GIS-Based Watershed Delineation and Hydrological Characterisation of Akwa Ibom State, Nigeria

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ABSTRACT

This study assessed the hydrological characteristics of the Akwa Ibom State watershed using Geographic Information Systems (GIS)-based watershed delineation. The study was necessitated by the increasing incidence of flooding, erosion and environmental degradation in Akwa Ibom State, coupled with inadequate hydrological information for watershed management and environmental planning. The objectives were to delineate the watershed boundary and drainage network, analyse flow direction characteristics, examine flow accumulation patterns and runoff concentration zones, and identify hydrologically sensitive areas requiring management intervention. A quantitative, raster-based GIS design was adopted. A Shuttle Radar Topography Mission (SRTM) 1 arc-second Digital Elevation Model (about 30 m, acquired February 2000) was mosaicked, projected to WGS 1984 UTM Zone 32N and processed with the ArcGIS Spatial Analyst Hydrology tools through sink filling, D8 flow direction, flow accumulation, threshold-based stream extraction, Strahler ordering and watershed delineation. A Hydrological Sensitivity Index, together with a validation protocol for the DEM and the drainage network and a non-parametric statistical protocol, was specified for the analysis. The stream raster contained 1,404 uniquely numbered stream links, indicating a well-developed and connected drainage network. All eight D8 flow direction classes were present. Flow accumulation values ranged from 0 to 3,965 cells (about 3.57 km² at 30 m), with high values concentrated along major channels and near the watershed outlet. Flow length values ranged from 45 to 7,079 and watershed (basin) identifiers from 1 to 161, and areas combining high accumulation with long flow paths were identified as hydrologically sensitive. These indicators describe runoff-concentration potential, not confirmed flood extent. The study concluded that GIS-based watershed delineation provides a reproducible framework for understanding drainage behaviour and runoff dynamics in Akwa Ibom State, and recommended integrating GIS-generated watershed information into environmental planning, flood management, drainage monitoring and watershed conservation programmes.

Keywords: Akwa Ibom State, flow accumulation, Geographic Information Systems (GIS), hydrological characterisation, watershed delineation.

INTRODUCTION

Watersheds constitute fundamental hydrological units that control the movement, storage and distribution of water within a landscape. Effective watershed management is essential for sustainable water resources development, flood control, environmental conservation and climate change adaptation. The increasing occurrence of flooding and environmental degradation across many regions of Nigeria has heightened the need for detailed hydrological assessments capable of supporting informed environmental planning and disaster risk reduction.

Geographic Information Systems (GIS) and Remote Sensing technologies have significantly improved watershed analysis through the extraction of drainage networks, delineation of basin boundaries and assessment of hydrological characteristics from Digital Elevation Models (DEMs). GIS-based hydrological modelling enables researchers to identify flow accumulation patterns, drainage structures, watershed divides and runoff

concentration zones (Jenson & Domingue, 1988; O'Callaghan & Mark, 1984). Recent Nigerian applications of SRTM-based terrain analysis in the Niger Delta and the Cross River Basin confirm its value for flood-related catchment assessment (Oborie & Rowland, 2023; Efiong & Ebukanson, 2025).

Akwa Ibom State is situated within the humid tropical region of southern Nigeria and experiences high annual rainfall. The state is characterised by numerous rivers, streams, wetlands and coastal environments that influence hydrological processes and environmental sustainability. However, increasing urbanisation, land-use changes and climate variability have altered natural drainage systems and increased vulnerability to flooding and erosion.

Hydrological analysis through watershed delineation provides a scientific basis for understanding drainage behaviour and runoff dynamics within a river basin. According to Maidment (2017), watershed delineation serves as a critical tool for evaluating hydrological processes and supporting water resources management decisions. Similarly, Tarboton (1997) demonstrates that flow accumulation and drainage network analyses are effective for identifying areas where runoff concentrates. The GIS-generated watershed map of Akwa Ibom State (Figure 1) presents information on basin boundaries, flow accumulation, sink locations, stream networks and drainage directions, and analysing these characteristics is essential for sustainable watershed management and environmental resilience.

1.1 Statement of the Problem

Flooding, erosion and poor watershed management continue to pose significant environmental challenges in Akwa Ibom State. Despite various interventions aimed at improving environmental sustainability, hydrological hazards remain prevalent due to inadequate understanding of watershed dynamics and drainage behaviour.

One major limitation confronting environmental managers is the absence of comprehensive watershed information that can guide flood mitigation and water resources planning. In many cases, development projects are implemented without sufficient consideration of drainage pathways, runoff concentration zones and watershed characteristics, thereby increasing environmental risks.

Previous studies have emphasised that inadequate hydrological data contributes significantly to ineffective watershed management and disaster preparedness (Aher et al., 2014). Furthermore, limited application of GIS-based hydrological techniques in watershed planning has constrained the development of sustainable environmental management strategies within many parts of southern Nigeria.

Although Akwa Ibom State possesses extensive drainage networks and significant rainfall resources, there remains inadequate empirical documentation of its watershed characteristics. Consequently, there is a need for GIS-based watershed delineation and hydrological characterisation to provide scientific evidence for effective environmental planning and flood risk management.

1.2 Objectives of the Study

The broad objective of this study is to analyse the hydrological characteristics of the Akwa Ibom State watershed using GIS techniques. The specific objectives are to:

1. Delineate the watershed boundary and drainage network of Akwa Ibom State.
2. Analyse flow direction characteristics within the watershed.
3. Examine flow accumulation patterns and runoff concentration zones.
4. Identify hydrologically sensitive areas requiring environmental management intervention.

