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Influences of Basin Morphometry Controls on Gully Development in the Ofu Catchment, Nigeria

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Abstract: *Gully erosion is a major form of land degradation whose occurrence and development are strongly influenced by basin morphometry through its control on runoff concentration, drainage efficiency, slope gradients, and sediment transport. This study assessed the influence of basin morphometric characteristics on gully formation and development in the Ofu River Catchment, Nigeria. A 30-m Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model was processed within a Geographic Information System to delineate the catchment, extract the drainage network, and derive key morphometric parameters. Field investigations identified 42 gully erosion sites where gully dimensions and the Gully Severity Index (GSI) were measured. Pearson and Spearman correlation analyses were used to examine relationships between morphometric variables and gully characteristics, while multiple regression evaluated the collective influence of selected predictors on gully severity. The Ofu River Catchment covers 1,641.74 km² and is characterized by a fourth-order drainage network with a total stream length of 264.00 km. Morphometric analysis revealed a drainage density of 0.161 km km⁻², stream frequency of 0.041 streams km⁻², bifurcation ratio of 3.97, form factor of 0.116, circularity ratio of 0.201, elongation ratio of 0.385, relief ratio of 0.0029, and mean basin slope of 2.86°. These indices indicate an elongated basin with localized runoff concentration along drainage pathways. Correlation analysis showed that drainage position had a strong positive relationship with gully length ($r = 0.643$, $p < 0.001$), while slope significantly influenced gully depth ($r = 0.502$, $p = 0.001$), catchment surface area ($r = 0.528$, $p < 0.001$), and gully severity ($r = 0.316$, $p = 0.042$). GSI also increased significantly with drainage position ($r = 0.423$, $p = 0.005$). The regression model was statistically significant ($R^2 = 0.384$, Adjusted $R^2 = 0.335$, $F = 7.891$, $p = 0.0003$), indicating that morphometric factors explained 38.4% of the variation in gully severity, while model validation produced an AUC of 0.769 and an accuracy of 71.4%. The findings demonstrate that basin morphometry exerts a significant control on gully formation and expansion through the interaction of slope, drainage position, and contributing area. Although the catchment exhibits low overall drainage density and gentle relief, localized topographic conditions create favorable environments for runoff concentration and gully enlargement. The study highlights the importance of incorporating morphometric indicators into watershed management strategies, gully stabilization programs, and erosion-risk planning within the Ofu River Catchment.*

Keywords: Basin morphometry, gully erosion, drainage network, watershed management, Gully Severity Index, Ofu River Catchment, Nigeria.

INTRODUCTION

Gully erosion represents a major pathway through which hillslope soil is rapidly transferred into drainage systems. Unlike diffuse sheet erosion, gully development produces concentrated channels that can enlarge through headward retreat, incision and lateral expansion. The resulting landform may remove productive soil, fragment agricultural fields, damage roads and settlements, and increase sediment connectivity between hillslopes and stream channels. These characteristics make gullies an important geomorphic and watershed-management concern, particularly where intense rainfall interacts with susceptible soils and substantial land-surface disturbance (Castillo & Gómez, 2016; Valentin et al., 2005; Vanmaercke et al., 2021). Recent synthesis of African research confirms that gully development is commonly associated with interactions among erosive rainfall, topography, soil conditions and human land-use practices rather than a single controlling factor (Falta et al., 2025).

The spatial development of gullies is strongly conditioned by the way a landscape receives, concentrates and transfers runoff. Rainfall intensity and antecedent moisture influence runoff generation, while soil properties and vegetation regulate the resistance of the surface to detachment. Topography controls the direction and potential energy of overland flow, whereas roads, cultivated fields, settlements and drainage infrastructure can redirect naturally diffuse runoff into concentrated pathways. Consequently, gully development is better understood as a threshold process in which hydraulic forces become sufficient to overcome the resistance of the soil and land surface (Poesen et al., 2003; Torri & Poesen, 2014).

Within this process framework, drainage-basin morphology provides an important means of characterizing the spatial organization of runoff. Basin morphometry describes the measurable geometric and drainage properties of a catchment and includes variables related to stream hierarchy, drainage density, stream frequency, bifurcation, basin shape, relief and slope. These properties influence runoff travel distances, flow concentration, drainage connectivity and the timing of water delivery to channels. Classical geomorphological studies established the quantitative basis for drainage-basin analysis, while subsequent GIS-based approaches have greatly increased the efficiency with which morphometric characteristics can be derived over large areas (Horton, 1945; Strahler, 1957).

The relevance of morphometry to gully erosion arises from its capacity to describe the physical setting in which runoff is generated and transferred. Drainage density reflects the degree of channel dissection, while stream frequency provides information on the abundance of drainage segments. Bifurcation ratio describes the branching structure of the drainage network. Basin shape indices, including form factor, circularity ratio and elongation ratio, provide information about the spatial arrangement of contributing areas and the likely temporal concentration of runoff. Relief ratio and slope provide complementary information about the potential topographic energy available to move water and sediment downslope.

However, basin morphometry should not be interpreted as a deterministic predictor of gully erosion. Catchment-scale averages can conceal considerable local variation. A basin may have low drainage density but still contain individual locations where runoff becomes strongly concentrated because of local slope breaks, valley heads, roads, cultivated surfaces or drainage outlets. Similarly, a catchment with a low mean slope can contain localized steep slopes capable of promoting incision. This scale dependency is particularly important in gully research because gully initiation is often associated with critical combinations of contributing area and local slope rather than with mean basin conditions alone (Torri & Poesen, 2014).

Recent research has reinforced the usefulness of morphometric information for understanding gully development. Ciccolini et al. (2024), for example, demonstrated that morphometric and hypsometric characteristics can provide information on the spatial conditions associated with gully initiation. Their approach highlights the importance of considering the internal structure of drainage basins rather than treating catchments as homogeneous units. At the African scale, Falta et al. (2025) found that gully development is related to drainage area, slope, rainfall and human activity, emphasizing the coupled nature of geomorphic controls.

