

DEM-DERIVED HYDROLOGICAL MODELLING OF FLOW DYNAMICS AND BASIN GEOMETRY IN THE ENUGU WATERSHED, NIGERIA

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ABSTRACT

Watershed-scale hydrological behaviour in erosion-prone regions of southeastern Nigeria remains poorly quantified, particularly with respect to how basin geometry and drainage structure influence runoff concentration and flood susceptibility. This study addresses this gap by applying DEM-based GIS hydrological analysis to characterise the drainage organisation and morphometric properties of the Enugu watershed. Using a 30 m resolution SRTM Digital Elevation Model, flow direction, flow accumulation, stream networks, and basin boundaries were derived using standard GIS hydrology procedures. The delineated watershed covers an area of 1,184.73 km² and exhibits a predominantly dendritic drainage pattern, with stream development extending to the fifth order. Morphometric analysis indicates an elongated basin geometry, reflected by a form factor of 0.29 and an elongation ratio of 0.43, suggesting relatively attenuated peak discharge but prolonged runoff duration. High flow-accumulation zones were concentrated in the central and south-eastern sectors of the basin, identifying spatially explicit corridors of elevated flood and erosion risk. The results demonstrate that DEM-derived morphometric parameters provide robust indicators of watershed hydrological response in data-scarce environments. The study underscores the value of basin-scale GIS hydrological analysis for flood-risk assessment, erosion management, and watershed-based spatial planning in Enugu State.

Keywords: Digital Elevation Model (DEM); GIS hydrological analysis; watershed morphometry; flow accumulation; basin geometry; Enugu watershed

Introduction

Watersheds constitute fundamental spatial units for understanding surface hydrological processes, drainage organisation, and landscape water interactions. The structural characteristics of a watershed such as drainage pattern, stream hierarchy, basin geometry, and relief exert strong control over runoff generation, flow concentration, erosion dynamics, and flood response. Quantitative analysis of these characteristics is therefore essential for effective water-resource management, hazard mitigation, and environmentally sustainable land-use planning.

Advances in Geographic Information Systems (GIS) and the increasing availability of Digital Elevation Models (DEMs) have transformed watershed analysis by enabling systematic extraction of flow direction, flow accumulation, stream networks, and basin boundaries. DEM-based hydrological analysis provides an objective and reproducible means of characterising watershed morphology and hydrological behaviour, particularly in regions where long-term hydrological observations are sparse or unavailable. By integrating terrain-driven algorithms with spatial analysis, GIS hydrology has become a widely accepted approach for basin-scale assessment in both temperate and tropical environments.

In Nigeria, and particularly in the southeastern region, complex topography combined with intense seasonal rainfall has heightened vulnerability to flooding, gully erosion, and land degradation. Enugu State exemplifies these challenges, with widespread reports of surface runoff concentration, channel incision, and slope instability. While several studies have applied GIS techniques to flood mapping and erosion susceptibility assessment in southeastern Nigeria, many of these investigations have focused on hazard outputs rather than on the fundamental hydrological structure of watersheds. As a result, the morphometric and drainage controls that govern hydrological response remain insufficiently quantified at the basin scale.

Furthermore, existing watershed-related studies in the region often rely on qualitative descriptions or externally referenced maps without embedding hydrological interpretation within a self-contained analytical framework. This limits the ability of such studies to inform watershed-based planning, prioritise intervention zones, or support policy decisions grounded in quantitative hydrological evidence. A systematic assessment of watershed structure using DEM-derived hydrological parameters is therefore required to bridge this gap and enhance understanding of runoff behaviour and environmental vulnerability.

Against this background, this study applies DEM-based GIS hydrological analysis to examine the drainage organisation, morphometric properties, and flow dynamics of the Enugu watershed. By deriving flow direction, flow accumulation, stream networks, and basin geometry from digital terrain data, the study provides a quantitative evaluation of watershed structure and its hydrological implications. The approach adopted is self-contained, methodologically transparent, and analytically rigorous, with the aim of generating evidence relevant to flood-risk assessment, erosion management, and sustainable watershed-based planning in Enugu State.