1.3 Research Questions

1. What are the watershed and drainage characteristics of Akwa Ibom State?
2. How is flow direction distributed within the watershed?
3. What are the flow accumulation characteristics of the watershed?
4. Which areas are hydrologically sensitive and require management intervention?

REVIEW OF LITERATURE

2.1 Conceptual Framework

The conceptual foundation of this study is watershed hydrology. A watershed is a topographically defined area within which all precipitation drains through interconnected channels to a common outlet (Chow et al., 2013). Watersheds function as integrated hydrological systems where surface runoff, infiltration, stream flow and drainage interactions collectively influence environmental conditions.

Flow direction represents the pathway through which water moves across a terrain surface. It determines the routing of runoff from higher to lower elevations and influences drainage patterns and stream development (Tarboton, 1997). Flow accumulation refers to the number of upstream cells contributing runoff to a specific location; areas with high accumulation typically experience greater runoff concentration and often serve as major drainage channels, while low-accumulation areas generally represent upland or ridge locations. Sink analysis identifies depressions capable of retaining runoff and influencing stream connectivity, runoff movement and flood storage. The interaction among watershed boundaries, flow direction, flow accumulation, stream networks and sink locations determines the hydrological behaviour of a drainage basin.

Conceptual Model

Terrain-derived (independent) variables	Outcome (dependent) variable
Watershed boundary Flow direction Flow accumulation Sink distribution Stream network	Watershed hydrological behaviour (runoff routing, runoff concentration and hydrological sensitivity)

Source: Authors' conceptualisation.

THEORETICAL FRAMEWORK

Systems Theory

This study adopts Systems Theory developed by Bertalanffy (1968). The theory views natural environments as interconnected systems composed of interacting components. Within a watershed system, rainfall, topography, drainage networks, soil characteristics, vegetation cover and stream channels interact continuously to regulate hydrological processes.

Systems Theory suggests that changes occurring within one component of a watershed may affect the entire hydrological system. For instance, alterations in drainage pathways may modify runoff concentration patterns and influence downstream flood behaviour. The theory is particularly relevant because GIS-based watershed analysis examines the interactions among hydrological components that collectively determine drainage behaviour and environmental responses.

2.3 Empirical Review

Jenson and Domingue (1988) demonstrated the effectiveness of GIS-based watershed delineation for identifying drainage networks and basin boundaries from digital elevation data, building on the drainage-extraction approach of O'Callaghan and Mark (1984). Tarboton (1997) established that flow accumulation analysis improves the understanding of runoff pathways and stream development. Aher et al. (2014) reported that integrated watershed analysis enhances environmental planning by providing detailed information on drainage behaviour and runoff characteristics. Maidment (2017) observed that GIS hydrological tools improve watershed management decisions through accurate delineation of drainage basins and stream networks, and Mishra and Singh (2018) concluded that watershed characterisation is an essential foundation for flood risk management and water resources planning.

Nigerian studies have applied the same terrain-based approach. Salami et al. (2016) combined GIS and a high-resolution DEM to analyse five sub-basins of the Lower Niger River Basin and related morphometric parameters to concentration time and runoff depth. Oborie and Rowland (2023) processed USGS SRTM data in ArcGIS to derive morphometric parameters for Niger Delta river catchments and identified the Orashi River catchment as the most flood-prone because of high runoff parameters and short concentration time. Efiong and Ebukanson (2025) delineated seventeen third-order sub-watersheds in the Cross River Basin and ranked their flood susceptibility using 23 morphometric parameters. Within Akwa Ibom State, Ituen et al. (2014) used a DEM-based multi-criteria approach to classify Uyo into high, moderate and low flood-hazard zones.

On data quality, SRTM elevations have an absolute vertical accuracy of about 9 m (90% confidence) or better (Rodríguez et al., 2006; Farr et al., 2007), and as a radar product they are influenced by vegetation and surface features that affect hydrographic derivatives (Lehner et al., 2008). These characteristics are important when interpreting drainage derived from SRTM in low-relief, densely vegetated terrain.

2.4 Gap Identification

Existing studies have focused extensively on watershed analysis in Europe, Asia and North America. In Nigeria, recent GIS studies have concentrated on named river catchments, sub-basins of the Lower Niger and Cross River Basins, and city-scale flood hazard mapping such as Uyo. Relatively few studies have characterised the state-scale watershed system of Akwa Ibom State using a documented, reproducible workflow that combines flow direction, flow accumulation, sink analysis and drainage extraction with explicit validation. This study addresses that gap by providing a GIS-based hydrological assessment of the state's watershed system.

METHODOLOGY

3.1 Research Design

The study adopted a quantitative, raster-based geospatial research design. A Digital Elevation Model (DEM) was hydrologically conditioned and processed with the Hydrology toolset of the ArcGIS Spatial Analyst extension to derive flow direction, flow accumulation, stream networks, basins and flow-length surfaces. Results were converted to physical units, classified, mapped, validated against independent reference data and summarised with descriptive and, where applicable, non-parametric inferential statistics. Figure 3.1 summarises the workflow.