Evidence from Nigeria similarly demonstrates that gully susceptibility varies according to combinations of terrain, soil, geology, vegetation and human disturbance. Fagbohun et al. (2024), working in the Agulu–Nanka watershed, found vegetation cover, geology, slope and soil to be among the most important controls of gully susceptibility. Okoeka et al. (2025) also demonstrated that terrain and soil characteristics can provide useful discrimination of gully-prone locations in Etsako West, Edo State. These studies demonstrate the value of spatial modelling, but they also reveal the need for more localized studies that directly examine the relationship between measured gully characteristics and drainage-basin morphology. Research on Nigerian drainage basins has historically placed considerable emphasis on morphometric characterization, watershed prioritization and hydrological interpretation. Ocheri et al. (2025), in a review of Nigerian morphometric studies, showed that GIS and remote sensing have become important tools for extracting drainage-basin properties and assessing their environmental implications. Nevertheless, morphometric characteristics are frequently interpreted in relation to general runoff or erosion potential without directly testing their statistical relationships with observed gully dimensions and severity.

The Ofu River Catchment provides an appropriate setting for addressing this limitation. The catchment occurs within a tropical sub-humid environment characterized by seasonal rainfall, sedimentary geological formations, undulating-to-hilly terrain and substantial agricultural activity. Changes in vegetation cover and land use have the potential to modify surface runoff and connectivity, while the basin's drainage organization determines how generated runoff is progressively transferred through the landscape.

The specific problem addressed in this study is therefore not simply whether the Ofu River Catchment possesses particular morphometric characteristics, but whether those characteristics are measurably associated with observed gully development. The study combines GIS-derived basin morphometry with field observations from 42 gully sites to examine relationships between drainage position, slope and measured gully characteristics. The study further evaluates the predictive contribution of selected morphometric variables to Gully Severity Index.

The objectives were to:

i. characterize the linear, areal and relief morphometric properties of the Ofu River Catchment;
ii. map and characterize gully erosion sites within the catchment;
iii. determine the relationships between morphometric/site characteristics and gully dimensions and severity; and
iv. evaluate the predictive contribution of selected morphometric variables to gully severity and discuss their implications for sustainable watershed management.

REVIEW OF LITERATURE AND CONCEPTUAL

Gully Development Thresholds

Gully initiation is commonly interpreted as a threshold response to the interaction between runoff concentration, contributing area and surface resistance. Rather than occurring uniformly across a landscape, incision develops where the hydraulic force generated by concentrated flow exceeds the resistance of the soil and underlying material. Topographic threshold studies have particularly emphasized the combined influence of slope and upslope contributing area, with gully initiation becoming more likely where sufficient contributing area is associated with adequate slope to generate erosive flow conditions (Torri & Poesen, 2014).

Recent studies indicate that slope or contributing area considered independently may not adequately explain gully occurrence. Gao et al. (2024), for example, demonstrated that a composite topographic factor incorporating slope and contributing area can provide a better representation of gully development than either variable alone. This suggests that gully susceptibility is related not simply to steepness but to the ability of the terrain to collect, concentrate and transmit runoff. Consequently, morphometric variables that represent drainage organization and topographic position provide a useful basis for examining spatial differences in gully development.

Basin Morphometry and Hydrological Response

Basin morphometry describes the geometric and topographic organization of a drainage basin and provides an indirect representation of how water is distributed and routed through the landscape. The principal parameters relevant to erosion studies include drainage density, stream frequency, bifurcation ratio, basin shape, elongation, circularity, relief and slope. Horton (1945), Schumm (1956) and Strahler (1957) established the foundation for relating these characteristics to drainage development and basin response.

For gully studies, the significance of morphometry lies less in individual parameter values than in their combined expression of runoff pathways and drainage connectivity. Drainage density and stream frequency can indicate the degree of channel development and potential runoff concentration, while basin shape influences the spatial and temporal organization of flow towards drainage outlets. However, these parameters should be interpreted cautiously because similar basin-scale morphometric conditions can produce different erosion responses where local topography, soil properties and land disturbance differ.

Vanmaercke et al. (2021) therefore emphasized the importance of considering gully erosion as a spatially variable process governed by interacting environmental controls rather than by a single explanatory factor.

Topographic and Drainage Controls on Gully Development

Topography directly affects the concentration and energy of surface runoff. Slope influences flow velocity and erosive capacity, whereas contributing area determines the volume of runoff potentially delivered to a particular location. Their interaction can therefore influence both gully initiation and subsequent enlargement. Recent research has shown that the relationship between topography and gully development is spatially variable. Gao et al. (2024) found that the importance of topographic controls differs according to gully setting, indicating that hillslope and valley-floor gullies may respond differently to the same terrain variables.

Drainage position is also important because it represents the location of a site within the basin's runoff-routing system. Upper drainage areas generally receive runoff from smaller contributing areas, whereas downstream positions progressively integrate flow from larger portions of the basin. Consequently, drainage position can serve as a spatial indicator of increasing runoff connectivity. This provides a basis for examining whether gully dimensions and severity vary systematically along the drainage system rather than assuming that erosion is controlled solely by local slope.

The interaction between slope and drainage connectivity is particularly important for interpreting gully morphology. A relatively gentle basin-wide slope does not necessarily indicate low gully susceptibility because localized steep terrain, concentrated flow paths and expanding contributing areas may generate conditions favorable for incision. This distinction is important when applying basin-scale morphometric indices to site-specific gully measurements.

