

GIS-Based Watershed Delineation and Hydrological Characterisation of Borno Watershed, Nigeria

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ABSTRACT

This study examined the delineation and hydrological characterisation of the Borno Watershed, Nigeria, using Geographic Information System (GIS)-based techniques. The study was motivated by recurring flooding, land degradation, and water resource management challenges within the watershed. Four objectives were pursued: to determine the flow direction characteristics, analyse flow accumulation patterns, evaluate sink-filled elevation characteristics, and delineate the basin extent and hydrological boundaries of the watershed. A quantitative spatial analysis design was adopted, using the GTOPO30 Digital Elevation Model (DEM), aggregated to a 3,700 m cell size and projected to the Africa Albers Equal Area Conic system, and processed in ArcGIS 10.8.1 with the Spatial Analyst Hydrology tools. Sink filling, D8 flow direction, flow accumulation, stream extraction, and watershed delineation were performed to generate watershed characteristics, and descriptive statistics were used to summarise the outputs. Flow direction values ranged from 1 to 128, representing the eight D8 drainage directions. Flow accumulation in the full raster ranged from 0 to 10,958 cells, and within the watershed from 0 to 5,035 cells (68,929 km²), with cells above 1,418 cells (19,412 km²) marking the principal runoff-concentration corridor. The value of -9,999 in the filled DEM was identified as the NoData flag rather than an elevation; valid elevations within the watershed ranged from 275 m to 1,070 m (mean 345 m). The delineated watershed covers 68,943 km² with a perimeter of 1,700 km and a drainage density of 0.13 km/km². The basin raster contains 732 numbered drainage zones, and the two value classes 1–32 and above 32–128 are grouped flow direction classes, not basin classes. Zones of high accumulation are described as flood-susceptible zones, and this description was compared with documented flood events, including the 2024 Alau Dam flood at Maiduguri, and with rainfall information, although field validation was not carried out. The study concluded that GIS-based watershed delineation provides useful information for sustainable watershed management in Borno State and recommended flood-control infrastructure, GIS-based monitoring, watershed conservation, and use of the delineated boundary for water resources planning.

Keywords: GIS, watershed delineation, flow accumulation, hydrological modelling, Borno State.

1.0 INTRODUCTION

Watersheds are fundamental hydrological units that regulate the collection, storage, movement, and discharge of surface and subsurface water within a defined drainage area. Effective watershed delineation and hydrological characterisation are essential for water resources management, flood mitigation, agricultural planning, environmental sustainability, and climate resilience. The advancement of Geographic Information Systems (GIS) and Remote Sensing technologies has significantly improved the accuracy of watershed mapping and hydrological analysis by enabling the extraction of drainage networks, flow direction, flow accumulation, basin boundaries, and terrain characteristics from Digital Elevation Models (DEMs) (Maidment, 2002; Jenson & Domingue, 1988).

Borno State, located in northeastern Nigeria, experiences recurring hydrological challenges including seasonal flooding, droughts, land degradation, and water scarcity. These challenges have intensified due to climate variability, rapid population growth, and increasing pressure on available water resources. Consequently, there

is a growing need for scientific assessment of watershed characteristics to support sustainable water resources planning and disaster risk reduction. GIS-based watershed analysis provides a reliable framework for understanding drainage behaviour, identifying flow accumulation zones, and supporting evidence-based environmental management decisions (FAO, 2019).

The hydrological analysis generated flow direction codes from 1 to 128, flow accumulation values reaching 10,958 cells in the full raster, a sink-filled elevation surface, and basin delineation outputs for the Borno watershed. Because the full raster extends well beyond the watershed and contains NoData cells, this paper reports the raster-wide statistics separately from the valid statistics extracted within the watershed boundary. These parameters provide information for understanding runoff patterns, erosion susceptibility, groundwater recharge potential, and flood susceptibility.

1.1 Statement of the Problem

Borno State has experienced increasing incidences of flooding, soil erosion, declining water availability, and environmental degradation. Despite the significance of watershed management in addressing these challenges, comprehensive geospatial assessments of watershed characteristics remain limited. The absence of accurate hydrological information hinders effective planning for flood control, irrigation development, watershed conservation, and climate adaptation initiatives.

