"E. It covers a total land area of about 48,168.15Km<sup>2</sup> (Figure 1). The predominant occupations in the state include farming – both rainfed and irrigated, agribusiness and animal husbandry, and trading. Other common livelihoods in Bauchi State are in education and government service (both public and civil). The State shares boundary with Jigawa State to the west, Yobe State to the east; Gombe and Plateau States to the south-east and south respectively. The Study area, Northern part of Bauchi State comprises of 10 LGAs and their headquarters as (Dambam – Dambam; Darazo – Darazau; Gamawa – Gamawa; Giade – Giade; Itas/Gadau – Itas; Jama'are – Jama'are; Katagum – Azare; Misau – Msau; Shira – Yana; Zaki – Zaki; in northern Bauchi State. The Area is geographically lying between Latitudes 10°45'46" N and 12°31'23" N; and from Longitudes 9°37'23" E to 11°01'30" E, as shown in Figure 1C. The area occupies land areas of approximately 15,025.0 km<sup>2</sup>.

## **II. Flood Hazard Parameters Considered**

According to several scholars (Dandapat & Panda, 2017; Danumah *et al.*, 2016; Roy & Blaschke, 2015; Sulaiman *et al.*, 2015; and Cabrera & Lee 2020), key flood hazard parameters typically include elevation, slope, rainfall, drainage density, land use pattern, and soil type. To make study more comprehensive, this study

considered the 7 parameters in addition to distance from river and streams; vegetation cover (not fully captured in LULC); and topographical wetness index; are critical and for objective and comprehensive detection of flood landscapes, were used in this study. The assessment employed a GIS-based Multi-Criteria Decision Analysis (MCDA) framework, allows for the integration of multiple spatial and non-spatial datasets (Samanta, *et al.*, 2016). Dandapat & Panda (2017); Samanta, *et al.*, (2016); and Akoteyon, & Kwaku, (2016) popularized the application of the Analytical Hierarchy Process (AHP) within MCDA to quantify the relative weights of flood-influencing factors, a method also considered in this study. Following the approach of Khanday & Sujatha (2022), flood vulnerability was classified into five categories – Very High, High, Moderate, Low, and Very Low – based on integrated spatial analysis and use of K-Means (introduced by MacQueen, 1967). This categorization provides a distinction spatial representation of flood risk across Northern Bauchi State, supporting targeted intervention strategies.

### **2.1 Analytical Hierarchy Process (AHP) Model**

The Analytical Hierarchy Process (AHP) is a widely used multi-criteria decision-making approach developed by Saaty (1980) and further applied in flood hazard studies (Yang, *et al.* 2013; Akoteyon & Kwaku, 2016; Dou *et al.*, 2017; Meshram, *et al.*, 2019; Cabrera & Lee 2020; Khanday & Sujatha 2022; and Nwanchukwu & Ilaboya, 2024). AHP is particularly effective in solving complex decision problems, such as assessing flood risk, by enabling the systematic allocation of weights and ranking of multiple influencing parameters. According to Khanday & Sujatha 2022; and Nwanchukwu & Ilaboya, 2024; the method facilitates the prioritization of parameters for delineating Flood Vulnerable Zones (FVZ). Therefore, this study aims to apply geospatial techniques in conjunction with the AHP model to delineate FVZs in Northern Bauchi State. The resulting spatial outputs will be used to predict future flood occurrences, thereby providing a robust decision-support tool for disaster risk reduction and early warning systems in the region.

## **III. MATERIALS AND METHODS**

### **3.1 Materials**

This study employed both primary and secondary data. The preliminary data included coordinates of historical flooded areas in the study area collected using a Global Positioning System (GPS) device during field observations. The secondary data collected for the study included Landsat 8 OLI and ALOS Palsar Digital Elevation Model (DEM). Table 1 shows characteristics of the data acquired and their sources, including ArcGIS 10.8 as the major software package used for processing and analyzing both the primary and secondary datasets used for the study.

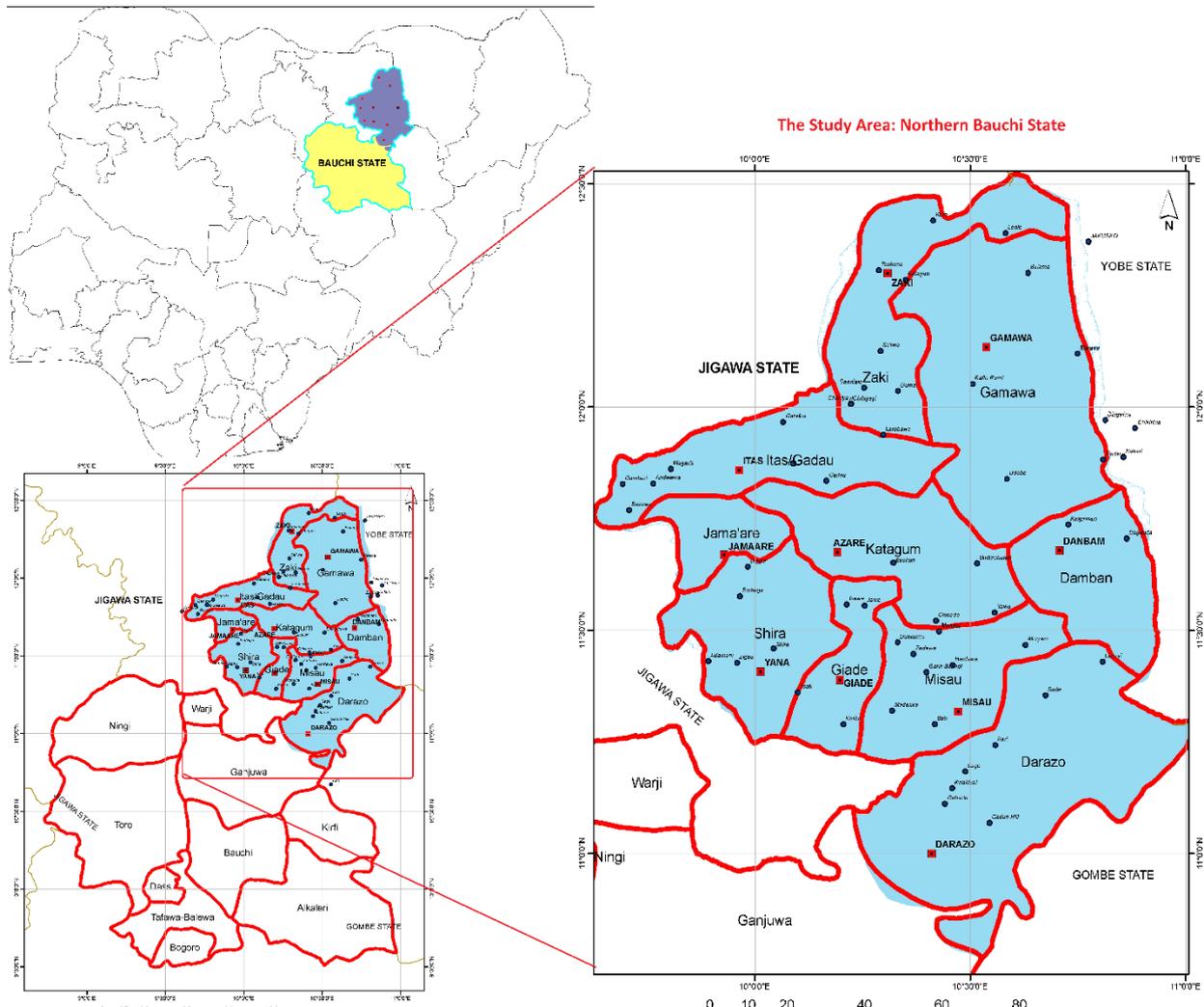


Figure 1: The Study Area, Northern Bauchi State, North-east Nigeria

Table 1: Characteristics of Datasets Acquired for the Flood Susceptibility Mapping

S/No.	Data Type	Purpose	Source	Year	Resolution
1.	Landsat 8 OLI	LU LC & NDVI	USGS	December 2023	30 m
2.	Rainfall	Surface runoff	Validated TAMSAT Data stream and Tropical Rainfall Measuring Mission	1991 & 2020	250 m
3.	ALOS Palsar DEM	Relief, Slope TWI, DD, Dist. to River/Stream	Free: Alaska Satellite Facility: <a href="https://asf.alaska.edu">https://asf.alaska.edu</a>	2019	12.5 m
4.	Soil	Soil texture	FAO Soil Info. System	1996	1:5,000
5.	Historic flood locations	Frequency Ratio Model	Questionnaire tool	2020	—

Source: FUHSA Flood Team, (2024)

### 3.2 Methods

The study considered nine (9) flood causative/influencing factors to delineate flood vulnerability zones in Northern Bauchi State. These factors are: land use land cover (LULC); normalized difference vegetation index (NDVI); elevation, slope, rainfall; drainage density; proximity to river; soil types; and topographic wetness index (TWI). These factors were organized into five (5) main steps for mapping the flood-vulnerable zones, as modified in Alimin, *et al.*, 2022, methodological flow chat, see Figure 2, a methodological Flow Chart modified from Alimi, *et al.*, 2022.