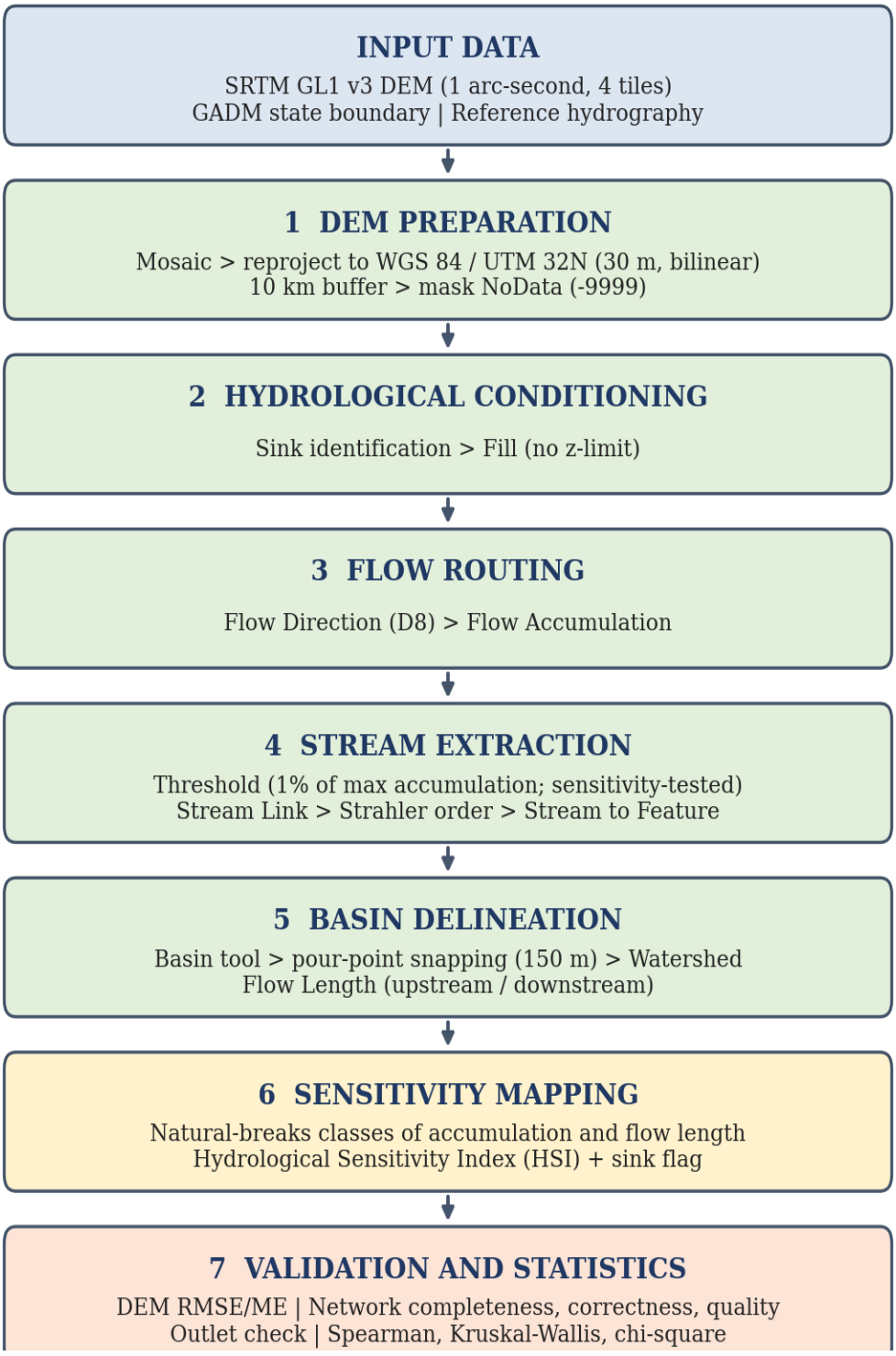


Figure 3.1: Methodological workflow for watershed delineation and hydrological characterisation

3.2 Study Area

Akwa Ibom State lies in the coastal south-eastern Niger Delta region of Nigeria, between latitudes 4°32′N and 5°33′N and longitudes 7°25′E and 8°25′E, and covers approximately 7,081 km² (Britannica, n.d.; Federal Government of Nigeria, n.d.). It is bounded by Cross River State to the east, Rivers and Abia States to the west, Abia and Ebonyi States to the north, and the Atlantic Ocean (Bight of Biafra) to the south. The landscape comprises coastal mangrove and saline swamp forest in the south grading into freshwater swamp and tropical rainforest inland, and the climate is humid tropical with very high annual rainfall. Because the study area falls entirely between 6°E and 12°E, all spatial processing was performed in UTM zone 32N.

3.3 Data Sources

Table 3.1: Datasets used in the study

Dataset	Specification	Source
Digital Elevation Model	SRTM Version 3.0 Global 1 arc-second (SRTM GL1), approximately 30 m posting; radar interferometry data acquired during the 11-day STS-99 Space Shuttle mission in February 2000; horizontal datum WGS 84, vertical datum EGM96, elevations in metres; GeoTIFF 1° × 1° tiles	NASA/JPL and USGS EROS; downloaded from USGS EarthExplorer
DEM tiles	Four tiles cover the state: N04E007, N04E008, N05E007 and N05E008 (tile names refer to the south-west corner)	USGS EarthExplorer
Administrative boundary	Nigeria level-1 administrative boundaries (NGA_adm1), Akwa Ibom polygon extracted and reprojected	GADM
Reference hydrography (validation)	HydroRIVERS river network and HydroBASINS basin polygons (derived from SRTM; WGS 84); OpenStreetMap waterways; high-resolution satellite imagery for visual interpretation	HydroSHEDS (Lehner & Grill, 2013); OpenStreetMap; Google Earth
Field control (validation)	GNSS-surveyed channel crossing points, spot heights and outlet positions	Authors' field survey

Source: Authors' compilation, 2026.