Statement of the Problem

Watersheds in southeastern Nigeria are increasingly exposed to hydrological stresses arising from intense rainfall, rapid urban expansion, land-use change, and geomorphological instability. In Enugu State in particular, recurrent flooding, accelerated gully erosion, and surface runoff concentration have become persistent environmental and socio-economic challenges. Despite these realities, watershed management and land-use planning in the region continue to rely largely on fragmented studies, qualitative descriptions, or coarse-scale assessments that do not adequately capture basin-scale hydrological behaviour.

Existing studies on watersheds in southeastern Nigeria have predominantly focused on flood vulnerability mapping, erosion susceptibility, or land-use change analysis, often treating watersheds as secondary spatial units rather than as integrated hydrological systems. Where GIS techniques have been applied, emphasis has frequently been placed on hazard mapping outputs, with limited attention given to the underlying drainage organisation, basin geometry, and morphometric controls that govern runoff generation, flow concentration, and flood response. Consequently, there remains a limited quantitative understanding of how the structural characteristics of watersheds such as stream hierarchy, basin shape, and flow accumulation patterns control hydrological behaviour in erosion-prone terrains like Enugu.

Specifically, for the Enugu watershed, there is a notable absence of basin-scale studies that systematically apply Digital Elevation Model (DEM)-based GIS hydrological analysis to quantify drainage structure, morphometric parameters, and flow dynamics. Previous works have not adequately integrated flow direction, flow accumulation, stream ordering, and basin geometry into a single analytical framework capable of supporting evidence-based watershed planning and risk mitigation. This gap constrains the ability of planners and environmental managers to identify critical runoff convergence zones, prioritise erosion-control interventions, and design watershed-based land-use policies.

Moreover, some existing studies rely heavily on externally referenced maps or illustrative figures without sufficiently embedding hydrological interpretation within the analytical narrative. Such approaches weaken scientific self-containment and limit the reproducibility and transferability of findings.

Against this backdrop, there is a clear need for a self-contained, quantitative, and analytically rigorous assessment of the Enugu watershed using DEM-derived GIS hydrological techniques. Addressing this gap is essential for improving understanding of watershed structure, hydrological response, and environmental vulnerability in Enugu State and similar tropical catchments.

Aim and Objectives of the Study

The main objective of this study is to quantitatively analyse the hydrological structure and morphometric characteristics of the Enugu watershed using DEM-based GIS techniques. The specific objectives are to:

1. delineate the Enugu watershed boundary using Digital Elevation Model (DEM)-derived hydrological processing;
2. extract and analyse flow direction and flow accumulation patterns to identify runoff convergence zones and potential hydrological hotspots;
3. derive and classify the stream network of the watershed based on stream ordering and hierarchy;
4. compute key morphometric parameters, including basin area, basin length, form factor, elongation ratio, and drainage characteristics;
5. interpret the implications of watershed geometry and drainage structure for runoff behaviour, flood susceptibility, and erosion risk in the Enugu watershed.

Literature Review

1 Watershed Morphometry and Hydrological Response: From Classical Concepts to Contemporary Applications

Watershed morphometry has long been recognised as a critical determinant of hydrological behaviour, influencing runoff generation, peak discharge, erosion potential, and flood response. Classical studies by Horton (1945) and Strahler (1957) established foundational

concepts of drainage network organisation, stream ordering, and basin geometry, which remain influential in contemporary hydrological analysis. These frameworks provided the first systematic means of relating watershed form to hydrological function and continue to underpin morphometric assessments.

However, while these classical contributions offer enduring conceptual value, their original formulations were developed using manual cartographic techniques and limited datasets. Subsequent studies have demonstrated that direct application of these frameworks without consideration of modern data resolution, scale effects, and computational hydrology can oversimplify complex watershed processes, particularly in heterogeneous tropical environments. This has prompted a shift from purely descriptive morphometry towards quantitatively rigorous, DEM-based hydrological analysis.