In the first step, all spatial and non-spatial data were acquired, viz: Landsat-8, TAMSAT-rainfall, ALOS Palsar DEM, soil and historic flood locations. Second step the acquired data were pre-processed (input) into GIS environment. The third step, the data were managed, where all the spatial data were clipped to the boundary of the study area; and only the specific flood causative/influencing factors were processed. The fourth step, the relevant flood influencing data were manipulated (extract) to produce thematic layers of slope, relief, drainage density, proximity to river and TWI, LULC. Finally, the flood vulnerability zones map was generated.

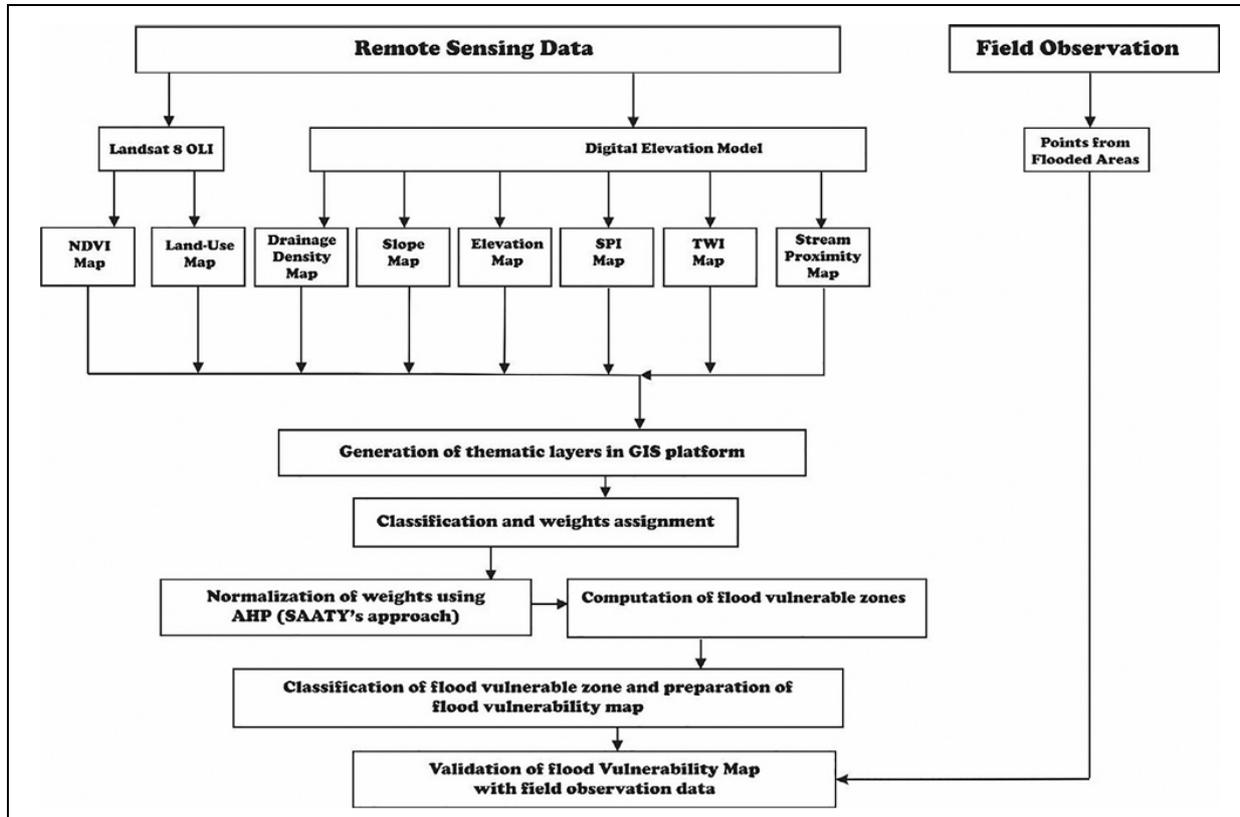


Figure 2: Methodological Flow Chart for the Flood Study

Modified from Alimi, *et al.*, 2022.

Using unsupervised classification method, Landsat 8 OLI data was used to generate the LULC and Normalized Difference Vegetation Index (NDVI) map of the area was generated, see Equation 3.1.

$$NDVI = \frac{NIR - R}{NIR + R} \quad \dots \quad \dots \quad \dots \quad Eq^a 3.1$$

Where: NIR = Near Infrared (Band 5), R = Red Band (Band 4) in Landsat8. Negative NDVI value and 0 indicate water and bare surface, 0.2 – 0.4 NDVI values represent grassland, and between 0.5 and 1 represent forest area (Khosravi *et al.*, 2019).

### 3.3 Analytical Hierarchy Process (AHP) Model

The Analytical Hierarchy Process (AHP) is a widely used multi-criteria decision-making approach developed by Saaty (1980) and further applied in flood hazard studies (Dou *et al.*, 2017; Cabrera & Lee 2020; and Majeed *et al.*, 2023). AHP is particularly effective in solving complex decision problems, such as assessing flood risk, by enabling the systematic allocation of weights and ranking of multiple influencing parameters. According to Khanday & Sujatha (2022), the method facilitates the prioritization of parameters for delineating Flood Vulnerable Zones (FVZ). Therefore, the present study aims to apply geospatial techniques in conjunction with the AHP model to delineate FVZs in Northern Bauchi State. The resulting spatial outputs will be used to predict future flood occurrences, thereby providing a robust decision-support tool for disaster risk reduction and early warning systems in the region.

All the flood causative/influencing factors were categorized into five classes; each factor formed a layer and assigned weight using the Analytic Hierarchy Process (AHP) method. The flood vulnerable zones were

verified using historical flood points collected during field observations with GPS during the 2023 flood incidence that occurred in the area. The flood causative/influencing layers were classified, and weights assigned using the Analytic Hierarchy Process (AHP) method. The flood vulnerable zones map was verified using 63 historical flood points collected with GPS GARMIN during the 2023 flood incidence that occurred in the area.

#### **IV. RESULTS AND DISCUSSION**

##### **4.1 Presentation of Flood Causative/Influencing Factors Considered in this Study**

The aim of flood vulnerable zones mapping is to produce a map of flood vulnerability which will reveal the feasibility of spatial dispersion of flood in the area. The flood causative factors considered in this study area are: elevation (used to generate slope, drainage density, proximity to river and TWI) and rainfall were also combined with risk elements: NDVI, LULC and Soil, for weighting overlay index to generate Figures 4.1 to 4.10 and Tables 4.1 to 4.2. The topography in the Northern Bauchi State reveals the crucial role in determining the intensity of floods, as relief directly impacts the rate of runoff and water discharge. Low-lying areas are more susceptible to flooding, while higher elevations are generally safer. Northern Bauchi, which is typically lower in elevation compared to the southern region, is at a higher risk of flooding. The elevation in Northern Bauchi varies from 314m to 650m and is divided into five categories ranging from very low to very high. A significant portion of Northern Bauchi consists of low to moderate elevations, making these areas more prone to flood hazards, while the higher elevations are less susceptible to flooding. Moreover, the slope of the land also plays a crucial role in determining flood vulnerability by influencing runoff and infiltration. Steep slopes facilitate rapid water flow, which reduces recharge and minimizes flood risk, whereas gentle slopes retain more water, increasing the likelihood of flooding.