MATERIALS AND METHODS

Study Area

The Ofu River Catchment is located in eastern Kogi State, Nigeria, within the Anambra–Imo River Basin system. The catchment extends approximately from 6°46′48.38″ N to 7°38′31.20″ N and from 6°42′43.56″ E to 7°20′54.60″ E. It covers approximately 1,642 km², catchment area. The area experiences a tropical sub-humid climate, broadly corresponding to the Köppen Aw classification. Rainfall is strongly seasonal, with the principal wet period extending approximately from April to October and the dry period from November to March. Mean annual rainfall is approximately 1,600 mm, while mean annual temperature is about 26 °C. Seasonal rainfall provides the principal source of runoff responsible for hillslope erosion and channel flow.

The catchment is underlain predominantly by Cretaceous sedimentary formations, with sandstone- and shale-associated units influencing soil development, drainage characteristics and differential resistance to erosion. Relief ranges from approximately 100 m in lower areas to more than 450 m in elevated portions

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of the catchment. The terrain consists mainly of undulating surfaces, ridges, valley sides and low-lying drainage corridors.

Soils include sandy loam, lateritic and hydromorphic/alluvial materials. Sandy and disturbed surfaces can have relatively low resistance to concentrated runoff, particularly where vegetation cover has been removed. Vegetation comprises derived savanna, secondary vegetation, riparian vegetation and cultivated landscapes. Agricultural expansion, settlement growth and vegetation disturbance have modified portions of the natural land surface and may increase runoff connectivity.

The Ofu River constitutes the principal drainage channel, with tributaries forming a predominantly dendritic drainage pattern as shows in Figure 1. The combination of seasonal rainfall, sedimentary geology, variable relief and land-use pressure provides a suitable environment for investigating relationships between drainage-basin morphology and gully development.

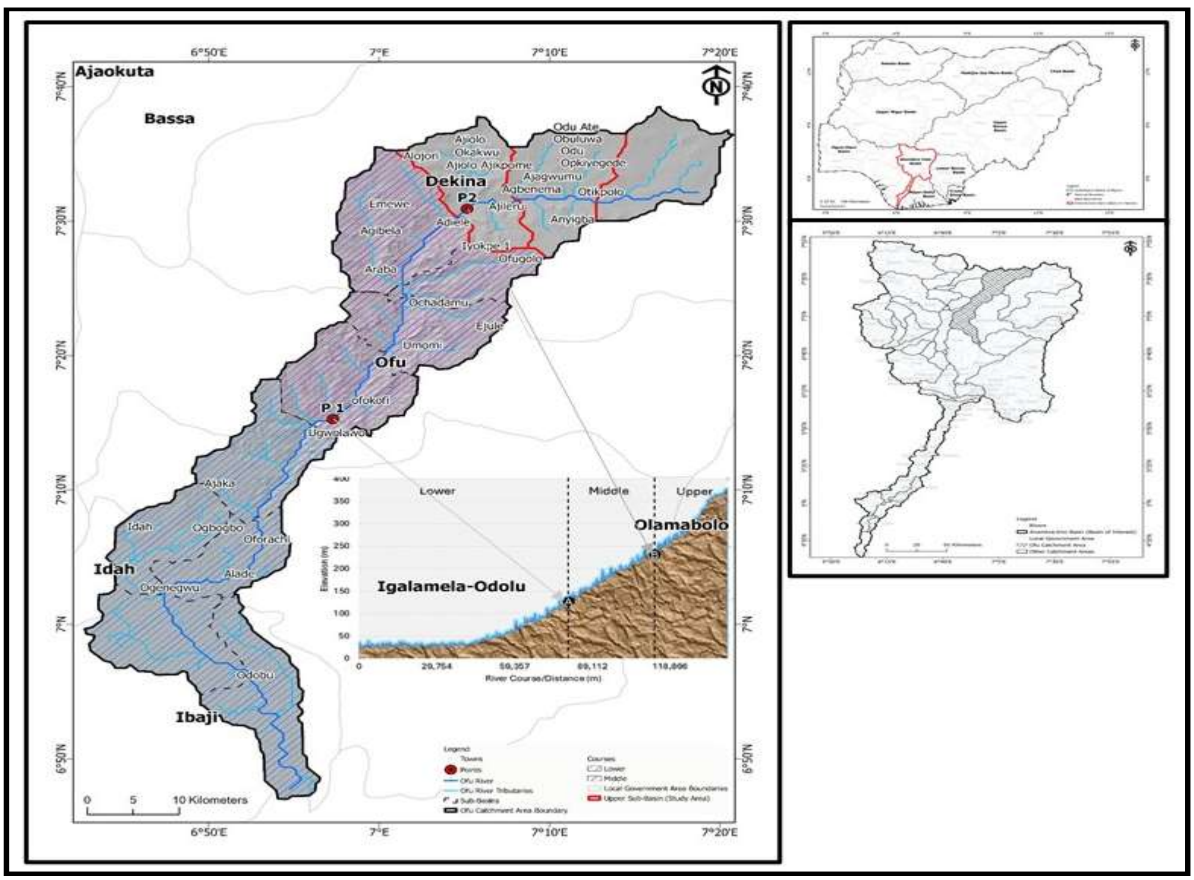

Figure 1. Location and drainage network of the Ofu River Catchment.
Source: Authors' GIS analysis, 2026.