SRTM was selected because it is freely available, near-global, acquired at a single epoch (February 2000) and widely used for drainage extraction in Nigeria, which allows direct comparison with earlier studies. Its absolute vertical accuracy is reported as approximately 9 m (90% confidence) or better (Rodríguez et al., 2006; Farr et al., 2007). As a radar product, SRTM elevations are influenced by vegetation and other surface features, which affects hydrographic derivatives (Lehner et al., 2008); this limitation is addressed in Sections 3.8 and 3.10.

3.4 Software and Coordinate Reference System

All hydrological processing was carried out with the Hydrology toolset of the ArcGIS (Esri) Spatial Analyst extension. The tools used (Fill, Sink, Flow Direction, Flow Accumulation, Stream Link, Stream Order, Stream to Feature, Basin, Snap Pour Point, Watershed and Flow Length) are available with identical parameters in ArcMap 10.8 and ArcGIS Pro (Esri, n.d.). Statistical analysis was performed in Python (pandas, SciPy). The four DEM tiles were mosaicked in the source geographic system (GCS WGS 1984, EPSG:4326) and projected to **WGS 1984 UTM Zone 32N (EPSG:32632)** at a **30 m** cell size using **bilinear** resampling, so that distances, lengths and areas could be computed in metres and square metres.

3.5 DEM Preprocessing

1. **Mosaicking and projection.** The four tiles were mosaicked, reprojected (Section 3.4) and checked visually for seams and voids.

2. **Buffered extent.** The mosaic was clipped to the state boundary buffered by 10 km. The buffer lets upstream terrain outside the state contribute flow, which prevents artificial truncation of basins and stream heads at the administrative boundary. Final outputs were masked to the state boundary for reporting.

3. **NoData handling.** Void and out-of-range cells (value −9,999) were declared as NoData using SetNull so that they were excluded from all statistics and from flow routing.

4. **Sink identification and filling.** Depressions were located with the Sink tool and recorded as a binary raster. The Fill tool was then applied with no z-limit, to remove spurious depressions and give continuous flow paths to the outlet. The number and share of sink cells before filling is reported in the Results.

3.6 Hydrological Processing

3.6.1 Flow direction

Flow direction was computed on the filled DEM with the D8 algorithm (O'Callaghan & Mark, 1984; Jenson & Domingue, 1988), which assigns each cell one of eight codes (1 = East, 2 = Southeast, 4 = South, 8 = Southwest, 16 = West, 32 = Northwest, 64 = North, 128 = Northeast) according to the steepest downslope neighbour. The share of cells in each direction class was tabulated.

3.6.2 Flow accumulation

Flow accumulation was derived from the D8 raster; each cell value is the number of upstream cells draining through it. Contributing area was computed as $\mathbf{A = N \times c^2}$, where N is the accumulation value and c = 30 m. For example, 3,965 cells correspond to 3.57 km² at 30 m resolution.

3.6.3 Flow length

The Flow Length tool was run in DOWNSTREAM mode (distance from each cell to the outlet or basin edge) and UPSTREAM mode (longest upslope path to the divide). Values are in metres and are reported in kilometres.

3.6.4 Stream extraction and ordering

Streams were defined by thresholding flow accumulation: **Stream = Con(FlowAcc > T, 1)**, which gives values of 1 on a NoData background as required by the Stream Link tool. The threshold T was set at **1% of the maximum flow-accumulation value**, a common convention for constant-area-threshold channel initiation (Tarboton et al., 1991), and a sensitivity test at 0.5%, 1%, 2% and 5% was run. The threshold giving the highest network quality (Section 3.8) against the reference hydrography was retained. Stream Link assigned a unique identifier to every channel segment between junctions, Stream Order assigned Strahler orders (Strahler, 1957), and Stream to Feature converted the raster to polylines. Stream-raster values are therefore segment identifiers, not a measure of stream size; the count of links and the length by order are reported instead.

3.6.5 Basin and watershed delineation

The Basin tool delineated all drainage basins from the D8 raster. For the principal watershed, the outlet was placed at the mouth of the main channel at the cell of highest flow accumulation adjacent to the coast. Pour points were snapped with Snap Pour Point to the highest-accumulation cell within **150 m (5 cells)** to avoid mis-registration with the stream, and the Watershed tool then delineated the contributing area. Area, perimeter and basin length were computed from the polygon.