##### **i. Land use Land cover**

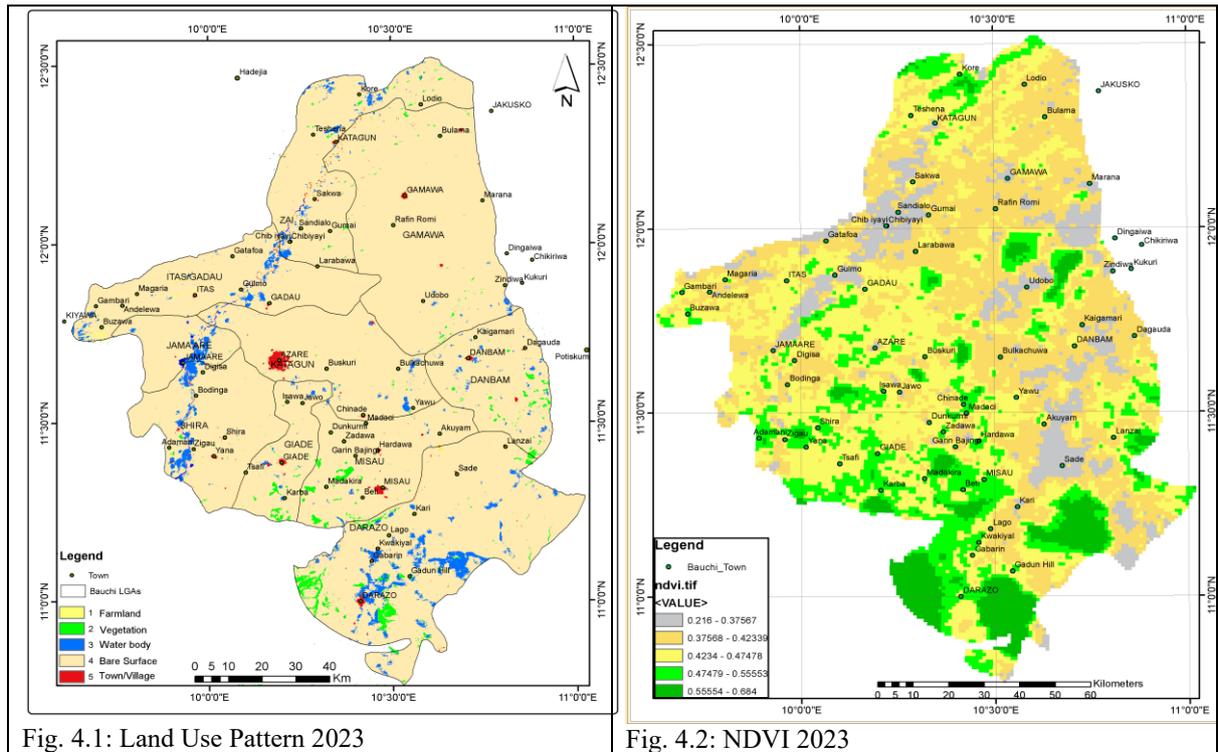
Five land use land cover classes were purposely selected. These are farmland, vegetation (forest cover), waterbody (including open water/wetlands and hydrology), bare surface, Town/village Settlement as shown in Figure 4.1, the land use land cover of the study area, Northern Bauchi State. Bare Surface/dispersed shrubs covered 94.64% (14,220 km<sup>2</sup>), waterbody/hydrology of the area covered about 2.94% (442.1km<sup>2</sup>) of the study area. The other land use land cover surfaces (farmland, vegetation and Settlement, maintained only 2.42%. The distribution of the Land use Land cover (2023) is represented in Appendix A.

##### **ii. Normalized Difference Vegetation Index (NDVI)**

As the relative management of flood, vegetation cover plays effective role in mitigating flooding. The study considered Normalised Difference Vegetation Index as representative of the rigour of green cover in an area, is mostly used in mitigating flooding, where rainfall absorption, reducing runoff and encourages infiltration. In most case, roots of vegetation cover hold and compact soil in place and regulate water cycle by releasing water vapour into the atmosphere. Figure 4.2 presents the vigour of vegetation cover of the area. More than half of the spatial extent of the area is weak vegetation cover (1,773.20 km<sup>2</sup> or 50.15%). The results of the NDVI show that bare surface and healthy vegetation covered 4,837.62 km<sup>2</sup> (31.82%) and 937.1 km<sup>2</sup> (6.16%) of the entire study area respectively, indication that the area is prone to floodings. It is therefore composed of bare and dispersed shrubs, see Appendix B. This informed the extent of weak vegetation cover in the area, which makes the area more vulnerable to flooding.

##### **iii. Elevation of the Study Area**

According to Natarajan *et al.*, (2021), elevation and slope are essential factors for mapping flood susceptibility. Likewise, Stieglitz *et al.*, (1997), Botzen *et al.*, (2013), and Das *et al.*, (2019) have also noted that the direction, movement, and depth of overflowing water are critical for flooding in residential areas. Therefore, elevation and slope play a significant role in controlling surface runoff and infiltration. High rates of water infiltration result in decreased runoff, while saturated soil from excessive percolation increases runoff, ultimately causing flooding.



The elevation and slope maps were generated using the ArcGIS Spatial Analyst extension and a 12.5 m ALOS PALSAR DEM. Surface runoff naturally flows from higher to lower elevations, making low-lying areas more prone to rapid flooding (Dahri and Abida, 2017). In Northern Bauchi State, elevation values, using K-means 5 classes of Natural Break method ranged from 314 m to 650 m is presented in Table 4.1, derived from the ALOS DEM Data. The area is relatively flat (see Figure 4.3 and Table 4.1, with 55.93% (8,253.79 km<sup>2</sup>) traverses between Very Low and Low Relief (314 – 422 m). This is a strong indication that more than half of the study area has low relief elevation that can accumulate and retain flooding for long period. This confirmed the warning by NiMet (2024), that plains and low terrains conditions are likely to cause flash flooding. While 21.73% (3,265.21 km<sup>2</sup>) of the study area is Marginally Low relief landscape, the remaining portion is between Slightly High and High Relief and not vulnerable to floods occupying 23.34% in the area.

Table 4.1: Topography Vulnerability and Extent in the Study Area

Value	Topography Vulnerability	Relief Interval (m)	Area (Km <sup>2</sup> )	Proportion (%)
1	Very Low Relief	314.0 – 394	3,839.01	26.55
2	Low Relief	394.1 – 422	4,414.78	29.38
3	Marginally Low Relief	422.1 – 453	3,265.21	21.73
4	Slightly High Relief	453.1 – 491	2,896.32	19.28
5	High Relief	491.1 – 650	610.67	4.06
<b>TOTAL</b>			<b>15,025.69</b>	<b>100.00</b>

iv. **Slope of the Study Area**

Slope is a critical topographic factor regulating surface runoff, infiltration and water retention, and thus strongly influences the flood susceptibility of an area (Celik *et al.*, 2012; and Das and Pardeshi, 2018). The results of this parameter shown (Table 4.2) and were mapped (Figure 4.4) generated from the ALOS DEM Data in the ArcGIS 10.8 environment. The slope values were computed based on the rate of change in elevation in the horizontal (dz/dx) and vertical (dz/dy) directions from the centre cell, as expressed in Equation 4.1.

$$Slope\ Degrees = ATAN(\sqrt{[dz/dx]^2 + [dz/dy]^2}) * 57.29578 \dots Eq_{4.1}$$

Where: ATAN is ArcTangent; dz, dx, dy are change in x, y, z and with product of constant (57.29578).

The slope values, (using Natural Break method) were ranged between 0°00'00" and 46°00'40" and were categorized into five classes: very high; high; moderate; low and very low vulnerability to flood, as presented in Figure 4.4 and Table 2.2, extracted from the ALOS DEM Data. The Table shows that about 75.2% (3,362.75

km<sup>2</sup>) of the study area has slopes that ranges between classes 0° and 1°04'57", which represents very high flood vulnerability landscape. This conforms to interpretation of Pradhan, 2009; and Li *et al.*, (2012) that areas with gentle slopes or low slopes tend to accumulate water, increasing the likelihood of flooding due to stagnation and slower drainages. Additionally, 20.4% (6,769.6 km<sup>2</sup>) of the area is highly flood vulnerability. This is in agreement with NiMet (2024) that the study area is a flat terrain thus making it susceptible to flash flood vulnerability. With very high and high slope vulnerability in the Table 4.2, coupled with the weak vegetation cover (Appendix B) the area is highly composed to flooding.