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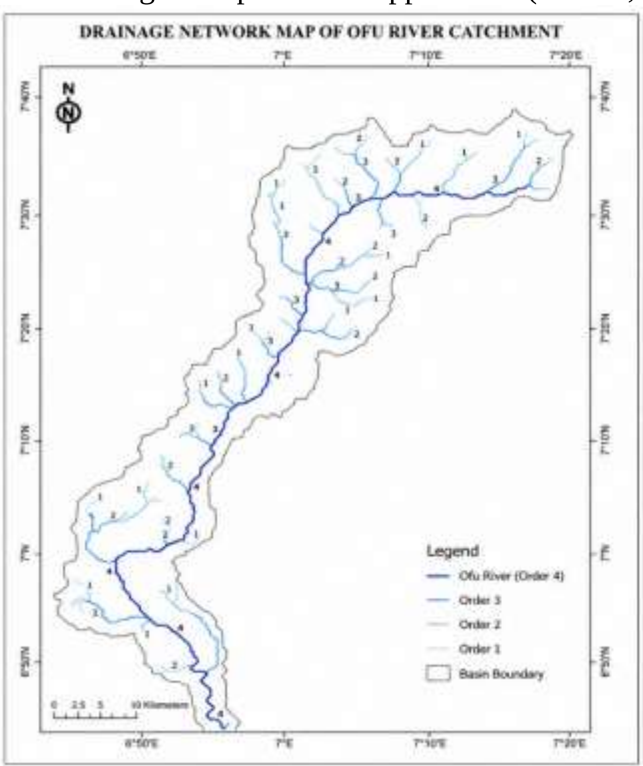
Drainage-Basin Delineation and Stream Extraction

The Ofu River Catchment boundary were downloaded from the HydroSHEDS database, a hydrologically conditioned watershed dataset derived from Shuttle Radar Topographic Mission (SRTM) elevation data (Lehner et al., 2008). and imported into a Geographic Information System (GIS) for morphometric analysis.

To characterize the drainage network, a 30-m SRTM Digital Elevation Model (DEM) was processed using standard hydrological tools. The DEM was first corrected by filling surface depressions, after which flow direction and flow accumulation layers were generated. The drainage network was then extracted and integrated with the HydroSHEDS basin boundary.

Streams were classified using the Strahler (1957) stream-order system, where unbranched channels were assigned first order, and the junction of two streams of the same order produced the next higher order. Stream lengths and stream numbers were subsequently computed and used to derive Morphometric analysis was organized into linear, areal and relief characteristics. The equations were derived from established geomorphometric approaches (Horton, 1945; Schumm, 1956; Strahler, 1957). Figure 2.



MORPHOMETRIC PARAMETERS, SYMBOLS AND FORMULAE

Parameter	Symbol	Formula
Catchment area	A	$A = \Sigma$ individual grid-cell areas
Catchment perimeter	P	$P = \Sigma$ boundary-segment lengths
Highest stream order	U	U = highest stream order in the drainage network
Number of streams	N_u	$N = \Sigma N_u$
Stream length	L_u	$L_u = \Sigma$ individual stream lengths of order u
Mean stream length	L	$L = L/N$
Bifurcation ratio	R_β	$R_\beta = N_u / N_{u+1}$
Mean bifurcation ratio	R_β	$R_\beta = \Sigma R_\beta/(U-1)$
Drainage density	D^d	$D^d = L/A$
Stream frequency	F_s	$F_s = N/A$
Drainage intensity	D_i	$D_i = F_s/D^d$
Length of overland flow	L_o	$L_o = 1/(2D^d)$
Form factor	F^f	$F^f = A/L_\beta^2$
Circularity ratio	R_c	$R_c = 4\pi A/P^2$
Elongation ratio	R_e	$R_e = 2\sqrt{(A/\pi)}/L_\beta$
Relief ratio	R_h	$R_h = H/L_\beta$
Basin slope	S_β	$S_\beta = (H/L_\beta) \times 100$

Figure 2: Ofu River Basin showing River Ofu and its tributaries
Source: Author's Data Analysis, 2026

Gully Inventory and Field Measurements

Gully sites were identified through satellite-image interpretation, reconnaissance surveys, and field verification. A total of 42 gully sites distributed across the Ofu River Catchment were selected for detailed analysis. At each site, geographic coordinates were recorded using a handheld GPS, while gully length, width, and depth were measured using standard field techniques. Measurements were taken at representative sections where gully dimensions varied.

Information on slope, drainage position, land use, and visible runoff-concentration conditions was also recorded. The measured dimensions were used to estimate gully volume and calculate the Gully Severity Index (GSI), which was subsequently used to assess relationships between gully development and basin morphometric characteristics.

Statistical Analysis

The field and morphometric data from the 42 identified gully sites were analyzed using descriptive and inferential statistical techniques. Descriptive statistics were used to summarize gully dimensions, slope, drainage position, contributing surface area and derived morphometric variables. The relationships between gully characteristics and selected morphometric/site variables were examined using Pearson product–moment correlation and Spearman rank correlation. Pearson correlation was used to assess linear relationships, whereas Spearman correlation was applied to evaluate monotonic relationships where the data did not necessarily satisfy linearity or distributional assumptions. Statistical significance was assessed at the 5% level ($p < 0.05$).

A multiple linear regression model was subsequently developed to examine the combined influence of slope and drainage position on the Gully Severity Index (GSI). Drainage position was represented by categorical variables for the middle and lower drainage corridors, with the upper/headwater corridor serving as the reference category. The model was expressed as:

where S represents slope, M the middle drainage corridor, L the lower drainage corridor, β_0 is the intercept, β_1–β_3 are the regression coefficients, and ε is the error term. Model performance was evaluated using the coefficient of determination (R^2), adjusted R^2, F-statistic and associated significance level. Differences in gully development among the 2015, 2020 and 2025 observation periods were assessed using the Friedman test, a non-parametric test for related observations. Where significant differences were detected, paired comparisons were used to identify the periods responsible for the observed differences.

Finally, the predictive performance of the regression-based susceptibility assessment was evaluated using the area under the receiver operating characteristic curve (AUC) and overall classification accuracy. An AUC value closer to 1 indicates better discrimination between areas of higher and lower gully severity. All statistical analyses were performed using standard statistical software, with results interpreted at the 5% significance level.

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RESULTS AND DISCUSSION

Morphometric Characteristics of the Ofu River Catchment

The Ofu River Catchment covers 1,641.74 km² and has a perimeter of 320.31 km. The drainage network reaches fourth order and contains 68 stream segments with a cumulative channel length of 264.00 km The calculated drainage density is 0.161 km km^{-2}, while stream frequency is 0.041 streams km^{-2}. Drainage intensity is approximately 0.258. The mean bifurcation ratio is 3.97. The catchment has a calculated length of overland flow of 3.11 km. The form factor, circularity ratio and elongation ratio are 0.116, 0.201 and 0.385, respectively. These values indicate a strongly elongated catchment. The relief ratio is 0.0029 and mean basin slope is 2.86°.