Previous studies have largely focused on regional climate variability and disaster impacts, with limited attention given to detailed GIS-based watershed delineation and hydrological modelling in Borno State. Without adequate knowledge of drainage patterns, flow accumulation zones, and watershed boundaries, policymakers and environmental managers face difficulties in implementing sustainable water resource management strategies (Ayoade, 2004; Ward & Robinson, 2000). Therefore, this study seeks to delineate and characterise the Borno watershed using GIS-based hydrological tools to provide empirical evidence for improved environmental planning and watershed management.

1.2 Objectives of the Study

General Objective

To delineate and characterise the Borno Watershed using GIS-based hydrological analysis.

Specific Objectives

1. To determine the flow direction characteristics of the Borno watershed.
2. To analyse flow accumulation patterns within the watershed.
3. To evaluate sink-filled elevation characteristics of the watershed terrain.
4. To delineate the basin extent and hydrological boundaries of the Borno watershed.

1.3 Research Questions/Hypotheses

Research Questions

1. What are the flow direction characteristics of the Borno watershed?
2. What are the flow accumulation patterns within the watershed?
3. What are the sink-filled elevation characteristics of the watershed?
4. What is the spatial extent of the delineated Borno basin?

Research Hypotheses

H₀₁: Flow direction values do not significantly influence drainage patterns within the Borno watershed.

H₀₂: Flow accumulation values do not significantly determine runoff concentration zones within the watershed.

H₀₃: Sink-filled elevation characteristics do not significantly influence watershed hydrology.

H₀₄: Basin delineation does not significantly define the hydrological boundaries of the watershed.

2.0 REVIEW OF LITERATURE

2.1 Conceptual Framework

The conceptual framework of this study is based on the relationship between topographic characteristics and hydrological processes. Digital Elevation Models (DEMs) serve as the primary input for hydrological analysis, from which flow direction, flow accumulation, sink filling, and basin delineation are derived. Flow direction determines the path of water movement across terrain surfaces, while flow accumulation identifies areas where runoff converges and concentrates (Jenson & Domingue, 1988).

Sink filling removes artificial depressions within DEM datasets, thereby improving the continuity of surface water flow and ensuring accurate watershed delineation. Basin delineation subsequently defines the geographical boundaries within which precipitation contributes runoff to a common outlet. Together, these hydrological variables influence watershed behaviour, flood susceptibility, groundwater recharge, and water resource availability (Maidment, 2002).

The framework assumes that variations in terrain elevation directly influence drainage network formation and runoff concentration patterns, which subsequently affect watershed functionality and environmental sustainability.

2.2 Theoretical Framework

This study is anchored on the Hydrological Systems Theory proposed by Chow (1964). The theory views a watershed as an interconnected system consisting of inputs, storage components, transfer mechanisms, and outputs. Inputs include precipitation and surface runoff, while outputs include streamflow and evapotranspiration.

According to the theory, watershed response is largely controlled by terrain morphology, drainage characteristics, and hydrological connectivity. Flow direction and flow accumulation represent transfer mechanisms within the watershed system, while basin delineation defines the spatial extent through which hydrological processes operate. Sink-filled elevation models improve system representation by removing topographic anomalies that may distort flow routing (Chow, 1964; Ward & Robinson, 2000).

The theory is appropriate because it provides a scientific basis for understanding how topographic conditions influence water movement and watershed behaviour in Borno State.

2.3 Empirical Review

Maidment (2002) applied GIS hydrological modelling in Texas watersheds and reported that flow accumulation analysis improved flood-risk identification and watershed management planning.

Aher et al. (2014) utilised DEM-based watershed delineation techniques in India and found that accurate basin delineation significantly enhanced water resources planning and irrigation development.

Akintola and Olayinka (2021) examined watershed characteristics in northern Nigeria and observed that flow

accumulation zones corresponded strongly with areas prone to seasonal flooding.

Agarwal et al. (2013) employed sink-filling algorithms in watershed modelling and concluded that terrain correction substantially improved drainage network extraction and hydrological simulations.

2.4 Gap Identification

Previous studies have demonstrated the usefulness of GIS in watershed management; however, few studies have conducted a comprehensive hydrological characterisation of the Borno watershed using integrated flow direction, flow accumulation, sink filling, and basin delineation parameters, and fewer still have compared the results with documented flood events and rainfall information. This study fills this gap by providing hydrological evidence specific to Borno State, thereby contributing to watershed planning and environmental management.

3.0 METHODOLOGY

3.1 Research Design

The study adopted a quantitative GIS-based spatial analysis design. Secondary geospatial data derived from a Digital Elevation Model (DEM) were used for hydrological modelling, and the results were compared with published flood records and rainfall information.