Table 4.2: Slope Vulnerability and Extent in the Study Area

Value	Slope Vulnerability	Class Interval (Degree)	Area (km <sup>2</sup> )	Proportion %
1	Very High Vulnerability	0°00'00" – 1°04'57"	3,362.75	75.20
2	High Vulnerability	1°04'57" – 2°53'13"	6,769.58	20.37
3	Moderate Vulnerability	2°53'13" – 5°03'08"	4,022.46	3.81
4	Low Vulnerability	5°03'08" – 10°38'45"	857.44	0.57
5	Very low Vulnerability	10°38'45" – 46°00'40"	13.46	0.05
<b>Total</b>			<b>15,025.69</b>	<b>15025.69</b>

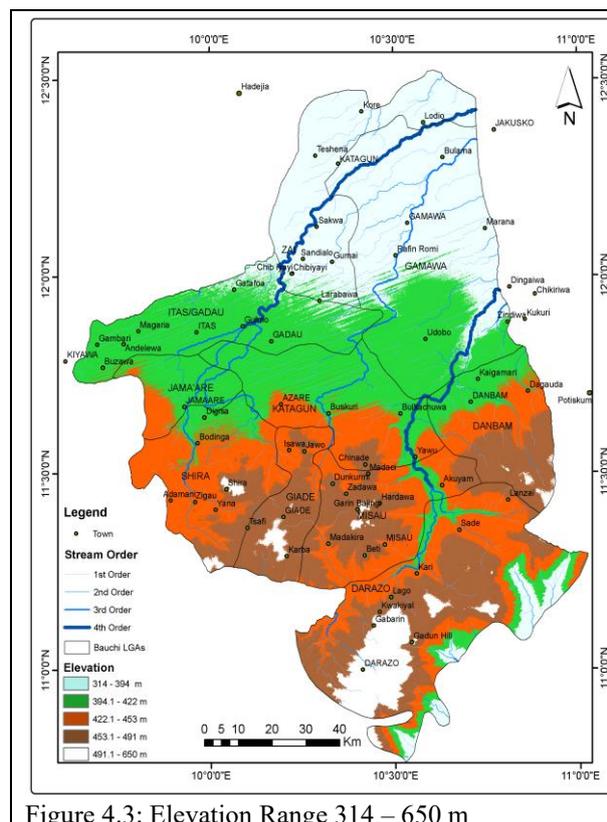


Figure 4.3: Elevation Range 314 – 650 m

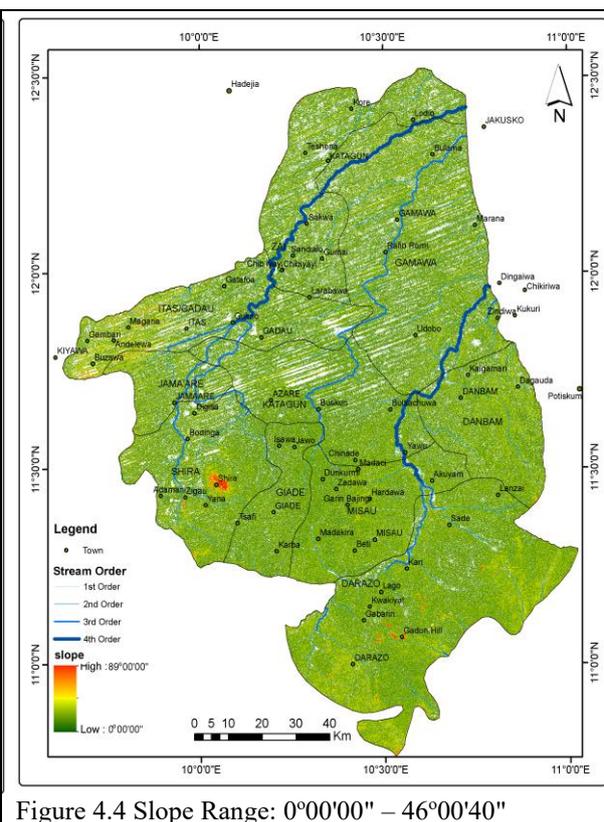


Figure 4.4 Slope Range: 0°00'00" – 46°00'40"

**v. Rainfall**

The climate of Northern Bauchi is semi-arid characterized by dry and wet seasons with low annual rainfall (585.5 – 640; and 820 – 890 mm mm) for a period of four to five months, low relative humidity and high temperatures as shown in Figure 4.5. Potential evapotranspiration in the study area is high. Moisture availability (ratio of rainfall to potential evaporation) is moderate as is within Moisture Zone 3 between 55 – 70%, similar to the study by Sambo, (2017) or normal monthly rainfall used to be below 250 mm in August (peak month) and 619 mm per annum using Potiskum Met. Station 1981 to 2010 base year as documented by Sambo (2017).

**vi. Hydrology/Drainage**

The map in Figure 4.6 shows the hydrology of the study area indicating Stream Orders from 1<sup>st</sup> Stream Order through the 4<sup>th</sup> Stream Order towards two outlets. First Outlet traverses between Gadau and Itas towns continues Northeastward Sakwa near Katagun and Gamawa towns to Lodio, towards northward of Jakusko in Yobe State.

The second outlet of 4<sup>th</sup> Order Stream transverses mid-way Misau – Kari toward north-eastward to Akuyam, around Bulkachuwa and Dingaiwa village in Yobe boundary.

The total length of the Rivers and Streams in the study area is 7,263.94 km. While the 1<sup>st</sup> and 2<sup>nd</sup> Stream Orders stretched to 5,862.71 km and 820.96 km, the 3<sup>rd</sup> and 4<sup>th</sup> Stream Orders also stretched to 366.26 km and 214.01 km respectively. The Figure therefore, indicates the area is well drained, Appendix C. The 1<sup>st</sup> and 2<sup>nd</sup> stream orders account for 6.683.67 km making up 92.01% of the total stream orders in the area.

**vii. Proximity to River/Stream and Drainage Density**

The study area considered distance from river as an additional zone for vulnerability to flood, where closer to river/streams as more vulnerability to flood and farther away as less vulnerability. The area is drained by three main Rivers (4<sup>th</sup> and 3<sup>rd</sup> Order Streams – see Figures 4.6 and 4.7). Two main 4<sup>th</sup> Order Streams Gulmo/Gadau and Misau River respectively run North-eastward. The 3<sup>rd</sup> Order stream runs between Jawo and Chinade leaving Azare to the left to Jakusko in Yobe State. The 3<sup>rd</sup> Order Stream is one of the main tributaries of Gulmo/Gadau meet at Karage in Yobe State. The two 4<sup>th</sup> Order Streams traverse into Yobe State to meet River Komadugu Yobe to the North-west of Yobe State. Drainage Density (DD), is a ratio of the sum of the drainage lengths to the surface area (Greenbaum, 1989). The DD of the study area shows 7,263.94km/15,204.01km<sup>2</sup> (0.478 km/km<sup>2</sup>) as shown in Figure 4.8. This is interpreted as low runoff area and is also flat or gentle sloping terrain as shown from elevation and slope maps. The result is a key conditioning factor that strongly contributes to flooding, also observed as occurrence by Tehrany & Kumar (2018).