Table 1. Principal morphometric characteristics of the Ofu River Catchment

Parameter	Value
Catchment area	1,641.74 km²
Perimeter	320.31 km
Highest stream order	4th order
Total number of streams	68
Total stream length	264.00 km
Mean bifurcation ratio	3.97
Drainage density	0.161 km/km²
Stream frequency	0.041 streams/km²
Drainage intensity	0.258
Length of overland flow	3.11 km
Form factor	0.116
Circularity ratio	0.201
Elongation ratio	0.385
Relief ratio	0.0029
Basin slope	2.86°

Stream-Order Characteristics

First-order streams constitute the dominant component of the drainage network. Of the 68 mapped stream segments, 42 are first-order, 18 are second-order, seven are third-order and one is fourth-order. Thus, first-order streams account for approximately 61.8% of all identified stream segments.

Table 2. Stream-order distribution and bifurcation ratios

Stream Order	Number of Streams	Stream Length (km)	Bifurcation Ratio
1st	42	118	2.33
2nd	18	74	2.57
3rd	7	43	7.00
4th	1	29	—
Total	68	264	11.9
Mean		3.88	7.23

Source: Author's Data Analysis, 2026

The calculated bifurcation ratios are 2.33, 2.57 and 7.00 for the first-to-second, second-to-third and third-to-fourth order transitions, respectively. The mean value of 3.97 indicates an overall moderate degree of branching, although the third-to-fourth-order transition is considerably higher than the lower-order ratios. The value of 7.00 should not be interpreted independently as proof of strong structural control. It may reflect the small number of higher-order channels, lithological influence, topographic organization or the particular geometry of the extracted drainage network. Consequently, the drainage pattern should be interpreted alongside geological and terrain evidence rather than from bifurcation ratio alone.

Spatial Distribution of Gully Sites

Forty-two gully sites were identified within the Ofu River Catchment. Their spatial distribution demonstrates that gully erosion is not uniformly distributed across the catchment. The sites occur particularly along cultivated surfaces, drainage corridors, locally steeper terrain and areas where runoff is likely to become concentrated.

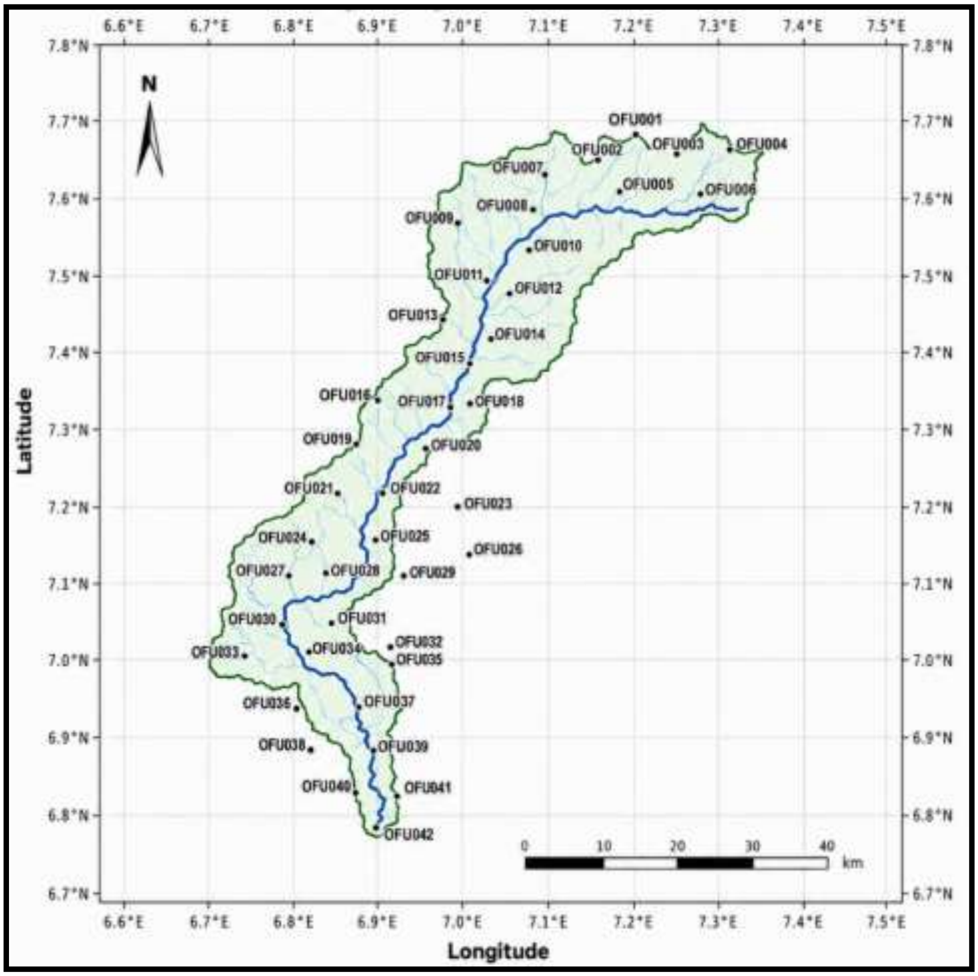

Figure 3: Spatial pattern of mapped gully sites within the Ofu River Catchment.
Source: Author's data analysis, 2026

The spatial pattern indicates that the occurrence of gullies is associated with the interaction between drainage organization and local land-surface conditions. The distribution also supports the distinction between basin-scale morphometry and site-scale controls: the overall catchment may have relatively low drainage density, while individual gully sites can receive concentrated flow from locally connected contributing areas.