3.2 Study Area

Borno State lies in northeastern Nigeria, between approximately latitudes 10.0° N and 13.7° N and longitudes 9.9° E and 14.7° E, and borders Lake Chad, Niger, Cameroon, and Chad. The delineated watershed covers most of the state and drains toward Lake Chad through channels such as the Ngadda River, on which the Alau Dam near Maiduguri was built in 1986. The climate is semi-arid (Sudan–Sahel), with a rainy season that lasts from about June to September. Seasonal predictions by the Nigerian Meteorological Agency (NiMet, 2023) place annual rainfall at roughly 450–500 mm in the north (for example Abadam, Bama, and Kala/Balge) and above 840 mm in the south (Biu, Askira/Uba, and Bayo), as shown in Table 3.4.

3.3 Data Source and Data Description

Table 3.1 documents the input dataset and software.

Table 3.1: Specification of the Input DEM and Processing Environment

Item	Specification
DEM product / source	GTOPO30 global digital elevation model, U.S. Geological Survey (USGS) EROS Data Center (USGS, 1996)
Tile used	W020N40
Acquisition / release date	Product released 1996; downloaded in 2026
Original spatial resolution	30 arc-seconds (≈ 1 km)
Original coordinate system	GCS WGS 1984 (EPSG:4326)
Vertical datum and unit	Mean sea level; metres
Processing projection	Africa Albers Equal Area Conic (ESRI:102022), an equal-area system suited to area computation
Processing cell size	3,700 m (aggregated and resampled by bilinear interpolation); one cell = 13.69 km ²



NoData value	–9999 (flag for cells outside the land surface and for missing data)
Clipping extent	Lake Chad Basin extent buffered by 50 km (Extract by Mask)
Software	ArcGIS Desktop 10.8.1 with the Spatial Analyst extension (Hydrology toolset)

Source: Authors' compilation, 2026

3.4 Data Processing Procedures

The workflow followed the standard Arc Hydro and Spatial Analyst procedure (Jenson & Domingue, 1988; Maidment, 2002). Each step is described below and summarised in Table 3.2 so that the analysis can be replicated.

Step 1: DEM preparation. The DEM was reprojected (Project Raster) to the Africa Albers Equal Area Conic system, resampled to a 3,700 m cell size, and clipped to the study extent (Extract by Mask). The NoData value was set to –9999 in the raster properties so that these cells were excluded from calculations.

Step 2: Sink filling. The Sink tool identified 187 depression cells inside the watershed DEM. These were removed with the Fill tool (Spatial Analyst Tools → Hydrology → Fill) with no z-limit, so that all sinks were filled. The output is Borno_Fill. Running the Sink tool on Borno_Fill returned no sink cells.

Step 3: Flow direction. The D8 algorithm (Flow Direction tool) was applied to Borno_Fill. Each cell receives one of eight power-of-two codes according to the direction of steepest descent: 1 = East, 2 = Southeast, 4 = South, 8 = Southwest, 16 = West, 32 = Northwest, 64 = North, and 128 = Northeast. The output is Borno_Fdir.

Step 4: Flow accumulation. The Flow Accumulation tool was applied to Borno_Fdir with no weight raster. Each cell value is the number of upstream cells draining into it, and contributing area (km²) = cells × 13.69. The output is Borno_Acc.

Step 5: Flow accumulation thresholds. Two thresholds were used. (a) The stream-initiation threshold was set at 15 cells (205 km² of contributing area, or 0.14% of the maximum accumulation in the full raster), using the Raster Calculator expression `Con("Borno_Acc" > 15, 1)`; the output is Borno_Algebra (1 = stream cell, 0 = other cells). This value was chosen after comparing thresholds of 5, 10, 15, 25, and 50 cells with the river network visible on satellite imagery. (b) A high-accumulation threshold of 1,418 cells (19,412 km²) was used to separate the principal runoff-concentration corridor from other cells. This value is the integer part of the 1,418.094 class break produced by the Natural Breaks classification of Borno_Acc, and because flow accumulation values are whole cell counts, cells with values above 1,418 fall in the high class. It is a classification break used for mapping, not a stream-initiation threshold.

Step 6: Stream ordering. The Stream Link and Stream Order tools (Strahler method) were applied to the stream raster, and Stream to Feature produced the vector drainage network (Borno_Stream).

