

Morphometric Analysis of Gullies in Gombe Metropolis, Gombe State, Nigeria

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Abstract: This paper quantified gully morphological characteristics in Gombe metropolis, Gombe State. The purposive sampling procedure was used to select ten gully sites which are Tunfure, Arawa, Bolari East, Pantami, Liji, Bye Pass, Shamaki, Kagarawal, Mallam Inna area and Barunde for this study. Thereafter, the systematic sampling procedure was used at interval of 20m to segment the gully channels for data collection on gully morphological parameters such as gully length, depth, gully top and bed width, slope angle and cross sectional area. Descriptive statistics such as mean was used to show average values of the data set and the Pearson Product Moment correlation statistic was used to assess the nature and strength of the interrelationship between gully parameters. Results of the study shows that the measured sections of gully length in the study area ranged from above 100m to above 380m with a mean value of 125.69m, implying that the gullies in the study are medium to large gullies. Also, the gully top width ranged from 4.70m to 76.50m, implying that the top width strongly influences sediment delivery in the gully catchments. The gully bed widths ranged from 2.50m to 34.60m with a mean value of 14.40m, and the gully depths ranged from 1.30m to 18.90m. Moreover, the cross-sectional area ranged from 11.75m² to 1391.04m² with a mean value of 315.68m². The interrelationship between morphological parameters showed that there is strong positive relationship between the gullies' top widths and bed widths ($r = 0.89$), indicating a concurrent adjustment between the two properties, given most of the gullies a V-shape and U-shape forms. This shows a fine adjustment to forms and processes, indicating lateral recession or gully side wall collapse due to mass wasting. It is concluded that gully erosion in the study area has gone to a disastrous level with severe impact on roads and houses, and it is therefore recommended that the Gombe State government should use engineering methods such as building of embankments to stabilise the gully banks and storm drains to remove excess runoff from the environment for controlled gully development in the area.

Key words: Gullies, Morphometric analysis, Gombe metropolis, Gombe State

INTRODUCTION

Gully erosion is one of the most serious environmental disasters in the world, which directly damage the productivity of land and affects human well-being. Sun *et al.* (2022) noted that gullies are effective links for transferring runoff and soil from uplands to valley bottoms and permanent channels; where they aggravate onsite and offsite effects of water erosion such as development of bad land topography,

soil degradation, flooding and river poisoning. Gully erosion is triggered by the action of falling raindrops and surface flow, which begins as sheet erosion and develops into rills and subsequently gullies (Sun *et al.*, 2022). Moreover, many studies suggest that gully erosion causes severe problems on the environment, and if left unabated its impact on the environment becomes exacerbated. Soil erosion is a severe degradation agent that reduces soil fertility via topsoil translocation, leading to soil quality deterioration (Ezeh *et al.*, 2024). Also, Oladosu *et al.* (2022) reported that gully erosion remains one of the most worrisome soil degradation mechanisms in different parts of the world including Nigeria, and it results to considerable soil loss over time.

Gullies are initiated as a result of a combination of factors which influence the gullying processes, this include among others vegetation cover, slope gradient, soil, relief, anthropogenic influence; as well as the exceeding of threshold values of these environmental factors (Songu, 2019). Gullies are also formed when a break in the vegetation cover allows erosional hollows to form, in which water accumulates. If sufficient flow concentration occurs, an incipient gully head, or head cut forms. Erosion is focused at this point and, if overland flow occurs on a regular basis, material is eroded at the headcut to deepen and enlarge the hollow. This produces a more permanent feature, further concentrating flow and leading to more erosion as a result of positive feedback. Once a gully channel has formed, head ward retreat continues as long as the rate of erosion exceeds the sediment supply (Yang *et al.*, 2021).

Gully morphological properties are the geometric attributes of a gully system; and they obviously influence the manner and the rate by which water and sediments are transmitted through the system. The local characteristics also determine exactly how a gully system responds to a particular climatic input to produce output in stream flow (Iorkua *et al.*, 2019). The morphological characteristics of a gully channel such as gully length, depth, top and bed width, cross sectional area, sinuosity, slope angle and gully intensity do not only depict its morphology, but also, the rate of gully development (Iorkua *et al.*, 2019). These gully morphometric properties usually exist in a complex inter-relationship, which often reflects the nature of the underlying materials, the dynamics and processes operating in the gully channel (Iyiola and Ololade, 2018). These adjustments are usually tending towards a steady state of dynamic equilibrium with the environmental conditions and the prevailing gully processes (Yang *et al.*, 2021).

The problem observed in the study area is that gully erosion is a major cause of collapse of buildings, menace to livestock as well as, soil detachment and entrainment leading to development of bad land topography and other environmental consequences. Moreover, available literature on gully erosion studies in Gombe metropolis revealed that studies conducted in the area focused on determining some gully characteristics and control measures in Gombe town using satellite imageries (see Mbaya, 2017) and factors of gully erosion in Gombe town (see Igwe *et al.*, 2020). Hence, there is an observed dearth of data on direct field assessment of gully morphological properties in Gombe metropolis, and the relationship between gully parameters vis-a-vis, the dominant sub-aerial processes in the gully catchments, which ought to be useful for gully control measures. It is against this backdrop that this paper assessed gully morphological properties in Gombe metropolis, with a view to provide information needed to curb gully development in the study area and bridge the observed literature gaps.