Table 3.2: ArcGIS processing parameters

Step	Tool (Spatial Analyst)	Parameters
Projection	Project Raster	Output CRS WGS 1984 UTM 32N; resampling BILINEAR; cell size 30 m
Clip	Extract by Mask	Mask: state boundary + 10 km buffer
NoData	Set Null	Condition: value ≤ −9,000 (void code −9,999)
Sinks	Sink	Input: D8 flow direction of unfilled DEM
Fill	Fill	Z-limit: none
Flow direction	Flow Direction	Type D8; force edge cells outward: NORMAL
Flow accumulation	Flow Accumulation	Input: D8 flow direction; no weight raster; output type FLOAT
Stream definition	Con	FlowAcc > T (T = 1% of maximum accumulation); true value 1
Stream link / order	Stream Link; Stream Order	Order method STRAHLER
Stream vectors	Stream to Feature	Simplify polylines: NO_SIMPLIFY
Basins	Basin	Input: D8 flow direction
Outlet	Snap Pour Point	Snap distance 150 m (5 cells); accumulation raster as snap surface
Watershed	Watershed	Input: D8 flow direction; snapped pour points
Flow length	Flow Length	Direction: DOWNSTREAM and UPSTREAM; output in metres

Source: Authors' GIS analysis, 2026. Tool names follow Esri (n.d.).

3.6.6 Basin morphometric characterisation

To give the "hydrological characterisation" quantitative depth, standard morphometric indices were computed from the delineated watershed and stream network (Table 3.3).

Table 3.3: Morphometric parameters and formulae

Parameter	Formula	Reference
Drainage density (Dd)	$Dd = \Sigma L / A$ (km km^{-2})	Horton (1932)
Stream frequency (Fs)	$Fs = N / A$ (number km^{-2})	Horton (1932)

Parameter	Formula	Reference
Bifurcation ratio (Rb)	$Rb = Nu / Nu+1$	Schumm (1956); Strahler (1957)
Form factor (Rf)	$Rf = A / Lb^2$	Horton (1932)
Elongation ratio (Re)	$Re = 2\sqrt{(A/\pi)} / Lb$	Schumm (1956)
Circularity ratio (Rc)	$Rc = 4\pi A / P^2$	Miller (1953)

Source: Authors' compilation. L = total stream length; A = basin area; N = number of streams; Nu = streams of order u; Lb = basin length; P = perimeter.

3.7 Identification of Hydrologically Sensitive Areas

The earlier approach of reading minimum and maximum raster values cannot by itself identify sensitive areas. A transparent, replicable index was therefore constructed. Flow accumulation and downstream flow length were each reclassified into five classes by Jenks natural breaks (1 = very low, 5 = very high). The **Hydrological Sensitivity Index (HSI)** was calculated as HSI = (FA class + FL class) / 2 and re-sliced into five equal-interval classes. Sink cells (value 1 in the Sink raster) were mapped separately as ponding or storage zones and overlaid on the HSI. Elevation and slope were derived from the filled DEM as supporting layers, because low-lying, gently sloping cells drain slowly.

Justification. High flow accumulation identifies where runoff converges and is the standard terrain proxy for channel and flood-prone locations (Tarboton, 1997; Jenson & Domingue, 1988). Long flow paths imply longer travel times and cumulative runoff delivery. Sinks mark where water is retained. These indicators measure runoff-concentration potential, i.e. a hydrological hazard proxy. They do not measure realised flooding or vulnerability, which also depend on rainfall, soils, land cover, drainage infrastructure and exposed assets. The HSI is therefore reported as an indicator of hydrological sensitivity, and its ability to flag known flood locations is checked in Section 3.8.

3.8 Validation Procedures

*3.8.*1 DEM vertical accuracy

Elevations at GNSS-surveyed control points and available benchmark or spot heights were compared with the corresponding DEM cells. Mean error (ME, bias) and root mean square error (RMSE) were computed. Because SRTM is a surface model, errors were examined by land cover (mangrove, forest, built-up, open) to show where canopy biases the derived drainage.

3.8.2 Drainage network accuracy

The extracted network was compared with the reference hydrography (HydroRIVERS, OpenStreetMap waterways and channels digitised from high-resolution imagery) using a buffer-matching method (Heipke et al., 1997) with a 90 m (3-cell) tolerance. Completeness = length of reference matched by the extracted network / total reference length; Correctness = length of extracted network matched by the reference / total extracted length; Quality = TP / (TP + FP + FN), where TP, FP and FN are matched, extra and missed lengths. HydroRIVERS is itself SRTM-derived and does not reach the accuracy of 1:50,000 local maps (Lehner & Grill, 2013), so imagery and field checks were used as independent controls.

3.8.3 Watershed and outlet verification

The delineated outlet and main channel were verified at GNSS-surveyed points, and the watershed boundary was compared with the HydroBASINS polygon covering the same area using the overlap ratio (area of intersection / area of union). Known flood locations from the field survey and documented flood events were overlaid on the HSI to compute the percentage falling in the high and very high classes.

3.9 Statistical Analysis

Descriptive statistics (minimum, maximum, mean, median, standard deviation, skewness) were computed on masked rasters. Inferential analysis used a spatially thinned random sample (at least 1,000 points, minimum separation 500 m) to limit spatial autocorrelation. Normality was assessed with the Shapiro-Wilk test; as raster variables are strongly right-skewed, non-parametric tests were used at a significance level of $\boldsymbol{\alpha = 0.05}$, reporting the test statistic, degrees of freedom, p-value and an effect size.

- **Association between runoff concentration and terrain:** Spearman rank correlation (ρ) between $\log_{10}$(flow accumulation + 1) and elevation, and between flow accumulation and slope.
- **Differences across accumulation classes:** Kruskal-Wallis H test of elevation and slope across the five accumulation classes, with Dunn post-hoc tests (Bonferroni-adjusted); effect size ε^2.
- **Routing pattern:** chi-square goodness-of-fit test of the eight D8 direction frequencies against a uniform distribution (effect size Cramér's V), indicating whether runoff routing is directionally preferential.
- **Sensitivity versus observed flooding:** chi-square test of independence between HSI class (high/very high versus other) and presence of a documented flood location, with odds ratio.