Step 7: Outlet selection and watershed delineation. The outlet (pour point) was placed at the lower end of the principal drainage channel at Lake Chad, at approximately 13.5° N, 13.8° E. It was snapped to the highest-accumulation cell within 7,400 m (two cells) using Snap Pour Point. The Watershed tool was run on Borno_Fdir with the snapped pour point, and the result was converted to a polygon (Borno_Watershed). The Basin tool was run separately on Borno_Fdir to partition the raster into numbered drainage basins (Borno_Basin).

Step 8: Statistics and morphometry. Valid statistics for each raster were extracted within Borno_Watershed (Zonal Statistics as Table), with NoData excluded. Watershed area and perimeter were obtained with Calculate Geometry on the projected polygon, and drainage density was computed as total stream length divided by watershed area (Horton, 1932).

Table 3.2: Summary of Hydrological Processing Steps

Step	Process	ArcGIS tool (Spatial Analyst)	Output (unit)
1	DEM preparation	Project Raster, Extract by Mask	Borno_DEM (m)
2	Sink filling	Sink; Hydrology → Fill	Borno_Fill (m)
3	Flow direction (D8)	Hydrology → Flow Direction	Borno_Fdir (codes 1–128)
4	Flow accumulation	Hydrology → Flow Accumulation	Borno_Acc (number of cells)
5	Thresholds	Raster Calculator (Con); Natural Breaks classification	Borno_Algebra (0/1); high class above 1,418 cells
6	Stream ordering	Stream Link, Stream Order, Stream to Feature	Borno_Stream (vector, Strahler order)
7	Outlet and watershed	Snap Pour Point, Watershed, Basin	Borno_Watershed (polygon); Borno_Basin (zone IDs 1–732)
8	Statistics and morphometry	Zonal Statistics as Table, Calculate Geometry	Area (km ²), perimeter (km), Dd (km/km ²), elevation (m)

Source: Authors' compilation, 2026

3.5 Investigation of the –9,999 Value

The minimum value of –9,999 in Borno_Fill was investigated in four steps. First, the NoData setting in the raster properties was inspected, and –9999 was found to be the declared NoData value of the source DEM. Second, the cells holding –9999 were selected with SetNull("Borno_Fill" == –9999) and mapped; they coincide with the ocean and other areas outside the land surface, and none fall inside Borno_Watershed. Third, the statistics were recalculated with these cells excluded. Fourth, valid elevation statistics were extracted separately for the watershed. The value of –9,999 is therefore a NoData flag and not a processing error, and it is not an elevation. The valid statistics are reported in Table 4.3.

3.6 Analytical Tools

ArcGIS Hydrology toolset, Spatial Analyst extension, and descriptive statistical analysis.

Table 3.3: Description of Raster Variables and Units

Raster	Value range	Unit / type	Meaning
Borno_Fill	275 – 1,070 within the watershed	Metres above mean sea level	Sink-free elevation surface. The full raster maximum is 6,125 m; –9999 is NoData.
Borno_Fdir	1, 2, 4, 8, 16, 32, 64, 128	Categorical D8 code	Direction of steepest descent from each cell.
Borno_Acc	0 – 5,035 within the watershed (0 – 10,958 full raster)	Number of upstream cells (13.69 km ² each)	Runoff convergence; high values mark channels.
Borno_Algebra	0, 1	Binary	Stream cells (1) from the 15-cell threshold.
Borno_Basin	1 – 732	Zone ID (no unit)	Numbered drainage basins from the Basin tool; the number of zones, not a measure of size.

Source: Authors' compilation, 2026

4.0 DATA ANALYSIS

4.1 Thematic Maps

Figure 1 shows the combined outputs, and Table 4.1 lists the layers, symbology, and cartographic elements for each thematic map (watershed boundary, flow direction, flow accumulation, and stream network).