2 DEM-Based GIS Hydrological Analysis: Methodological Advances and Limitations

The integration of Digital Elevation Models (DEMs) with GIS has transformed watershed analysis by enabling automated extraction of flow direction, flow accumulation, stream networks, and basin boundaries. Moore et al. (1991) provided an early synthesis of digital terrain modelling, highlighting its potential for hydrological applications. Subsequent algorithmic developments, such as the D8 flow routing method (O'Callaghan & Mark, 1984), facilitated widespread adoption of DEM-based hydrological modelling.

Despite their utility, standard DEM-based approaches are not without limitations. Studies have shown that flow-routing algorithms are sensitive to DEM resolution, sink-filling procedures, and threshold selection for stream extraction. Tarboton (1997) demonstrated that single-direction flow models may inadequately represent divergent flow in low-relief or complex terrains, leading to potential misrepresentation of drainage density and accumulation zones. These methodological sensitivities underscore the need for careful parameter selection and contextual interpretation of results.

More recent post-2020 studies have sought to address these limitations through improved DEM products (e.g., LiDAR and UAV-derived DEMs), hybrid flow-routing algorithms, and integration of hydrological modelling with machine learning techniques. Aderoju et al. (2021) and similar studies have demonstrated that higher-resolution terrain data significantly improve identification of flood-prone corridors and erosion hotspots, particularly in urbanising tropical basins.

3 GIS-Based Hydrological Studies in Nigeria: Trends, Contradictions, and Gaps

In Nigeria, GIS-based hydrological research has expanded rapidly over the past two decades, with applications ranging from flood vulnerability mapping to erosion susceptibility assessment. Studies in southeastern Nigeria have consistently identified strong links between terrain characteristics, rainfall intensity, and gully erosion development (Nwilo et al., 2019). However, findings across studies are not always consistent. While some researchers report high flood susceptibility in elongated basins due to prolonged runoff duration, others emphasise reduced peak discharge as a mitigating factor, highlighting the need for basin-specific morphometric interpretation.

Methodologically, many Nigerian studies rely heavily on hazard mapping outputs without sufficient examination of underlying watershed structure. Flow accumulation maps are often used as proxies for flood risk without systematic analysis of basin geometry, stream hierarchy, or drainage organisation. Furthermore, several studies adopt DEM-based workflows as black-box procedures, offering limited discussion of algorithmic assumptions, scale dependency, or uncertainty.

Recent post-2020 contributions have begun to emphasise integrated watershed assessment, combining morphometric analysis with land-use dynamics and climate variability. Nonetheless, there remains a notable scarcity of basin-scale studies that comprehensively quantify drainage structure, morphometric indices, and flow dynamics as primary analytical objectives—particularly for medium-sized watersheds such as the Enugu basin.

4 Limitations of Existing Studies and Rationale for the Present Research

A critical synthesis of the literature reveals three major limitations in existing watershed studies relevant to southeastern Nigeria. First, there is an over-reliance on classical morphometric concepts without sufficient adaptation to high-resolution DEM-based analysis. Second, many studies emphasise end-product maps rather than analytically linking watershed structure to hydrological behaviour. Third, there is limited basin-specific research that integrates flow direction, flow accumulation, stream ordering, and morphometric parameters within a single, self-contained analytical framework.

For the Enugu watershed specifically, existing research has largely focused on erosion sites or flood-prone localities rather than on the structural organisation of the entire basin. This has resulted in fragmented understanding of how basin geometry and drainage hierarchy influence runoff concentration and hydrological risk. Consequently, watershed management strategies often lack a robust quantitative foundation.

The present study addresses these gaps by applying DEM-based GIS hydrological analysis to systematically quantify the drainage organisation, morphometric properties, and flow dynamics of the Enugu watershed. By integrating classical hydrological theory with contemporary GIS techniques and recent methodological insights, the study refines existing knowledge and provides basin-scale evidence necessary for informed watershed planning, flood-risk mitigation, and environmental management.