Drainage Position and Gully Development

Gully length exhibits a strong positive association with drainage position (Pearson $r = 0.643$, $p = 0.000004$; Spearman $\rho = 0.595$, $p = 0.000032$). This indicates that gully length tends to increase from upper/headwater through middle to lower drainage positions. GSI also shows a significant positive relationship with drainage position ($r = 0.423$, $p = 0.005$; $\rho = 0.438$, $p = 0.004$). This indicate that gully severity changes systematically along the drainage system. The regression results provide additional evidence of this longitudinal pattern. Relative to the upper/headwater corridor, the middle corridor has a coefficient of 0.111 ($p = 0.010$), whereas the lower corridor has a coefficient of 0.188 ($p = 0.0002$). The larger coefficient for the lower corridor indicates a stronger association with GSI. The downstream increase should not be interpreted as evidence that downstream areas are intrinsically more erosive. Rather, it is consistent with progressive accumulation of runoff from upstream contributing areas, greater hydrological connectivity and increased integration of tributary flow. Local land-use disturbances may further amplify this effect.

Drainage Density, Stream Frequency and Overland Flow

The drainage density of 0.161 km km^{-2} indicates relatively limited channel development at the whole-catchment scale. Stream frequency is similarly low at 0.041 streams km^{-2}. Together, these values suggest that much of the catchment is not dissected by a dense natural drainage network. The relatively long estimated overland-flow length of 3.11 km is consistent with the low drainage density. Under relatively undisturbed conditions, longer flow paths can increase the opportunity for infiltration and reduce the proportion of rainfall converted immediately to concentrated runoff. However, this potential benefit depends on surface condition.

Where vegetation is sparse, soils are compacted or cultivated surfaces are connected to roads and drainage outlets, runoff can travel across relatively long distances before becoming concentrated. Consequently, the low drainage density does not imply an absence of gully risk. Instead, it indicates that localized runoff concentration may be particularly important in explaining where gullies develop.

Basin Shape

The form factor of 0.116, circularity ratio of 0.201 and elongation ratio of 0.385 indicate an elongated catchment. Such a configuration generally reduces the likelihood that runoff from the entire basin will reach the outlet simultaneously. The implication for gully erosion is different from the implication for basin-wide flood peaks. Gullies respond primarily to localized runoff concentration and erosive flow conditions. Therefore, an elongated basin can still contain highly susceptible locations where contributing area, slope and drainage connectivity combine to generate concentrated flow. The elongated geometry of Ofu is consequently best interpreted as a factor influencing runoff routing rather than as a diret indicator of low gully susceptibility.

Relief and Slope

The relatively low relief ratio of 0.0029 and mean basin slope of 2.86° indicate modest average topographic energy at the catchment scale. Nevertheless, local slope variation is important for explaining gully morphology. Gully depth is positively associated with slope angle ($r = 0.502$, $p = 0.001$; $\rho = 0.361$, $p = 0.019$). GSI also exhibits a significant Pearson correlation with slope ($r = 0.316$, $p = 0.042$), although the corresponding Spearman relationship is not statistically significant ($\rho = 0.252$, $p = 0.107$). The difference between the Pearson and Spearman results suggests that the relationship between slope and GSI may be relatively weak and sensitive to the form of the data distribution. Therefore, slope should be considered an important but not exclusive control of gully severity.

The relationship between slope and gully volume provides further evidence of non-linear behaviour. Pearson correlation is not significant (r = 0.280, p = 0.072), whereas Spearman correlation is significant (ρ = 0.517, p = 0.0005). This suggests that increasing slope is associated with increasing gully volume in rank order, although the relationship may not conform to a simple linear model. Gully length, however, decreases significantly with slope (r = −0.346, p = 0.025; ρ = −0.418, p = 0.006). This contrast is geomorphologically meaningful. Steeper slopes may favour incision and vertical enlargement, whereas gentler terrain can provide longer pathways for longitudinal extension.

Correlation Between Morphometric/Site Variables and Gully Characteristics

The strongest association involving a gully response variable is between drainage position and gully length. This result indicates that longitudinal gully development is closely related to position within the drainage system.

Table 3. Correlation relationships between selected variables and gully characteristics

Dependent Variable	Predictor	Pearson r	p-value	Spearman rho	p-value	Interpretation
Gully length	Slope angle	-0.346	0.025	-0.418	0.006	Significant negative relationship
Gully length	Drainage zone	0.643	0.000004	0.595	0.000032	Strong significant positive relationship
Gully depth	Slope angle	0.502	0.001	0.361	0.019	Significant positive relationship
CSA	Slope angle	0.528	0.0003	0.693	0.0000004	Strong significant positive relationship
Volume	Slope angle	0.280	0.072	0.517	0.0005	Rank relationship is significant
GSI	Slope angle	0.316	0.042	0.252	0.107	Pearson relationship is significant
GSI	Drainage zone	0.423	0.005	0.438	0.004	Significant positive relationship

Source: Authors' statistical analysis, 2026.

The positive relationship between slope and gully depth indicates that slope is more strongly associated with vertical incision than with longitudinal gully extension. This distinction emphasizes the need to treat gully length, depth and volume as different expressions of erosion rather than as interchangeable measures.

Regression Model of Gully Severity

The multiple regression model produced $R^2 = 0.384$ and adjusted $R^2 = 0.335$. The model was statistically significant ($F = 7.891$, $p = 0.0003$), indicating that the selected predictors collectively provide statistically significant information for explaining differences in GSI among the sampled sites.

Table 4. Summary of the GSI regression model

Model	R^2	Adjusted R^2	F-value	p-value	Decision
GSI model	0.384	0.335	7.891	0.0003	Significant

Source: Author's statistical analysis, 2026.