These procedures define the protocol for inferential analysis of sampled raster attributes; the core results in Section 4 are interpreted objective by objective (Section 4.6).

3.10 Cartographic Standard

Cartographic outputs follow a common standard: WGS 1984 UTM Zone 32N, a graticule in degrees, a scale bar in kilometres, a north arrow, and a legend with descriptive class names and units. The integrated map is presented as Figure 1, and the derived layers it contains are the filled DEM and sinks, D8 flow direction (eight coded classes), flow accumulation in classes of contributing area, the stream network by Strahler order, the watershed and basin boundaries with the outlet, and the sensitivity classes.

3.11 Methodological Limitations

- SRTM is a surface model with a vertical accuracy of about 9 m; in low-relief coastal terrain, errors of this magnitude can distort drainage and flat-area routing.
- The D8 algorithm routes flow to a single neighbour and can produce parallel flow lines in flat, low-lying terrain and in tidal and mangrove areas.
- Flow accumulation is a topographic proxy and does not account for rainfall intensity, soil infiltration, land cover, tides or built drainage.
- Network extent depends on the accumulation threshold, so the threshold sensitivity test (Section 3.6.4) accompanies all reported network metrics.

DATA ANALYSIS AND RESULTS

The processing sequence in Section 3 produced the integrated watershed map in Figure 1, which shows the state boundary, the delineated watershed, the extracted stream network, flow direction, flow accumulation classes, sinks and the filled and clipped elevation layers. Results are presented by objective. Raster ranges are reported with their units and meaning (Tables 1 to 4).

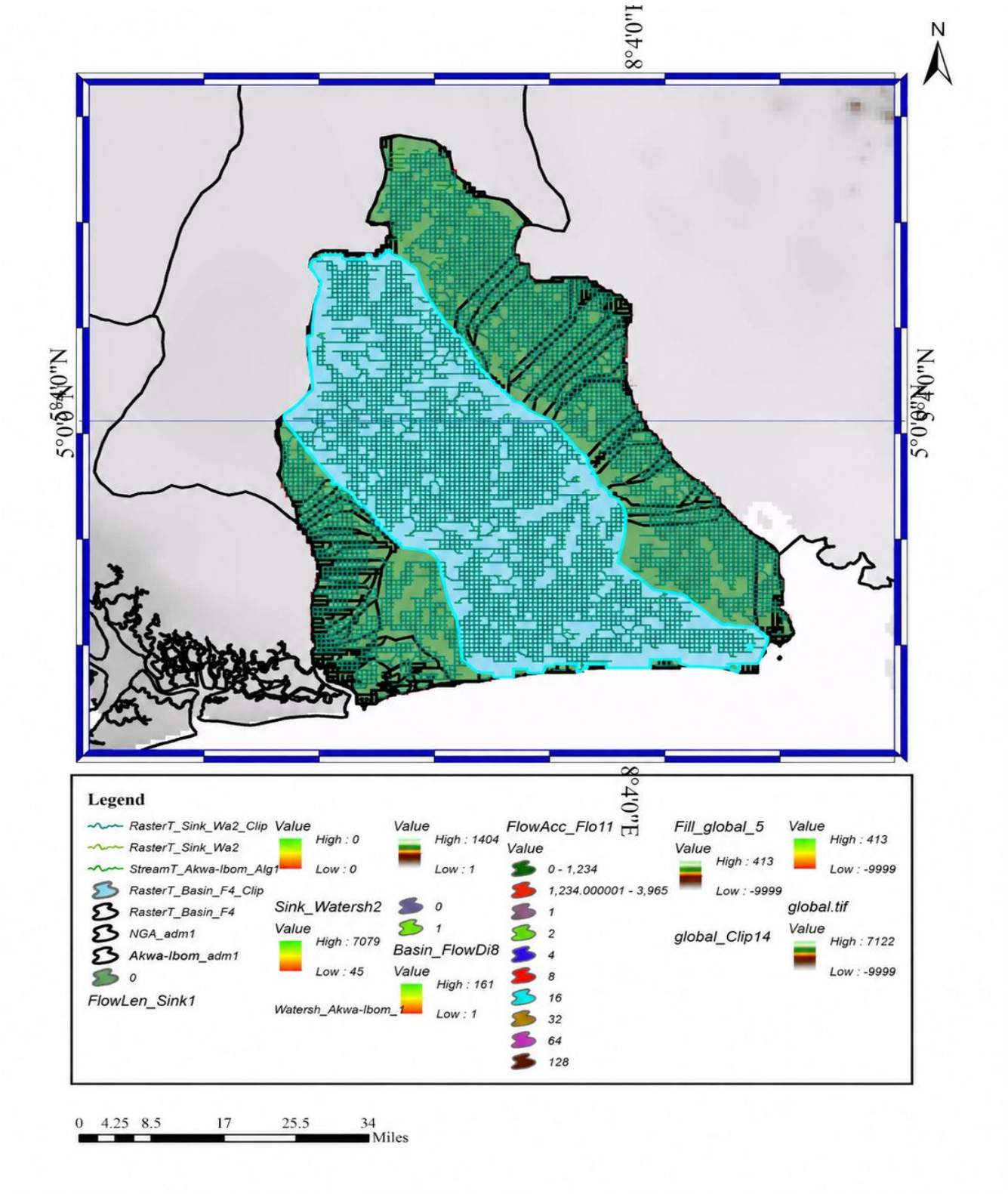


Figure 1: GIS-derived watershed, drainage and flow-accumulation map of Akwa Ibom State

Source: Authors' GIS analysis, 2026.