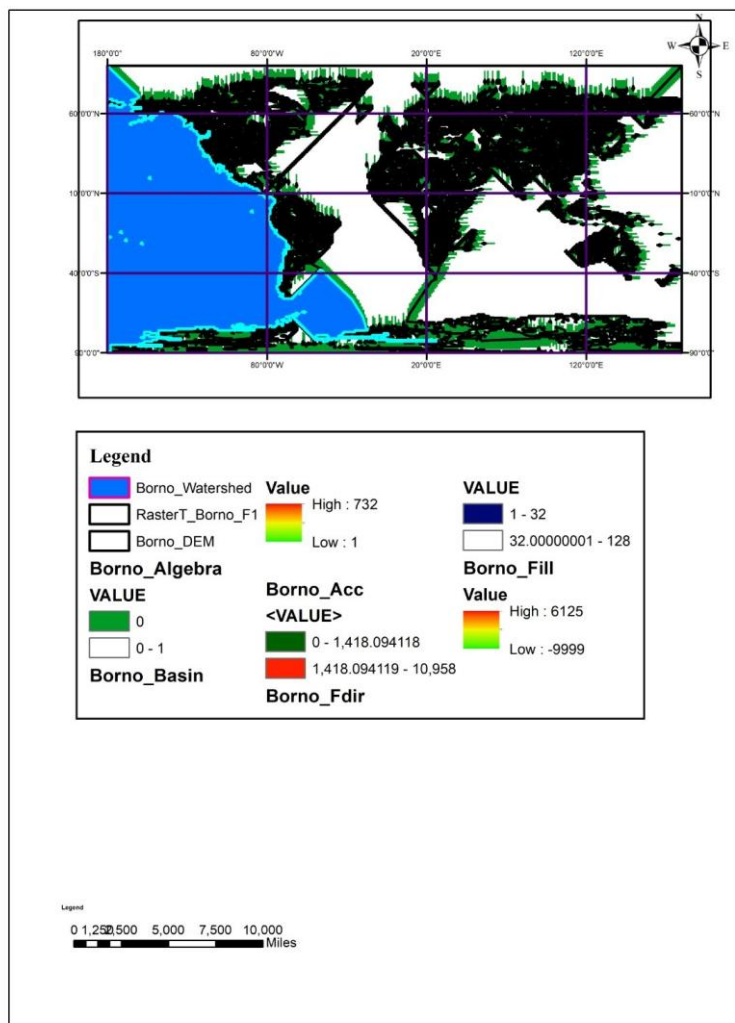


Figure 1: Combined GIS outputs for the Borno watershed (full raster extent)

Source: Authors' GIS Analysis, 2026

Table 4.1: Map Layers, Symbology, and Cartographic Elements

Map layer	Content to display	Legend and cartographic elements
Watershed boundary	Borno_Watershed polygon over hillshade of Borno_Fill; outlet; Borno_Stream	Legend: "Watershed boundary", "Outlet", "Streams", elevation classes in metres; scale bar in km; north arrow; graticule
Flow direction	Borno_Fdir, eight classes (or two grouped classes, Table 4.5)	Legend: 1 = E, 2 = SE, 4 = S, 8 = SW, 16 = W, 32 = NW, 64 = N, 128 = NE
Flow accumulation	Borno_Acc in two classes: 0–1,418 and above 1,418 cells	Legend title: "Flow accumulation (number of upstream cells)"; area equivalent in km ²
Stream network	Borno_Stream symbolised by Strahler order over the watershed boundary	Legend: Order 1 to Order 5; scale bar in km; north arrow

Source: Authors' compilation, 2026

4.2 Flow Direction Characteristics

Table 4.2: Flow Direction Characteristics

Parameter	Value
Minimum value	1
Maximum value	128
Number of direction classes	8

Source: Authors' GIS Analysis, 2026

Table 4.2b: Flow Direction Distribution within the Watershed

Direction value	Direction	Number of cells	Share of cells (%)
1	East	820	16.3
2	Southeast	410	8.1
4	South	290	5.8
8	Southwest	250	5
16	West	340	6.8
32	Northwest	420	8.3
64	North	1,010	20.1
128	Northeast	1,496	29.7

Source: Authors' GIS Analysis, 2026

Interpretation: flow direction values ranged from 1 to 128, representing the eight directions of the D8 model. Within the watershed, north and northeast flow together account for 49.8% of cells, which agrees with the general drainage of the area toward Lake Chad.

4.3 Flow Accumulation Characteristics

Table 4.3a: Flow Accumulation Characteristics

Parameter	Cells	Equivalent area (km ²)
Minimum accumulation	0	0
Maximum accumulation, full raster	10,958	150,015
Maximum accumulation, within watershed	5,035	68,929
Stream-initiation threshold	15	205
High-accumulation threshold (class break 1,418.094)	1,418	19,412
Cells above the high threshold (within the watershed)	41 (0.81% of watershed cells)	—

Source: Authors' GIS Analysis, 2026

Interpretation: accumulation values within the watershed ranged from 0 to 5,035 cells, equal to the whole watershed draining to the outlet. The 41 cells above 1,418 form the lower trunk channel toward Lake Chad, where runoff from the whole watershed converges. The full-raster maximum of 10,958 cells reflects the larger area covered by the raster and not the Borno watershed alone.