The model explains approximately 38.4% of the observed variance in GSI. The adjusted R^2 of 0.335 indicates that approximately one-third of the variation remains explained after accounting for model complexity. This result should be interpreted as evidence of partial morphometric control, rather than as evidence that morphometry alone determines gully severity. Approximately 61.6% of the variation in GSI remains unexplained by the variables included in the model. Factors potentially contributing to the remaining variation include rainfall characteristics, soil erodibility, lithology, vegetation condition, land-use practices, road drainage, local contributing area and other forms of anthropogenic disturbance.

Table 5. Regression coefficients for Gully Severity Index

Predictor	Coefficient	p-value	Interpretation
Slope angle	0.049	0.001	Significant positive effect
Middle drainage corridor	0.111	0.010	More severe than upper/headwater zone
Lower downstream corridor	0.188	0.0002	Most severe drainage zone

Source: Author's statistical analysis, 2026.

The coefficient for slope angle is positive, indicating that increasing slope is associated with greater GSI after accounting for drainage position. The middle and lower drainage corridors also have positive coefficients relative to the upper/headwater reference category. The lower-corridor coefficient is approximately 69% greater than the middle-corridor coefficient:
[\frac {0.188-0.111} {0.111} \times100 \approx 69.4%]

This result provides quantitative evidence for increasing gully severity along the drainage system.

Model Validation

The reported validation procedure produced an Area Under the Receiver Operating Characteristic Curve (AUC) of 0.769 and an overall classification accuracy of 71.4%. An AUC of 0.769 indicates good discriminatory ability, meaning that the model has useful capacity to distinguish relatively lower- and higher-severity conditions. However, it should not be described as an excellent or near-perfect predictive model.

The classification accuracy of 71.4% indicates that approximately seven out of every ten observations were correctly classified during the reported validation procedure. The remaining 28.6% demonstrates that morphometric information alone cannot capture the full complexity of gully development. This limitation is consistent with contemporary gully research. Vanmaercke et al. (2021) emphasize that gully occurrence and development are influenced by multiple environmental variables, including topography, vegetation, land use, soil, lithology and climate. The recent African synthesis by Falta et al. (2025) similarly identifies the interaction of climate, topography and anthropogenic disturbance as fundamental to gully development.

The reported AUC is also broadly comparable with recent Nigerian susceptibility research. Okoeka et al. (2025), for example, reported an AUC of approximately 0.765 for gully-susceptibility mapping in Etsako West, Edo State. The comparison suggests that the Ofu model has useful practical discrimination, although differences in modelling approach and predictor variables prevent direct performance ranking between studies.

DISCUSSION

Morphometric Structure and Gully Development

The morphometric configuration of the Ofu River Catchment provides important insights into the spatial organization of runoff and its influence on gully development. The dominance of first-order streams (61.8% of all channels) suggests that runoff generation is concentrated within numerous small headwater drainage pathways. These locations act as primary hydrological collection zones where diffuse surface flow is transformed into concentrated runoff capable of initiating incision.

findings are consistent with the observations of Vanmaercke et al. (2021), who reported that headwater environments represent critical locations for gully initiation because they facilitate hydrological connectivity between hillslopes and channel systems. Similarly, Ciccolini et al. (2024) demonstrated that drainage-network organization strongly influences the spatial distribution of gullies through its control on runoff convergence and flow accumulation patterns.

The moderate mean bifurcation ratio (3.97) obtained for the Ofu Catchment indicates a reasonably integrated drainage system with limited structural disturbance. Comparable bifurcation values have been reported in Nigerian sedimentary basins where gully development is influenced primarily by runoff concentration rather than tectonic controls (Ocheri et al., 2025). Nevertheless, the elevated bifurcation ratio between third- and fourth-order streams suggests progressive flow integration toward the main Ofu River, increasing the volume and erosive potential of downstream runoff. The implication is that morphometric characteristics provide the physical framework within which gully processes operate. While morphometry alone does not initiate gullies, it determines how efficiently runoff is collected, concentrated and transmitted across the landscape.

Drainage Density, Stream Frequency and Runoff Concentration

The drainage density (0.161 km km^{-2}) and stream frequency (0.041 streams km^{-2}) indicate a relatively sparse drainage network. Conventional hydrological interpretations often associate low drainage density with higher infiltration opportunities and reduced runoff generation. However, the occurrence of 42 active gullies demonstrates that low drainage density does not necessarily imply low erosion susceptibility. Anderson et al. (2021), also emphasizes that runoff concentration mechanisms are often more important for gully initiation than total runoff volume. Likewise, Falta et al. (2025) reported that many African gullies occur within catchments characterized by moderate-to-low drainage densities where anthropogenic alterations increase flow concentration.

The long overland-flow distance (3.11 km) further suggests that runoff can travel substantial distances before entering a defined channel. Under natural vegetation cover, such flow paths may enhance infiltration. However, where cultivated surfaces, compacted soils, roads or drainage outlets exist, runoff may remain connected over long distances and eventually converge at vulnerable points. Consequently, the low drainage density observed in the Ofu Catchment appears to increase the importance of localized runoff convergence rather than reducing gully susceptibility. These findings reinforce the argument that catchment-scale morphometric averages should be interpreted together with site-specific environmental conditions.

Local Slope Versus Mean Basin Slope

The mean basin slope of 2.86° suggests a generally gentle landscape. Nevertheless, significant correlations between local slope and gully depth ($r = 0.502$, $p = 0.001$) indicate that local topographic gradients exert a stronger influence on erosion processes than catchment-wide averages.This result agrees with Torri and Poesen (2014), who demonstrated that gully initiation is controlled by local topographic thresholds involving slope and contributing area rather than mean basin relief. Similar relationships were reported by Fagbohun et al. (2024) in southeastern Nigeria, where slope emerged as one of the strongest predictors of gully susceptibility despite relatively moderate basin-scale terrain conditions.