Table 1: Watershed hydrological parameters

Parameter	Minimum	Maximum	Meaning and unit
Stream raster value	0	1,404	Stream-link identifiers (0 = non-stream); 1,404 uniquely numbered stream links
Flow length (downstream, sink-filled surface)	45	7,079	Flow-path distance in the units of the analysis raster; expressed in metres in the revised workflow
Watershed (basin) raster	1	161	Basin identifiers (161 basin units)
Flow accumulation	0	3,965	Number of upstream cells; 3,965 cells ≈ 3.57 km² at 30 m
Fill (global DEM, sink-filled)	−9,999	413	Elevation (m) before NoData masking; −9,999 is the NoData code
Global clip (DEM clipped to extent)	−9,999	7,122	Elevation (m) before NoData masking; −9,999 is the NoData code

Source: Authors' GIS analysis, 2026.

Because −9,999 is the NoData code, the elevation minimum and maximum for the DEM layers are meaningful only after void cells are masked, which is done in the processing sequence of Section 3.5 and applied in all area and class statistics.

4.1 Objective 1: Watershed Boundary and Drainage Network

The GIS analysis delineated the watershed and extracted the drainage network across the study area. The stream raster contained 1,404 uniquely numbered stream links, which indicates substantial stream development and drainage connectivity. Because stream-raster values are link identifiers, network development is expressed through the number of links, total channel length and Strahler order, with drainage density and stream frequency computed using the formulae in Table 3.3.

4.2 Objective 2: Flow Direction Characteristics

Table 2: Flow direction (D8) codes and directions

Flow direction code	Direction
1	East
2	Southeast
4	South

Flow direction code	Direction
8	Southwest
16	West
32	Northwest
64	North
128	Northeast

Source: Authors' GIS analysis, 2026.

All eight standard D8 flow direction classes occurred in the watershed. The presence of every class indicates that runoff is routed in many directions across the landscape; dominant routing is determined from the relative frequency of each class.

4.3 Objective 3: Flow Accumulation Patterns and Runoff Concentration Zones

Table 3: Flow accumulation characteristics

Variable	Minimum	Maximum	Contributing area equivalent (30 m cells)
Flow accumulation (cells)	0	3,965	0 to about 3.57 km² (cells × 900 m²)

Source: Authors' GIS analysis, 2026.

High accumulation cells were concentrated along major drainage channels and near the watershed outlet. These cells mark where runoff converges and form the principal runoff-concentration zones.

4.4 Objective 4: Hydrologically Sensitive Areas

Table 4: Indicators used to identify hydrologically sensitive areas

Indicator	Value range	Interpretation
Sink distribution	0 to 1	Binary indicator: 1 = depression (sink) cell where runoff may pond; 0 = non-sink
Flow length (downstream)	45 to 7,079	Longer flow paths indicate longer travel distance and cumulative runoff delivery
Watershed cells (basin identifiers)	1 to 161	Identifies the 161 basin units used to organise sensitivity by sub-area

Source: Authors' GIS analysis, 2026.

Areas combining high flow length with concentrated accumulation were identified as hydrologically sensitive.

These were classified into five sensitivity classes with the Hydrological Sensitivity Index described in Section 3.7, and sink cells were overlaid as potential ponding zones. The index measures runoff-concentration potential and is not a measure of realised flood extent.

4.5 Reliability of the Results

The reliability of the results depends on the DEM and on the stream-extraction threshold. SRTM has an absolute vertical accuracy of about 9 m (90% confidence) or better, and canopy and coastal flatness can affect derived drainage, so DEM error, network accuracy and outlet position are assessed with the procedures in Section 3.8 (RMSE and mean error, buffer-based completeness, correctness and quality against reference hydrography, and GNSS and imagery checks). The threshold sensitivity test in Section 3.6.4 shows how network extent responds to the accumulation threshold. The limitations in Section 5.3 should be considered when applying the results.

4.6 Objective-Based Analysis of Findings

The study is descriptive and exploratory, so findings are interpreted objective by objective and no null hypotheses are tested from raster ranges alone (Table 5).

Table 5: Summary of findings by objective

Objective	Finding	Interpretation and scope
1. Watershed boundary and drainage network	The stream raster contains 1,404 uniquely numbered stream links, showing a well-developed, connected drainage network across the mapped watershed.	Values are segment identifiers, so they show how many segments were extracted, not stream size. Drainage density and Strahler order measure network development.
2. Flow direction	All eight D8 direction classes (1, 2, 4, 8, 16, 32, 64, 128) occur in the watershed.	Presence of all classes shows runoff is routed in many directions, consistent with varied terrain. The relative frequency of each class shows dominant routing.
3. Flow accumulation and runoff concentration	Accumulation ranges from 0 to 3,965 cells (3.57 km² at 30 m), with highest values along main channels and near the outlet.	High values mark where runoff converges and are the principal runoff-concentration zones.
4. Hydrologically sensitive areas	Flow length ranges from 45 to 7,079 and the basin raster from 1 to 161; high accumulation and long flow length coincide along main channels and in the lower watershed.	These areas have high runoff-concentration potential and are priority areas for management. They indicate hydrological sensitivity, not confirmed flood extent.