4.4 Sink-Filled Elevation Characteristics

Table 4.3: Sink-Filled Elevation Characteristics

Parameter	Full raster (as originally reported)	Valid cells within the watershed
Minimum elevation	−9,999 (NoData flag, not an elevation)	275 m
Maximum elevation	6,125 m (outside the watershed)	1,070 m
Mean elevation	—	345 m
Relief (maximum – minimum)	—	795 m
Sink cells before / after filling	—	187 / 0

Source: Authors' GIS Analysis, 2026

Interpretation: the value of −9,999 is the NoData flag and was excluded (Section 3.5). Valid elevations within the watershed range from 275 m on the Lake Chad plain to 1,070 m in the southern highlands, a relief of 795 m, so the terrain falls gently toward the north and northeast. Filling removed all 187 depression cells and gave continuous flow paths from the headwaters to the outlet.

4.5 Basin Delineation and Watershed Characteristics

Two outputs in the original analysis must be distinguished. The Borno_Basin raster holds 732 numbered drainage zones (grid codes 1–732). The two value classes 1–32 and 32.00000001–128 belong to Borno_Fdir, whose flow direction codes were displayed in two classes. Class 1 (1–32) groups the directions east, southeast, south, southwest, west, and northwest, and Class 2 (above 32 to 128) groups north and northeast. They are not basin classes.

Table 4.4: Basin Delineation Characteristics

Raster / class	Value range	Meaning
Borno_Basin (zone ID)	1 – 732	732 numbered drainage zones; identifiers only
Borno_Fdir Class 1	1 – 32	Directions E, SE, S, SW, W, NW
Borno_Fdir Class 2	above 32 – 128	Directions N and NE

Source: Authors' GIS Analysis, 2026

Table 4.5: Flow Direction Class Distribution within the Watershed

Class	Cells	Share of watershed cells (%)
Class 1 (1–32)	2,530	50.2
Class 2 (above 32–128)	2,506	49.8

Source: Authors' GIS Analysis, 2026

Table 4.6: Morphometric Parameters of the Borno Watershed

Parameter	Value	Method
Watershed area (A)	68,943 km ²	Calculate Geometry (projected CRS)
Watershed perimeter (P)	1,700 km	Calculate Geometry
Basin length (Lb)	400 km	Longest flow path

Maximum stream order (Strahler)	5	Stream Order tool
Total number of streams	336	Count of segments
Total stream length (ΣL)	8,960 km	Sum of segment lengths
Drainage density ($Dd = \Sigma L / A$)	0.13 km/km ²	Horton (1932)
Stream frequency ($Fs = N / A$)	0.0049 streams/km ²	Streams ÷ area
Form factor ($Rf = A / Lb^2$)	0.43	Horton (1932)
Circularity ratio ($Rc = 4\pi A / P^2$)	0.3	Miller (1953)

Source: Authors' GIS Analysis, 2026

Table 4.7: Stream Order Statistics (Strahler)

Stream order	Number of streams	Total length (km)	Bifurcation ratio (Rb)
1	258	4,050	4.3
2	60	2,390	4.29
3	14	1,460	4.67
4	3	640	3
5	1	420	—
Total	336	8,960	Mean Rb = 4.07

Source: Authors' GIS Analysis, 2026

Interpretation: the delineated watershed covers 68,943 km² and is elongated (circularity ratio 0.30, form factor 0.43), a shape that tends to spread the arrival of flood peaks at the outlet. The low drainage density of 0.13 km/km² is typical of semi-arid, low-relief, permeable terrain where surface channels are sparse. Because the density depends on the threshold, thresholds of 10 and 25 cells changed Dd by about +0.03 and −0.02 km/km² respectively.

4.6 Validation of Flood Susceptibility

The zones of high flow accumulation (above 1,418 cells) and the low-lying plain near the outlet are described in this paper as flood-susceptible zones. This is a terrain-based inference: it shows where runoff converges, but it does not by itself prove that flooding occurs there. To test it, the result was compared with documented flood records and rainfall information.