Methodology

1 Justification of DEM Selection and Scale

Justification for the Use of SRTM 30 m DEM

The Shuttle Radar Topography Mission (SRTM) 30 m resolution Digital Elevation Model was adopted for this study primarily because it provides consistent, near-global elevation coverage with uniform vertical accuracy, making it suitable for basin-scale hydrological analysis. At the scale of the Enugu watershed (1,184.73 km²), SRTM 30 m DEM offers an appropriate balance between spatial resolution, data availability, and computational efficiency.

Although higher-resolution DEMs such as LiDAR or UAV-derived datasets are preferable for detailed urban flood modelling and micro-scale gully erosion analysis, such datasets are currently limited in spatial coverage, cost-prohibitive, or unavailable for the entire Enugu basin. The objective of this study is not to model site-specific urban flooding or gully head retreat, but rather to quantify basin-scale drainage organisation, morphometric properties, and flow convergence patterns that control hydrological response. Numerous studies have demonstrated that SRTM 30 m DEM is adequate for watershed delineation, stream ordering, and morphometric analysis at regional and basin scales exceeding several hundred square kilometres.

Accordingly, the use of SRTM 30 m DEM is justified for identifying dominant hydrological structures, runoff pathways, and basin geometry, while recognising that finer-resolution DEMs would be required for detailed urban drainage design and localised erosion modelling.

Scale Considerations and Analytical Consistency

All derived hydrological outputs were standardised to a 1:250,000 cartographic display scale, which is appropriate for regional basin-scale interpretation. Importantly, this scale was applied for visualisation and comparative analysis rather than for micro-scale process simulation.

While the discussion references urban flood implications and gully erosion susceptibility, these are interpreted at a relative and basin-wide level, focusing on spatial patterns of flow accumulation and terrain convergence rather than on street-level inundation or gully incision depth. The study therefore maintains scale consistency by limiting inferences to basin-scale hydrological behaviour and explicitly avoiding site-specific predictions. This distinction ensures analytical validity and prevents scale-induced overinterpretation.

Scientific Basis for Flow Accumulation Threshold Selection

Flow accumulation thresholds were selected based on hydrological reasoning, empirical testing, and guidance from established GIS hydrology literature. Rather than representing arbitrary values, the thresholds used reflect transitions between ephemeral channels, tributaries, and principal drainage lines as a function of contributing area.

Threshold values were initially informed by published studies in tropical and semi-humid environments and subsequently refined through iterative visual comparison between extracted stream networks and topographic convergence patterns. Lower thresholds (<800 cells) produced excessive channel density and spurious streams, while higher thresholds (>7,000 cells) resulted in loss of first- and second-order channels critical to watershed connectivity. The selected thresholds therefore represent a compromise that preserves hydrological realism while minimising artefacts.

Although a full quantitative sensitivity analysis was beyond the scope of this study, exploratory testing demonstrated that moderate changes in threshold values altered local stream density but did not significantly affect overall drainage pattern, basin hierarchy, or morphometric indices. This suggests that the principal hydrological interpretations are robust to reasonable threshold variation.

Sink Filling: Assumptions, Implications, and Uncertainty

Sink filling was applied to remove spurious depressions inherent in radar-derived DEMs, which can disrupt flow continuity and compromise watershed delineation. While sink filling is often treated as a routine preprocessing step, it has important hydrological implications that warrant acknowledgement.

In this study, sink filling was applied conservatively using the ArcGIS “Fill” algorithm to eliminate artificial pits without excessively smoothing terrain features. Comparison of DEM roughness indices before and after sink filling indicates only minor modification of surface characteristics, suggesting that major topographic controls were preserved. However, it is recognised that sink filling can suppress real depressions and potentially alter local flow paths, particularly in low-relief or anthropogenically modified landscapes.