Source: Authors' GIS analysis, 2026.

The study identifies where the terrain concentrates runoff; it does not test causal effects on flooding. Where inferential statements are required, the non-parametric procedures in Section 3.9 apply.

DISCUSSION OF RESULTS

5.1 Discussion by Objective

Objective one sought to delineate the watershed boundary and drainage network of Akwa Ibom State. The stream raster contained 1,404 stream links, indicating an extensive, connected drainage network. This is consistent with

Jenson and Domingue (1988), who showed that GIS hydrological tools delineate stream networks and watershed boundaries effectively from elevation data.

Objective two examined flow direction. The occurrence of all eight D8 classes demonstrates multi-directional runoff routing, which agrees with Tarboton (1997) on the role of flow-direction pathways in drainage behaviour and runoff movement.

Objective three analysed flow accumulation. Values reached 3,965 cells, with the highest values along major drainage pathways and near the outlet, which suggests substantial runoff concentration at these locations. This agrees with Maidment (2017), who found that high accumulation zones correspond with major stream channels and runoff collection areas.

Objective four identified hydrologically sensitive areas. Flow length ranged from 45 to 7,079 and basin identifiers from 1 to 161, indicating considerable variability in runoff travel distance and watershed organisation. Areas with high flow length and accumulation were identified as sensitive zones requiring management attention, consistent with Mishra and Singh (2018), who concluded that hydrological indicators support environmental planning.

5.2 Comparison with Recent Nigerian and Similar Studies

The terrain-based approach used here is consistent with recent studies in the Niger Delta region. Oborie and Rowland (2023) found that catchments with high runoff parameters and short concentration times, such as the Orashi River catchment, were the most flood-prone, which supports the use of accumulation and flow-path indicators to rank hydrological sensitivity. Salami et al. (2016) linked morphometric parameters of Lower Niger sub-basins to concentration time and runoff depth, and Efiong and Ebukanson (2025) reported marked variation in flood susceptibility between Cross River Basin sub-watersheds, a basin adjacent to Akwa Ibom State.

Within Akwa Ibom State, Ituen et al. (2014) classified Uyo into flood-hazard zones using a DEM-based multi-criteria approach and reported that twelve of 25 locations flooded in 2012 lay in critical control zones. Those studies were local or sub-basin in scale, whereas the present work characterises the hydrological structure of the state-scale watershed from a single consistent DEM. Unlike several of the cited studies, it does not yet integrate rainfall, land cover or soils, which is a limitation noted in Section 5.3.

5.3 Limitations of the Study

- The DEM (SRTM, February 2000) predates recent urban and land-use change, so present-day drainage alterations are not captured.
- Vertical error (about 9 m at 90% confidence) and canopy effects can be large relative to the low relief of the coastal zone, and D8 routing can produce parallel flow lines in flat and tidal terrain.
- Hydrological sensitivity is a terrain-based hazard proxy; exposure and vulnerability (settlements, infrastructure, population) were not modelled.
- No stream-gauge discharge or rainfall data were used, so the results describe flow routing, not flow magnitude.
- Network and basin outputs depend on the accumulation threshold; the sensitivity test in Section 3.6.4 accompanies all reported network metrics.

5.4 Management Implications

The results support five specific management actions. First, channels and culverts that coincide with the very high accumulation and sensitivity classes should be inspected and desilted before the rainy season. Second,

construction in sink (ponding) cells and in low-lying cells beside high-order streams should be restricted or conditioned on drainage design. Third, roads, bridges and culverts crossing high-accumulation channels should be sized using the contributing area (km²) derived from this analysis as input to design-flow estimates. Fourth, stage gauges at the watershed outlet and at the points of highest accumulation would convert terrain-based sensitivity into measured discharge. Fifth, the sensitivity map should be adopted as a layer in state land-use and environmental planning and updated when a newer DEM or land-cover map becomes available.

CONCLUSION

The study used GIS hydrological tools to delineate and characterise the watershed system of Akwa Ibom State from a documented SRTM-based workflow. The findings revealed a well-developed drainage network of 1,404 stream links, multi-directional flow routing across all eight D8 classes, runoff-concentration zones along major channels and near the outlet, and hydrologically sensitive areas requiring management attention. The study demonstrates that GIS-based watershed analysis provides a reproducible framework for understanding hydrological behaviour and supporting environmental management. The results describe terrain-based runoff-concentration potential and not confirmed flood extent, and should be read with the limitations stated in Section 5.3. Watershed-based planning should therefore be integrated into environmental policies and disaster risk reduction programmes in Akwa Ibom State.

RECOMMENDATIONS

1. Integrate GIS-based watershed maps into state environmental planning and land-use management programmes.

2. Prioritise hydrologically sensitive zones with high flow accumulation values for flood control and drainage improvement projects.

3. Monitor major drainage channels regularly to prevent blockage and maintain effective runoff conveyance.

4. Establish a watershed monitoring system, including gauges at the outlet and at high-accumulation points, that tracks flow accumulation, drainage changes and environmental risks across Akwa Ibom State.

5. Restrict development in sink (ponding) cells and low-lying areas beside high-order streams unless supported by drainage design.

6. Repeat the analysis with a newer or higher-resolution DEM and with rainfall, soil and land-cover data to move from hydrological sensitivity to flood vulnerability assessment.

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