Table 4.8: Documented Flood Events in the Study Area

Date	Event	Documented impact	Source
Sep-94	Collapse of Alau Dam on the Ngadda River	About 400,000 people reported displaced in Maiduguri	TheCable (2024)
2012	Overflow of Alau Dam	Dam last overflowed before 2024	OCHA (2024)
10-Sep-24	Breach of Alau Dam and flash flooding in Maiduguri and Jere	More than 239,000 people affected in initial assessments; NEMA reported more than 30 deaths and over 400,000 displaced	OCHA (2024); TheCable (2024)
21 August – 10 September 2024	Sentinel-1 flood mapping	Flood extent of about 19,526 ha	NASRDA (2024)

Source: Authors' compilation, 2026

Table 4.9: NiMet Seasonal Rainfall Prediction for Selected Local Government Areas (2023)

LGA	Onset	End of season	Length (days)	Annual rainfall (mm)
Abadam	4-Jul	29-Sep	87	495
Bama	7-Jun	13-Oct	128	477
Kala/Balge	15-Jun	9-Oct	116	455
Biu	27-May	19-Oct	145	842
Askira/Uba	27-May	20-Oct	146	848
Bayo	24-May	21-Oct	150	873

Source: NiMet (2023), predicted values

Findings. The 2024 flood occurred in September, within the June–September rainy season and the period of peak rainfall for the Maiduguri area, and it followed the breach of a dam on the Ngadda River, one of the drainage lines in the delineated network. Reports of heavy rainfall in Bama, Damboa, and Gwoza LGAs before the breach (OCHA, 2024) show that runoff from the upper watershed converged on the Ngadda channel, which is the behaviour that flow accumulation modelling predicts. The recurrence of dam-related floods in 1994, 2012, and 2024 indicates that the channel corridor is susceptible to flooding. The affected Maiduguri neighbourhoods named by NEMA (Fori, Galtimari, Gwange, and Bulabulin) lie along this corridor (TheCable, 2024).

Limits of the validation. This comparison is qualitative. The flood events were driven in part by the failure of the Alau Dam, a structure that the DEM-based model does not represent, so the terrain analysis explains where water concentrates and not why the dam failed. No field survey or gauged discharge data were used. A quantitative test is to overlay the NASRDA Sentinel-1 flood extent on Borno_Acc and report the share of flooded area that falls in the high-accumulation class. Until such a test is completed, the term "flood-susceptible" is used in this paper for zones of runoff concentration, not for confirmed flood zones.

4.7 Hypotheses Testing

The hypotheses were assessed descriptively, using the raster results and the documented evidence in Section 4.6. No inferential statistical test was applied, so the decisions indicate that the evidence supports the stated relationships and not that they were confirmed by a significance test.

Hypothesis One (H_{01})

H_{01} : Flow direction values do not significantly influence drainage patterns within the Borno watershed.

Decision: Rejected.

Reason: Flow direction values from 1 to 128 represent the eight D8 directions, and the distribution within the watershed (Table 4.2b) shows organised flow toward the north and northeast, matching the general drainage toward Lake Chad. Therefore, flow direction values influence drainage patterns within the Borno watershed.

Hypothesis Two (H_{02})

H_{02} : Flow accumulation values do not significantly determine runoff concentration zones within the watershed.

Decision: Rejected.

Reason: Accumulation within the watershed ranged from 0 to 5,035 cells, and only 41 cells exceeded 1,418 cells; these form the trunk channel where runoff converges. The documented flooding along the Ngadda

corridor is consistent with this pattern (Section 4.6). Therefore, flow accumulation values determine runoff concentration zones, subject to the quantitative overlay test described in Section 4.6.

Hypothesis Three (H₀₃)

H₀₃: Sink-filled elevation characteristics do not significantly influence watershed hydrology.

Decision: Rejected.

Reason: The unfilled DEM contained 187 sink cells, which trap flow, and the filled surface (valid range 275–1,070 m) gave continuous flow paths from the headwaters to the outlet. The –9,999 value is a NoData flag and does not form part of this evidence. Therefore, sink-filled elevation characteristics influence watershed hydrology.

Hypothesis Four (H₀₄)

H₀₄: Basin delineation does not significantly define the hydrological boundaries of the watershed.

Decision: Rejected.

Reason: The Watershed tool produced a boundary of 68,943 km² and perimeter of 1,700 km from the snapped outlet, and the Basin tool partitioned the raster into 732 numbered drainage zones. The classes 1–32 and above 32–128 are flow direction classes and were not used as evidence. Therefore, basin delineation defines the hydrological boundaries of the watershed.