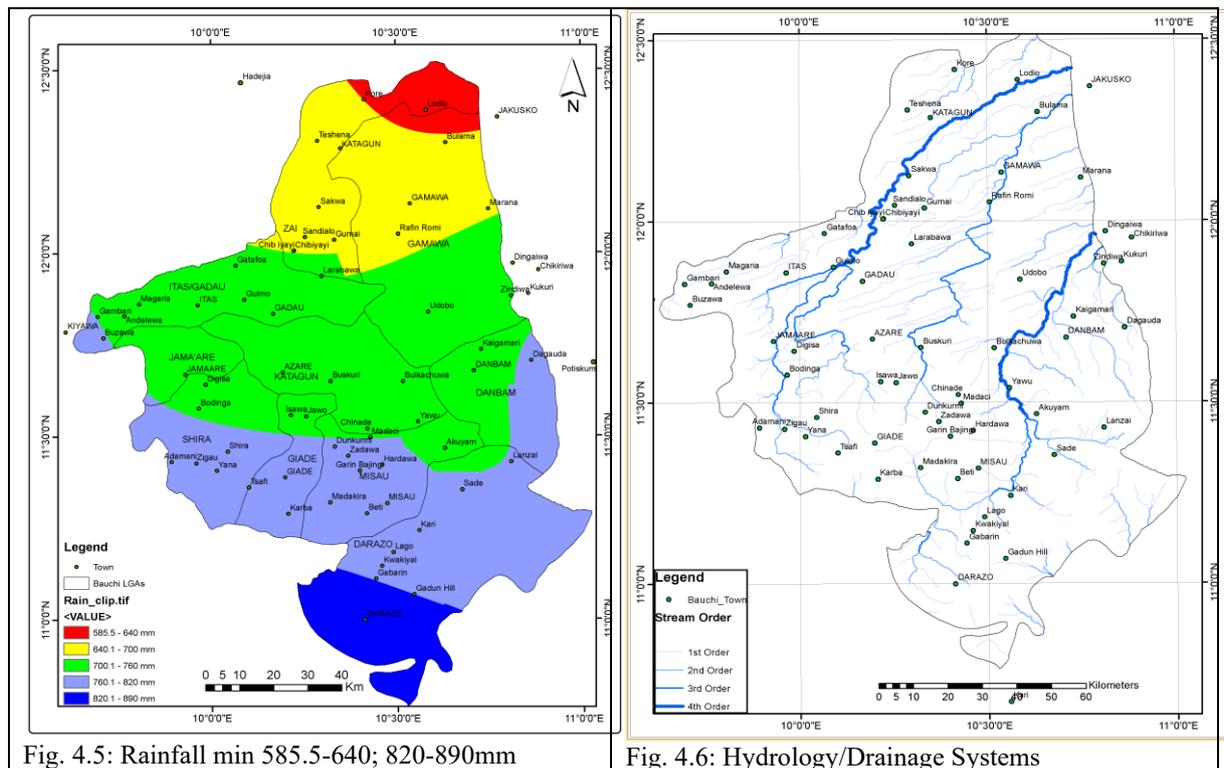


Fig. 4.5: Rainfall min 585.5-640; 820-890mm

Fig. 4.6: Hydrology/Drainage Systems

**viii. Soil Types**

The Soil Classification, Texture and Extent of the study area in Northern Bauchi State are used in soil erosion modelling. The Northern part of Bauchi State is covered by Six Soil Units (6 units) correspond to FAO Soil Classification Factors, viz: Je Eutric Fluvisols; Qc Cambic Arenosols; Re Eutric Gleysols; Ql Luvisols; Lp Plinthic Luvisols; and Nd Dystric Nitosols, see Figure 4.9 and Appendices B and C, within the 10 LGAs. The dominant soil type in the area is Ql Luvisols soil type covering 6,180.41 km<sup>2</sup> (41.13%). Others are Re Eutric Gleysols and Nd Dystric Nitosols soil classes covering 20% (3,107.85 km<sup>2</sup>) and 12.92% (1,940.82 km<sup>2</sup>) respectively, see the Appendices D and E that show the Tabular classes of soil and extent per class.

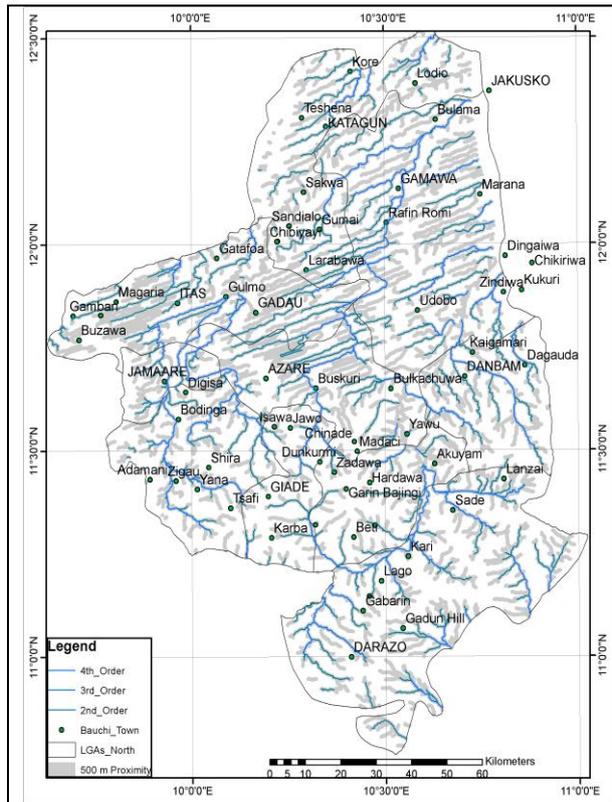


Fig. 4.7: 500 m Distance from Rivers/Streams

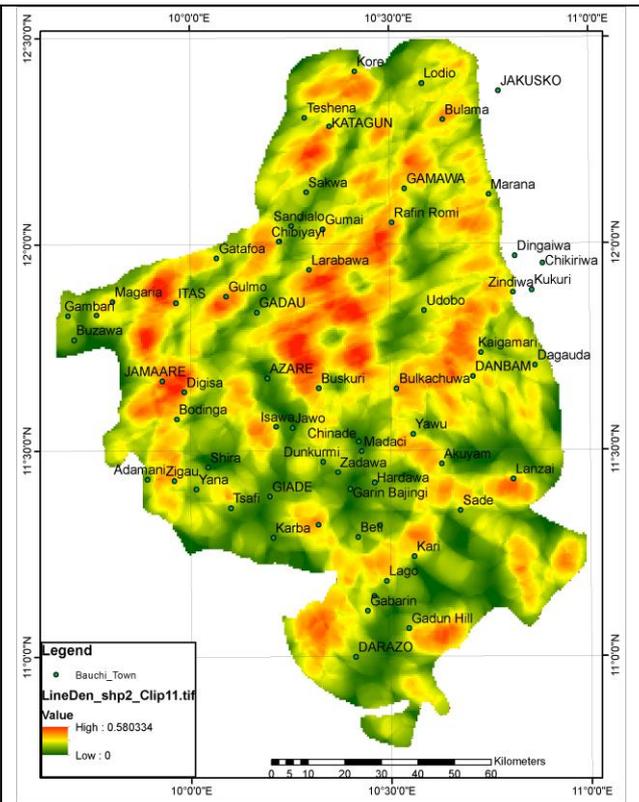


Fig. 4.8: Drainage Density

**ix. Topographic Wetness Index (TWI)**

The results of Topographic Wetness Index (TWI) show spatial distribution of wetness and it controls the overland flow of water in the area. Accordingly, the TWI shows its contribution to flood mapping in the area. The TWI, also known as the compound topographic index (CTI), is a steady-state wetness index. As the product of slope and upstream area per unit width perpendicular to the flow direction, the TWI results in the area shows good correlation with the soil properties and phosphorous and hence, directly influencing flood vulnerability. This confirms Haggard *et al.* (2002) discovery. The study calculated TWI from the Equation 4.2, as developed by Beven and Kirkby, (1979). The TWI looks similar to the results from Pourghasemi, *et al.*, 2013; and Haggard *et al.* (2002).

$$TWI = Ln\left(\frac{a}{\tan\beta}\right) \quad \text{Equation 4.2}$$

Where: "a" is the catchment area [a = A/L, total area (A) divided by length of contour (L)], and B is slope in degree.

High TWI values indicate area with high water accumulation potentials, which are floodplains, depression and valleys. The high value of TWI is represented by dark red colour, red and the low value is represented by blue colour. The TWI of the study area as shown in Figure 4.10 indicates fewer areas with very high to high vulnerability surface areas. These are surfaces that are either concave and/or flat surfaces that stagnate water.