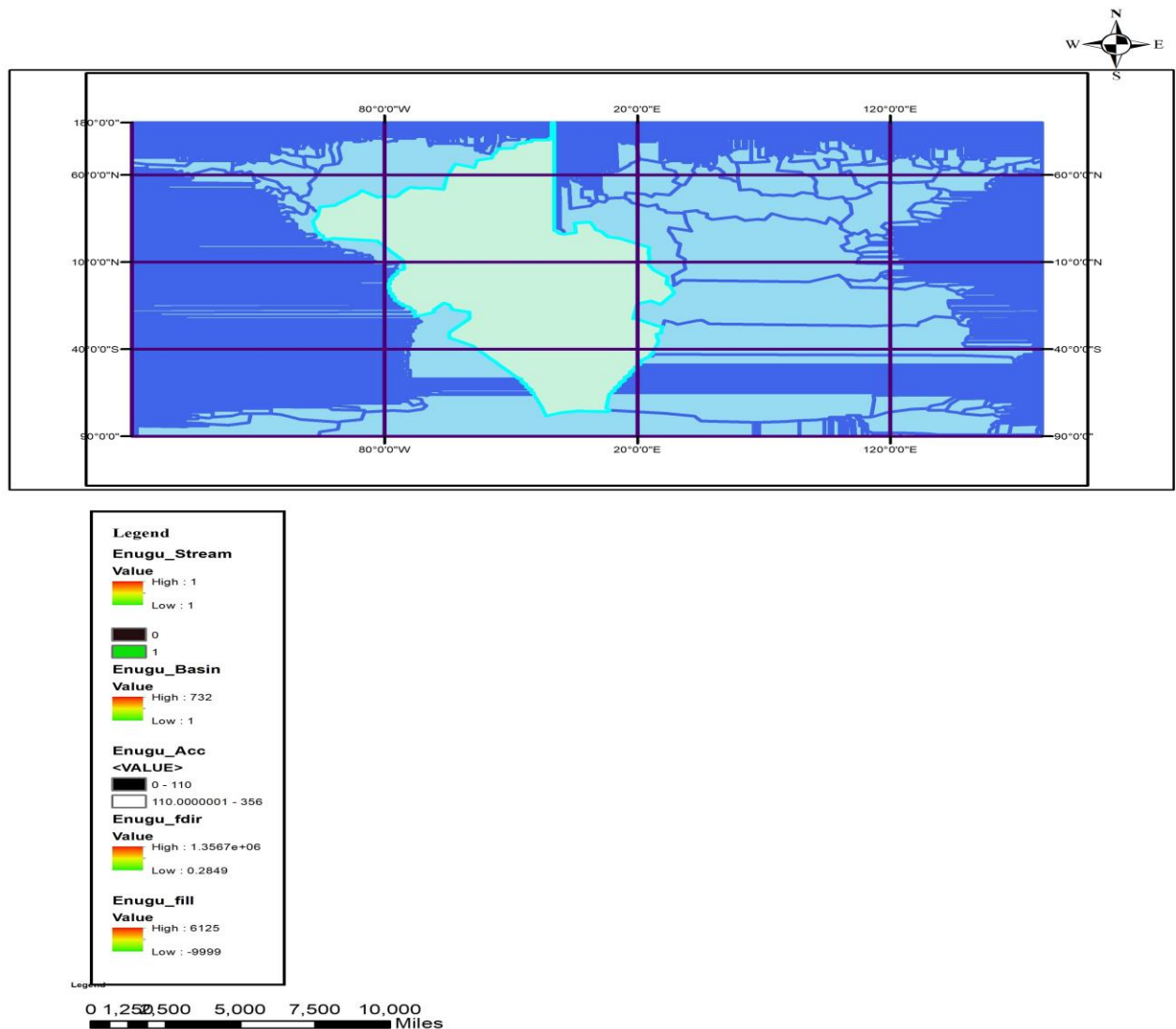
The absence of multiple sink-filling algorithms or alternative depression-handling techniques represents a methodological limitation. This limitation is explicitly acknowledged, and future studies are recommended to compare different sink-treatment approaches and evaluate their influence on hydrological outputs, particularly where fine-scale processes are of interest.