The contrasting relationship observed between slope and gully length is particularly noteworthy. While slope positively influenced gully depth, it showed a significant negative relationship with gully length. This suggests that steeper slopes favour vertical incision and channel deepening, whereas gentler slopes permit greater longitudinal extension of gullies. Such behaviour reflects the geomorphic adjustment of channels to available topographic energy and has also been observed in experimental and field studies summarized by Poesen (2018). The results therefore indicate that slope controls not only the intensity of erosion but also the dominant mode of gully evolution.

Drainage Position as a Major Control

Drainage position exhibited the strongest statistical relationship with gully length ($r = 0.643$, $p < 0.001$) and a significant association with GSI ($r = 0.423$, $p = 0.005$). These findings indicate that gully development becomes progressively more pronounced along the drainage network. A similar downstream increase in gully dimensions has been reported in several catchment-scale studies where larger contributing areas and increased runoff integration enhanced erosive power (Vanmaercke et al., 2021; Ciccolini et al., 2024). In the Ofu Catchment, runoff generated from multiple tributaries is progressively accumulated toward lower drainage positions, thereby increasing flow concentration and sediment transport capacity.

The regression analysis provides additional support for this interpretation. The higher coefficient recorded for the lower drainage corridor (0.188) relative to the middle corridor (0.111) suggests that downstream locations are more likely to experience severe gully conditions. However, drainage position should not be viewed as a direct causal factor. Instead, it functions as a surrogate indicator representing contributing area, hydrological connectivity, runoff accumulation and sediment transfer processes. This interpretation aligns with the conceptual framework proposed by Falta et al. (2025), who emphasized that gully development results from interactions among hydrological, topographic and anthropogenic factors rather than from any single environmental variable.

Morphometry as a Partial Predictor of Gully Severity

The regression model explained 38.4% of the variation in GSI ($R^2 = 0.384$), indicating that morphometric characteristics contribute substantially to gully severity but do not provide a complete explanation. The significant model performance ($F = 7.891$, $p = 0.0003$) confirms that slope and drainage position contain meaningful predictive information regarding gully development.

Comparable predictive capacities have been reported in recent gully susceptibility studies. Okoeka et al. (2025) reported an AUC of approximately 0.765 for terrain-based susceptibility modelling in Edo State, while Fagbohun et al. (2024) found that topographic variables explained a substantial but incomplete proportion of gully occurrence. The AUC value of 0.769 obtained in this study therefore indicates acceptable predictive performance within the context of geomorphological modelling.

The unexplained proportion of variance (61.6%) highlights the importance of additional controls not incorporated in the present model. Previous studies have consistently identified rainfall erosivity, soil erodibility, lithology, vegetation cover, land-use change and drainage infrastructure as significant contributors to gully development (Anderson et al., 2021; Vanmaercke et al., 2021; Falta et al., 2025). These findings therefore support a hierarchical interpretation of gully formation in which basin morphometry provides the structural framework governing runoff organization, while climatic, ecological and anthropogenic factors determine the extent to which that framework translates into actual erosion. Consequently, morphometric analysis should be regarded as an essential component of susceptibility assessment rather than a standalone predictor of gully development.

Implications for Sustainable Watershed Management

The results have direct implications for erosion-control planning within the Ofu River Catchment. The most important management implication is that intervention should be spatially differentiated rather than uniformly applied throughout the basin.

Upper/headwater corridor
Headwater areas should receive priority for preventive measures because they are important runoff-generation and initial flow-concentration zones. Measures should include:

i. protection and restoration of vegetation;
ii. contour farming;
iii. conservation tillage;
iv. grassed waterways;
v. maintenance of natural drainage pathways;
vi. stabilization of cultivated slopes; and
vii. interception of concentrated runoff before it reaches vulnerable valley heads.

Middle drainage corridor
The middle corridor should be managed as a runoff-transfer and gully-transition zone. Appropriate measures include:

i. controlled agricultural runoff;
ii. contour bunds and vegetative barriers;
iii. stabilization of drainage outlets;
iv. small check structures where technically appropriate;
v. protection of riparian corridors; and
vi. routine monitoring of developing gullies.

Lower drainage corridor
The lower corridor requires particular attention because it recorded the strongest positive regression coefficient for GSI. Management should emphasize:

i. stabilization of existing gully channels;
ii. check dams and grade-control structures where appropriate;
iii. sediment-retention measures;
iv. protection of downstream infrastructure;
v. restoration of channel-side vegetation; and
vi. prevention of uncontrolled discharge from roads and settlements.

These interventions should be based on site-specific engineering and hydrological assessment rather than the morphometric results alone.

The integration of morphometric information with rainfall erosivity, land-use/land-cover change, soil properties, vegetation indices and road/drainage infrastructure would provide a more comprehensive susceptibility framework. Such integration is consistent with contemporary approaches to large-scale gully monitoring and management, which emphasize the need to combine topographic, climatic, land-use and soil information.

CONCLUSION

The basin is characterized by low drainage density, low stream frequency, relatively long overland-flow distance and an elongated geometry. These characteristics indicate that the catchment does not possess a uniformly dense natural drainage system. Nevertheless, the occurrence of 42 gully sites demonstrates that low basin-wide drainage density does not preclude severe localized erosion.

The statistical results provide stronger evidence for the importance of local topography and drainage position. Drainage position was strongly associated with gully length, while slope was significantly related to gully depth and catchment surface area. GSI also increased significantly with both slope and drainage position. The negative association between slope and gully length, together with the positive association between slope and gully depth, suggests that topographic gradient influences the mode of gully development, favouring incision at steeper locations while longer longitudinal development may occur on gentler terrain.

From a watershed-management perspective, the findings support a spatially differentiated strategy in which headwater areas receive preventive runoff-management measures, middle drainage corridors receive connectivity and agricultural management interventions, and lower drainage corridors receive priority for stabilization, sediment control and protection of downstream infrastructure. Future modelling should integrate morphometry with rainfall erosivity, soil erodibility, vegetation condition, land-use change, lithology and road/drainage infrastructure to improve prediction of gully susceptibility across the catchment.

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