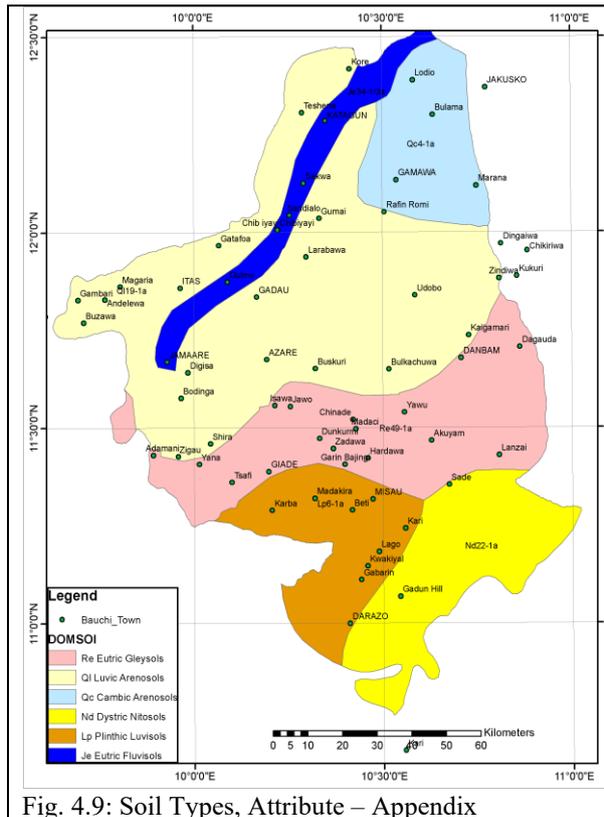


Fig. 4.9: Soil Types, Attribute – Appendix

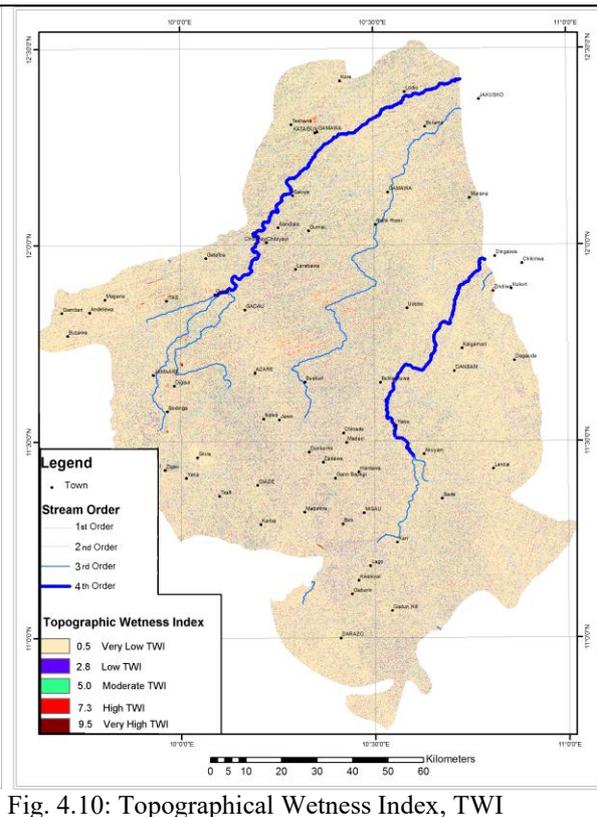


Fig. 4.10: Topographical Wetness Index, TWI

#### 4.2 Results of Weights Allocations and Standardisations

The results of the weight allocation and standardization for each flood-causative factor, proportionate to the K-Means classification (five classes ranging from 1 to 5), are presented in Table 4.3. The lowest class value (1) represents a low probability of flood risk, whereas the highest-class value (5) indicates a very high probability of flood risk. The class-wise allocation for each dataset was determined based on expert judgment and a review of relevant literature, taking into account the varying degrees of influence of each factor on flooding. Table 4.3 therefore summarizes the assigned weights, class rankings, and standardization of all factors incorporated into the flood vulnerability modelling process.

Land use/land cover (LULC) and Normalized Difference Vegetation Index (NDVI) were merged and assigned a combined 5% weight, as they function primarily as flood-receiving elements rather than direct causative factors. Elevation, slope, rainfall, drainage density, Topographic Wetness Index (TWI), and distance to river were assigned weights of 20%, 30%, 30%, 5%, 5%, and 5%, respectively. The distribution of these weights was carried out proportionally through standardization using the K-Means clustering method for the classification of each criterion, as contained in Table 4.3.

Table 4.3: Weights Allocations and Standardisations

S/No.	Flood Causative Factor	Susceptibility Class Ranges and Ratings	Susceptibility Class (K-Means)	Classes	Weight Standardization	Weight (%)
1&2	Land use land cover and NDVI (Vegetation Cover)	Very High	5	Hydrology /Open water	2.00	05
		High	4	Bare Surface	1.50	
		Moderate	3	Settlements	0.75	
		Low	2	Vegetation	0.50	
		Very Low	1	Forest	0.25	
<b>TOTAL</b>					<b>5.00</b>	
3.	Elevation	Very High	5	Very High Vulnerability	6.67	20
		High	4	High Vulnerability	5.33	
		Moderate	3	Moderate Vulnerability	4.00	
		Low	2	Low Vulnerability	2.67	
		Very Low	1	Very Low Vulnerability	1.33	

<b>TOTAL</b>					<b>20.00</b>	
4.	Slope	Very High	5	Very High Vulnerability	10.00	30
		High	4	High Vulnerability	8.00	
		Moderate	3	Moderate Vulnerability	6.00	
		Low	2	Low Vulnerability	4.00	
		Very Low	1	Very Low Vulnerability	2.00	
<b>TOTAL</b>					<b>30.00</b>	
5.	Rainfall	Very High	5	-	10.00	30
		High	4	-	8.00	
		Moderate	3	-	6.00	
		Low	2	-	4.00	
		Very Low	1	-	2.00	
		<b>TOTAL</b>				
6.	Drainage Density	Very High	5	Very High Vulnerability	1.67	05
		High	4	High Vulnerability	1.33	
		Moderate	3	Moderate Vulnerability	1.00	
		Low	2	Low Vulnerability	0.67	
		Very Low	1	Very Low Vulnerability	0.33	
<b>TOTAL</b>					<b>5.00</b>	
7.	Distance from River	Very Wet	5	Very High Vulnerability	1.67	05
		Wet	4	High Vulnerability	1.33	
		Moderate	3	Moderate Vulnerability	1.00	
		Dry	2	Low Vulnerability	0.67	
		Very Dry	1	Very Low Vulnerability	0.33	
<b>TOTAL</b>					<b>5.00</b>	
8.	TWI	Very High	5	Very High Vulnerability	1.67	05
		High	4	High Vulnerability	1.33	
		Moderate	3	Moderate Vulnerability	1.00	
		Low	2	Low Vulnerability	0.67	
		Very Low	1	Very Low Vulnerability	0.33	
<b>TOTAL</b>					<b>5.00</b>	
Total Weight Allocation and Standardization					100.00	100%

### 4.3 Results of Flood Vulnerability Mapping

Flood vulnerability zone mapping aims to produce a comprehensive flood vulnerability map that shows the spatial distribution and extent of flood susceptibility across the study area. The flood vulnerability map was generated using the Analytical Hierarchy Process (AHP) model through the weighted overlay of flood-causative parameters – Elevation, slope, rainfall, drainage density, distance from river, and Topographic Wetness Index (TWI) – alongside flood-receiving elements, namely land use/land cover (LULC) and Normalized Difference Vegetation Index (NDVI). This integrated approach was employed to establish flood risk knowledge for Northern Bauchi State.

Figure 4.11 presents the flood vulnerability map, which classifies the study area into five distinct zones: very low flood vulnerability, low flood vulnerability, moderate flood vulnerability, high flood vulnerability, and very high flood vulnerability. The results indicate that highly vulnerable zones are predominantly concentrated in the central and southwestern parts of the study area. Conversely, areas with low flood vulnerability are mainly located around the higher elevation regions of Darazo, Giade, and Misau. This has conformed to the documented evidence by NiMet, (2024), and Alimi, *et al.*, (2022) that areas with low flood vulnerability are mainly found in high elevations.

Table 4.4 summarizes the areal extent of each vulnerability zone calculated from Figure 4.11. Approximately 57.9% of the total landmass falls within the moderate to low flood vulnerability categories, while 42.1% lies within the high to very high flood vulnerability zones. This proportion is significantly high and is an indication that the Northern part of Bauchi State is vulnerable to flood (42.1%). Localities situated in the high and very high flood vulnerability zones are therefore more likely to experience severe impacts during periods of intense rainfall or flooding, whereas areas classified as low and very low flood vulnerable zones are least likely

to be affected by flood events.