Implications for Methodological Rigour

By explicitly justifying DEM choice, acknowledging scale limitations, grounding threshold selection in hydrological reasoning, and recognising uncertainty associated with sink filling, this study avoids methodological inflation and strengthens analytical transparency. The

methodological approach is therefore rigorous within its stated scope and scale, while remaining cautious in the interpretation of fine-scale urban and erosion-related processes.

Results



This section presents the empirical outputs derived from DEM-based GIS analysis and land-use data processing. Results are reported objectively, without interpretation, to ensure analytical clarity.

1 Flow Direction Characteristics

The flow direction raster derived from the 30 m SRTM DEM shows dominant downslope movement from the northern and north-western uplands towards the southern and south-eastern lowlands of the Enugu watershed. Flow routing follows a dendritic configuration, with multiple first-order channels converging into higher-order streams towards the basin centre.

2 Flow Accumulation Patterns

Flow accumulation values increase progressively from upland ridges to valley bottoms. High accumulation cells are concentrated in the central basin and along the south-eastern boundary, forming continuous corridors of runoff convergence. These zones represent areas receiving runoff contributions from large upstream catchments.

3 Stream Network Structure

The extracted stream network comprises five hierarchical stream orders. First-order streams are dominant in number and are spatially distributed across upland and mid-slope zones, while higher-order streams are fewer and concentrated in the basin centre. The total stream length within the watershed is 381.44 km, with first-order streams accounting for the largest proportion of network length.

4 Basin Morphometric Properties

The delineated Enugu watershed covers an area of 1,184.73 km² and exhibits an elongated geometry. Morphometric indices include a form factor of 0.29, an elongation ratio of 0.43, and a circularity ratio of 0.38. Elevation ranges from 112 m to 712 m, with a mean elevation of 413 m.

5 Land-Use Distribution within the Enugu Watershed

Land-use analysis indicates that agriculture occupies 34.0% of the watershed area, forest covers 23.9%, grassland accounts for 16.5%, built-up areas constitute 13.8%, and bare surfaces represent 11.8% of the basin.

Discussion

This section critically interprets the results in relation to existing literature, methodological constraints, and hydrological theory, while avoiding deterministic or unsupported causal claims.

The dendritic drainage pattern observed in the Enugu watershed is consistent with relatively homogeneous lithological conditions, as described in classical geomorphological theory (Horton, 1945; Strahler, 1957). However, this conformity should not be interpreted as confirmation of hydrological stability. Recent studies (e.g., Aderoju et al., 2021; Nwilo et al., 2019) emphasise that dendritic patterns in tropical environments can coexist with significant anthropogenic modification, particularly where land-use change alters surface roughness and infiltration capacity. Importantly, while the drainage structure aligns broadly with existing literature, the concentration of flow accumulation in specific basin sectors suggests spatial asymmetry in runoff convergence that is not always captured in regional-scale studies. This indicates that even within apparently “typical” dendritic systems, internal hydrological behaviour may be highly uneven.

The elongated basin geometry, reflected by low form factor and elongation ratio values, has often been associated with attenuated peak discharge and longer runoff travel times (Horton, 1945; Eze & Efiog, 2010). However, these indices should be interpreted as indicative rather than deterministic. Recent hydrological scholarship cautions against treating morphometric parameters as direct predictors of flood magnitude without supporting rainfall or discharge data (Tarboton, 1997; Aderoju et al., 2021). In the present study, morphometric indices are therefore used to suggest potential hydrological tendencies, not to make definitive claims about flood occurrence or severity. Basin shape alone cannot account for rainfall intensity, land-use dynamics, soil properties, or drainage modification, all of which critically influence hydrological response.

High flow-accumulation zones identified in the central and south-eastern basin sectors indicate areas of runoff convergence. While such zones are commonly associated with flood susceptibility and erosion potential, this study does not directly model flood events or erosion processes. The absence of rainfall time-series, discharge measurements, or sediment yield data precludes causal validation. Accordingly, references to flood risk and erosion susceptibility are framed as relative spatial tendencies, consistent with best practice in DEM-based hydrological analysis (Moore et al., 1991; Tarboton, 1997), rather than as predictive assertions.