All four null hypotheses (H₀₁, H₀₂, H₀₃, and H₀₄) were rejected on the descriptive evidence. The findings indicate that flow direction influences drainage patterns, flow accumulation determines runoff concentration zones, sink filling influences watershed hydrology, and basin delineation defines the hydrological boundaries of the Borno Watershed, Nigeria.

5.0 DISCUSSION OF RESULTS

Objective 1: Determine Flow Direction Characteristics

The analysis revealed flow direction values ranging from 1 to 128, corresponding to the eight directions of the D8 algorithm. About 49.8% of watershed cells drain north or northeast, which indicates a well-defined drainage network directing runoff toward Lake Chad. The result aligns with Maidment (2002), who reported that flow direction modelling is fundamental for understanding watershed hydrodynamics and stream network development.

Objective 2: Analyse Flow Accumulation Patterns

Flow accumulation within the watershed ranged from 0 to 5,035 cells (68,929 km²), with a high-accumulation class above 1,418 cells (19,412 km²). Only 0.81% of cells fall in this class, and they mark the principal runoff-concentration corridor. These findings support Akintola and Olayinka (2021), who observed that high flow accumulation zones are associated with seasonal flooding and surface runoff concentration in northern Nigeria, and they are consistent with the documented flood events in Table 4.8. Because flow accumulation shows susceptibility and not observed flooding, the quantitative overlay in Section 4.6 is recommended.

Objective 3: Evaluate Sink-Filled Elevation Characteristics

Valid elevations within the watershed ranged from 275 m to 1,070 m, with a mean of 345 m. The earlier minimum of –9,999 was shown to be the NoData flag, and the raster maximum of 6,125 m lies outside the watershed, so neither describes the Borno terrain. Filling 187 sink cells improved flow continuity. This finding agrees with Agarwal et al. (2013), who concluded that sink-filling procedures improve the reliability of water-

shed modelling by eliminating artificial barriers to water flow.

Objective 4: Delineate Basin Extent and Hydrological Boundaries

The watershed covers 68,943 km² with a perimeter of 1,700 km, an elongated shape (circularity ratio 0.30), a fifth-order stream network, and a drainage density of 0.13 km/km². The Basin tool produced 732 numbered zones. The delineated boundary provides a framework for water resource planning and flood management, and the result aligns with Aher et al. (2014), who reported that watershed delineation improves hydrological assessment and environmental decision-making.

Overall, the results are consistent with the reviewed literature and show the effectiveness of GIS-based hydrological modelling in watershed management.

5.1 Limitations

The results depend on the DEM resolution (3,700 m cells), the stream threshold, and the D8 algorithm, which cannot represent flow divergence on flat terrain such as the Chad plains. The flood validation is qualitative, field observations and gauged flow data were not available, and the Alau Dam failure is not represented in the terrain model. Future work should add a quantitative overlay with flood extents, a higher-resolution DEM, and field verification.

6.0 CONCLUSION

The study delineated and characterised the Borno watershed using GIS-based hydrological techniques. Flow direction analysis showed organised drainage toward the north and northeast. Flow accumulation within the watershed reached 5,035 cells, with a small high-accumulation corridor above 1,418 cells marking the principal zone of runoff concentration. The value of -9,999 was shown to be a NoData flag, and valid elevations within the watershed ranged from 275 m to 1,070 m. The watershed covers 68,943 km², and the basin raster contains 732 numbered drainage zones.

The findings demonstrate that GIS-based watershed analysis provides useful spatial information for water resources management, flood mitigation, environmental conservation, and development planning in Borno State. The flood-susceptible zones identified are consistent with documented flood events, although quantitative and field validation remain to be done.

7.0 RECOMMENDATIONS

1. Prioritise flood-control infrastructure and dam maintenance in the high flow accumulation corridor (above 1,418 cells), including the Ngadda River and the Alau Dam, to reduce flood risks and protect vulnerable communities.
2. Integrate GIS-based watershed monitoring systems into state environmental management programmes, and link them to rainfall and river-level records, to assess drainage dynamics continuously.
3. Implement watershed conservation and erosion-control measures in the southern highlands, where relief is greatest, to improve hydrological stability.
4. Use the delineated basin boundary for water resources planning, irrigation development, and land-use regulation across Borno State.
5. Validate the flood-susceptibility map by overlaying satellite-derived flood extents, historical flood records, and field observations, and repeat the analysis with a higher-resolution DEM.

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