One striking discovery from the results is that the pattern of the Flood Vulnerability Zones in Northern Bauchi follows the distribution of soil and rainfall in the area. This suggests that areas such as Jama'are, part of Azare, in the central and Gawawa, Sakwa in the north with certain soil types and high rainfall are more prone to flooding.

Table 4.4: Extent of Flood Vulnerability Zones

<i>Zone</i>	<i>Count</i>	<i>Vulnerability Class</i>	<i>Area km<sup>2</sup></i>	<i>Proportion (%)</i>
5	13,436,770	Very High Flood Vulnerability	2,099.29	14.1
4	26,737,789	High Flood Vulnerability	4,177.37	28.0
3	26,005,863	Moderate Flood Vulnerability	4,063.02	27.3
2	22,063,168	Low Flood Vulnerability	3,447.03	23.1
1	7,137,049	Very Low Flood Vulnerability	1,115.06	7.5
<i>Total</i>			<b>14,901.77</b>	<b>100.00</b>

#### 4.4 Validation of the Results

The results were validated using 63 historical flood locations collected with a Garmin eTrex® 10 GPS and overlaid on the flood vulnerability map. Validation of prediction results is crucial for reliable knowledge and ensuring acceptable prediction accuracy (Pourghasemi *et al.*, 2013; Alimi *et al.*, 2022; and NiMet, 2024). The overlay of the historical flood locations on the flood vulnerability zone map revealed that the 94% of the points fall within the very high and high flood vulnerable zones. This outcome confirms the reliability and validity of the methodology adopted in this study, as presented in Figure 4.11. Furthermore, the behaviour of the graph in Figure 4.12 exhibits a bell-shaped normal distribution curve, which further supports the robustness and consistency of the model's results and methodology applied.

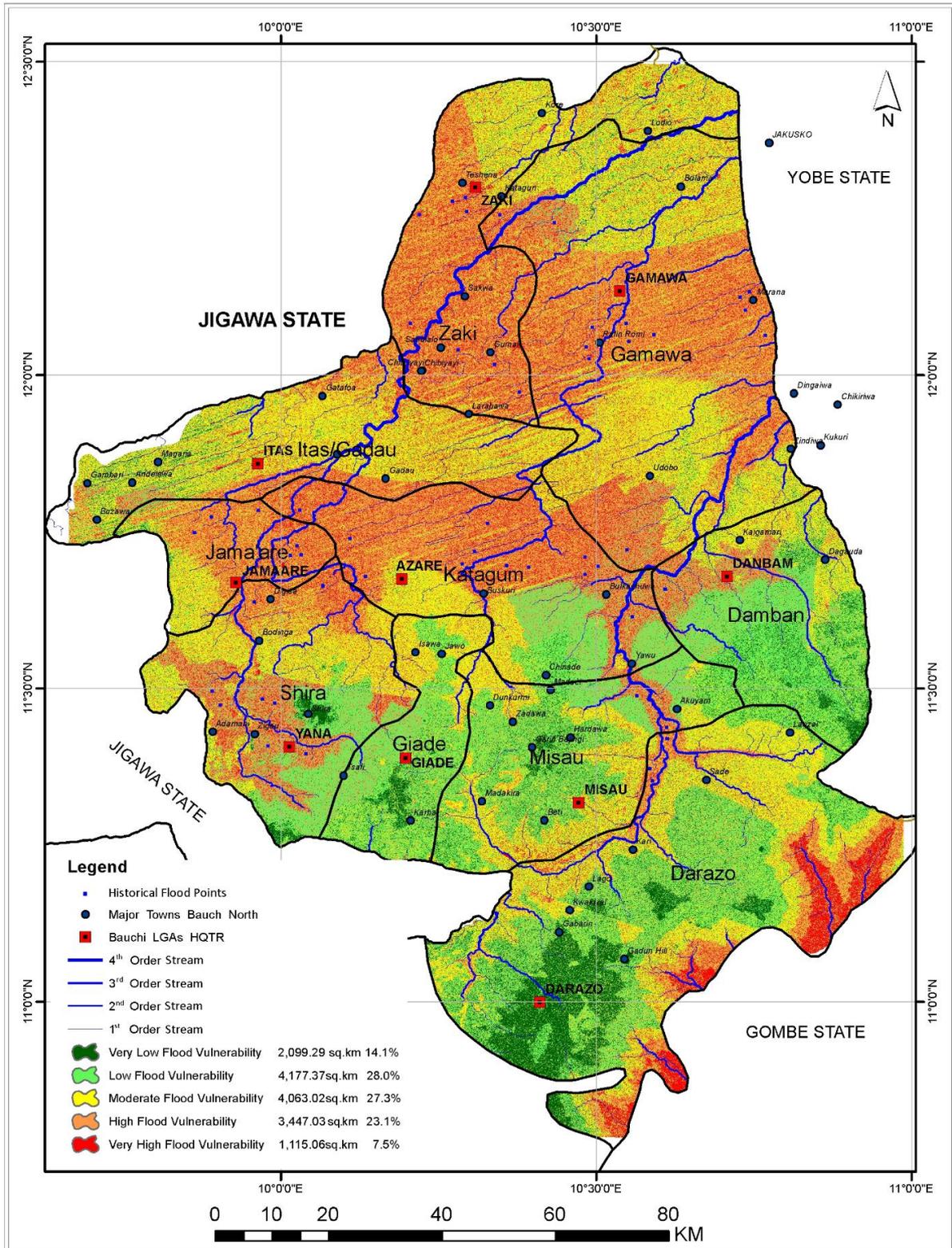


Figure 4.11: Flood Vulnerability Zones in Northern Bauchi State

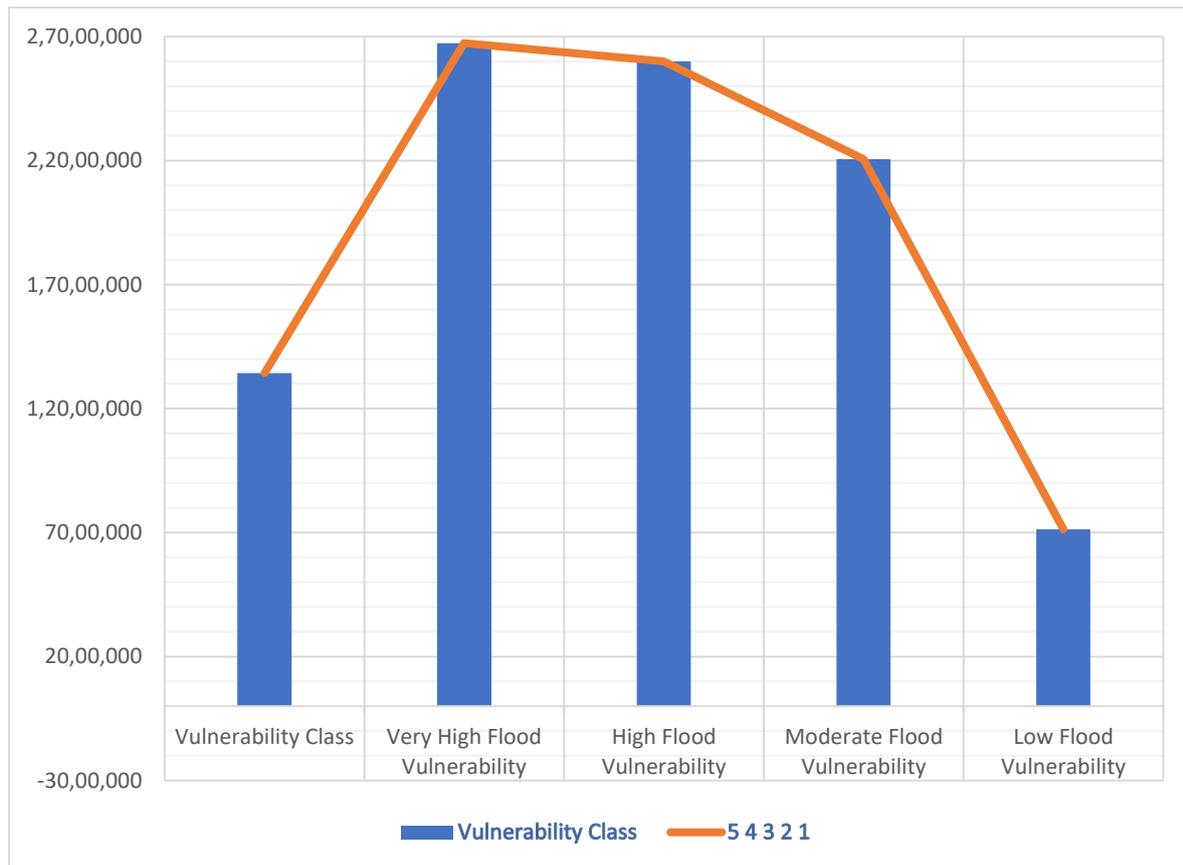


Figure 4.12: The Behaviour of the Flood Vulnerability Zones in Northern Bauchi State