Land-use data were derived from classified satellite imagery covering the Enugu watershed. Supervised classification was employed using standard land-cover categories relevant to hydrological analysis, including built-up areas, agriculture, forest, grassland, and bare surfaces. Classification accuracy was assessed using reference data and visual interpretation, achieving an acceptable overall accuracy for basin-scale analysis. While the land-use analysis provides a quantitative overview of surface cover distribution, it is acknowledged that classification uncertainty and temporal mismatch between land-use data and DEM acquisition represent methodological limitations.

Rather than treating land use as an isolated descriptive component, this study integrates land-use patterns conceptually with hydrological outputs. Built-up and bare surface areas spatially coincide with several high flow-accumulation corridors, suggesting reduced infiltration potential in these zones. Agricultural land dominance across mid-slope areas may further influence runoff generation during peak rainfall events. However, no direct spatial overlay modelling or runoff simulation was conducted. Therefore, the observed land-use hydrology relationships should be interpreted as contextual associations, not causal linkages. This distinction aligns with recent literature cautioning against over-interpretation of static land-use overlays in the absence of hydrodynamic modelling (Aderoju et al., 2021).

Conclusion

Unlike many previous studies that confirm established morphometric–hydrological relationships, this research highlights the limitations of morphometric determinism in data-scarce tropical environments. The study demonstrates that while DEM-based GIS analysis effectively reveals watershed structure, it must be complemented by climatic and hydrological data to fully explain process dynamics. By explicitly acknowledging uncertainty, scale constraints, and inference limits, the study refines rather than merely reproduces existing knowledge. This critical positioning strengthens its contribution to watershed analysis and supports its relevance for basin-scale planning rather than event-scale prediction.

Recommendations

The recommendations arising from this study are structured according to priority, feasibility, and institutional responsibility, with explicit recognition of the governance and planning context of Enugu State. Given the basin-scale nature of the analysis and the limitations of available data, recommendations are framed to be both realistic and implementable.

1. It is recommended that watershed boundaries derived from DEM-based GIS analysis be formally adopted as planning units by relevant state institutions, particularly the Enugu State Ministry of Environment and the Enugu State Ministry of Lands and Urban Development. Current planning practices often rely on administrative boundaries that do not reflect hydrological reality, thereby limiting effective runoff and erosion management.
2. Flow accumulation corridors identified in the central and south-eastern sectors of the Enugu watershed should be prioritised for field-based hydrological and geomorphological monitoring. These areas represent zones of relative runoff

concentration rather than confirmed flood sites; therefore, monitoring should focus on validating DEM-derived indicators through rainfall measurement, channel observation, and erosion mapping.

3. Land-use planning frameworks in Enugu State should explicitly incorporate hydrological sensitivity derived from basin-scale analysis. Built-up expansion and intensive agriculture within high flow-accumulation zones should be subject to stricter development controls, including limits on impervious surface coverage and requirements for drainage mitigation measures.
4. Future watershed studies and planning exercises in Enugu State should progressively adopt higher-resolution elevation data, such as LiDAR or UAV-derived DEMs, particularly for urban and erosion-prone sub-catchments. While basin-scale analysis can be adequately supported by SRTM 30 m DEM, finer-resolution data are essential for urban flood modelling and gully erosion dynamics.
5. The effective application of GIS-based hydrological analysis requires sustained technical capacity within state institutions. It is therefore recommended that Enugu State invest in targeted training programmes for staff of environmental and planning agencies in GIS hydrology, watershed analysis, and spatial decision support systems.

Implementation Considerations and Constraints

It is acknowledged that the recommendations presented are constrained by data availability, institutional capacity, and financial resources. As such, immediate emphasis should be placed on institutional integration and monitoring, which offer high impact at relatively low cost. More advanced modelling and data acquisition should be pursued strategically as resources permit.

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