#### IV. Conclusions

The recurrent flooding along the Jama’are River in Northern Bauchi State during the rainy season underscores the necessity of this study, which focused on mapping flood-vulnerable zones to determine the specific locations and extent of flood susceptibility. Flood vulnerability zone mapping is a vital pre-disaster management technique for predicting flood-prone areas (Alimia *et al.*, 2022). In this study, flood-vulnerable zones in Northern Bauchi State were delineated using the Analytical Hierarchy Process (AHP), incorporating eight identified flood-inducing factors. The resulting flood vulnerability zones were classified into five categories using the K-Means clustering approach: Very High Flood Vulnerable Zone, High Flood Vulnerable Zone, Moderate Flood Vulnerable Zone, Low Flood Vulnerable Zone, and Very Low Flood Vulnerable Zone.

The results reveal the spatial distribution of all vulnerability categories across the study area. Very high and high flood vulnerability zones cover 2,099.29 km<sup>2</sup> (14.1%) and 4,177.37 km<sup>2</sup> (28.0%) respectively. Moderate and low flood vulnerability zones occupy 4,063.02 km<sup>2</sup> (27.3%) and 3,447.03 km<sup>2</sup> (23.1%), while the very low flood vulnerable zone accounts for 1,115.06 km<sup>2</sup> (7.5%) of the study area.

Validation of the flood vulnerability map was carried out using observed historical flood incidence locations collected across the area. These locations, when overlaid on the final flood vulnerability map, were predominantly found within the very high and high flood vulnerable zones and in close proximity to the Jama’are River and its tributaries, which extend from the south-western to the north-eastern parts of the study area. These findings confirm the effectiveness of geospatial techniques in mapping flood-risk areas and enhancing flood risk knowledge. The AHP model proved useful in detecting and visualizing spatial information necessary for efficient flood management. Understanding flood vulnerability is therefore critical for effective flood risk reduction strategies.

Based on the findings, it is strongly recommended that settlement’s development along the banks of the Jama’are River be discouraged, particularly within the highly vulnerable zones depicted by the reddish landscape in Figure 4.11. Government authorities should also prioritize the desilting and dredging of major rivers traversing flood-prone areas. Furthermore, there is an urgent need for comprehensive land-use mapping and planning to achieve a sustainable solution to flood disasters. The methodology adopted in this study is robust and can be replicated for further flood vulnerability assessments in other parts of Bauchi State.

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**Appendix A**

**Distribution and Extent of Land Use Land Cover (2023) in Northern Bauchi State**

S/No.	Name	Area (km <sup>2</sup> )	Proportion %
1.	Farmland	44.4	0.30
2.	Vegetation/Forest	200.3	1.33
3.	Waterbody/Hydrology	442.1	2.94
4.	Bare Surface/ Dispersed shrubs	14,220.0	94.64
5.	Settlements	118.9	0.79
<b>Total</b>		<b>15,025.68</b>	<b>100.00</b>

**Appendix B**

**Distribution and Extent of Normalised Difference Vegetation Cover (NDVI) in Northern Bauchi State**

OBJECT-ID	NDVI Value (Range)	Class Name	Area_km <sup>2</sup>	%
1	0 - 0.216	Water & Marshy Area	30.74	0.20
2	0.217 - 0.428	Bare Surface	4,837.62	31.82
3	0.429 - 0.481	Weak Vegetation Cover	7,625.36	50.15
4	0.482 - 0.561	Moderate Vegetation Cover	1773.20	11.66
5	0.562 - 0.677	Good Vegetation Cover	937.18	6.16

**Appendix C**

**Distribution and Extent of Drainage Density in Northern Bauchi State**

FID	Shape	OBJECT-ID	Arc-ID	Stream Order	From-Node	To-Node	Length (Km)	%
1	Polyline	1.00	1	1	-1	-3	5,862.71	80.71
3	Polyline	9.00	9	2	18	-2	820.96	11.30
4	Polyline	269.00	269	3	245	246	366.26	5.04
5	Polyline	124.00	124	4	121	-109	214.01	2.95
<b>TOTAL</b>							<b>7,263.94</b>	<b>100.00</b>

Appendix D  
Soil Classification and Texture of Northern Bauchi State

S / N	Soil Classification	S o i l u n i t s y m b o l	s a n d % t o p s o i l	s a n d % s u b s o i l	s i l t % t o p s o i l	s i l t % s u b s o i l	c l a y % t o p s o i l	c l a y % s u b s o i l	P H 2 O t o p s o i l	P H 2 O s u b s o i l	O C % t o p s o i l	O C % s u b s o i l	N % t o p s o i l	N % s u b s o i l	B S % t o p s o i l	B S % s u b s o i l	C E C t o p s o i l	C E C s u b s o i l	C E C c l a y t o p s o i l	C E C c l a y s u b s o i l	C a C O 3 % t o p s o i l	C a C O 3 % s u b s o i l	B D t o p s o i l	B D s u b s o i l	C / N t o p s o i l	C / N s u b s o i l
1	Eutric Fluvisols	Je	70.8	67.8	12.8	14.1	16.5	18.9	6.6	6.9	1.1	0.6	0.2	0.1	8.6	9.0	1.1	1.1	5.4	5.9	0.0	0.0	0.9	0.8	1.4	1.3
2	Cambic Arenosols	Qc	92.3	92.3	3.2	2.9	4.8	6.5	6.4	0.2	0.1	3.0	0.0	8.2	7.9	3.6	3.2	5.8	5.5	0.1	0.2	1.4	1.4	1.0	1.1	
3	Eutric Gleysols	Re	68.3	71.6	15.1	15.2	16.6	3.2	6.4	6.8	0.5	0.5	0.6	0.6	8.3	7.6	1.0	0.6	4.4	4.2	1.6	0.4	1.4	1.2	9.9	7.7
4	Luvic Arenosols	Ql	92.8	91.7	2.7	2.9	4.7	5.5	6.3	6.1	0.2	0.2	0.2	0.2	7.4	7.2	3.5	3.2	5.8	5.7	0.2	0.4	-	-	1.0	0.5
5	Plinthic Luvisols	Lp	69.9	57.5	10.5	10.9	11.5	3.6	5.9	5.6	0.7	0.3	0.7	-	7.2	6.1	7.1	9.2	3.4	2.8	0.0	0.0	1.8	1.6	2.2	-
6	Dystric Nitosols	Nd	38.9	31.9	17.6	13.8	4.3	5.4	5.2	5.2	1.5	0.4	0.1	0.0	2.9	2.3	1.5	1.9	3.1	1.9	0.0	0.0	1.1	1.2	1.3	0.8

Source: Land and Water Development, FAO data, Version 3.6, (2003)

Appendix E  
Soil Classification and Extent in Northern Bauchi State

FID	Shape *	FAOSOIL	DOMSOI	Soil Classification	Area km2	%
1.	Polygon	Je34-1/3a	Je	Je Eutric Fluvisols	845.47	5.63
2.	Polygon	Qc4-1a	Qc	Qc Cambic Arenosols	1,381.43	9.19
3.	Polygon	Re49-1a	Re	Re Eutric Gleysols	3,107.85	20.68
4.	Polygon	Ql19-1a	Ql	Ql Luvic Arenosols	6,180.41	41.13
5.	Polygon	Lp6-1a	Lp	Lp Plinthic Luvisols	1,569.02	10.44
6.	Polygon	Nd22-1a	Nd	Nd Dystric Nitosols	1,940.82	12.92
<b>TOTAL</b>					<b>15,025.00</b>	<b>100.00</b>

Source: Processed FAO data, Version 3.6, (2003)