MATERIALS AND METHODS

The study was carried out in Gombe metropolis, Gombe State, northeast Nigeria. Gombe metropolis is located between latitudes $10^{\circ} 19'$ and $10^{\circ} 20'$ N and longitudes $11^{\circ} 01'$ E and $11^{\circ} 19'$ E. It shares common boundary with Akko LGA in the South and West; Yamaltu-Deba to the East and Kwami to the North (Ministry of Land and Survey Gombe, 2025). It is in the capital city of Gombe State and occupies an area of about 45km^2 . Gombe metropolis is well linked by road to other regional centres such as Biu / Maiduguri, Potiskum / Damaturu, Bauchi/Jos and Yola /Jalingo. The geology of Gombe metropolis is largely classified as cretaceous sedimentary sandstone of the Bima formation. Other formations are the Yolde formation and the Pindiga formation (Mbaya, 2017). There are granitic intrusions of basement complex exposed at the surface. More so, the upper part of Akko slope are developed in weakly consolidated sandy sediment of tertiary kerikeri formation, whereas the superficial geology consist of sand and silts stones belonging to the cretaceous Gombe formation. The central part of the town was founded on these older sedimentary rocks (Mbaya, 2017). Figure 1 is a map showing location of the study area.

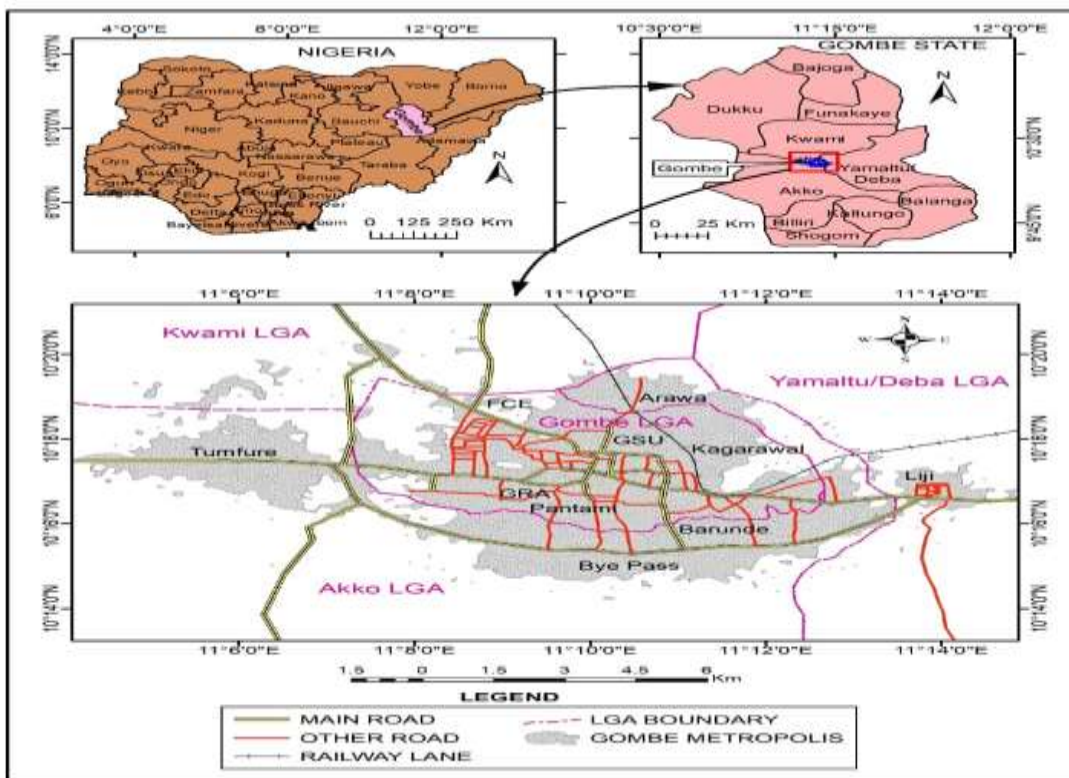


Figure 1: Gombe metropolis (the study area)

Source: Ministry of lands and survey Gombe State, 2025

The area is characterised with undulating landform with ephemeral gully erosion and streams flowing eastward from the kerikeri highland in the west. The major river is the Gongola River that has its source from the Jos Plateau and flows through Nafada to the Dadin Kowa before joining the upper River Benue basin at Numan Confluence (Mbaya, 2017). The climate of Gombe metropolis is described as tropical continental climate. Temperature is high all year round with a mean annual air temperature of

30° C The highest temperature are recorded during the dry heat wave months of March, April and May with maximum air temperature of above 37° C (Mbaya, 2017). During the rainy Season, the temperature drops considerably due to the cloud cover between July and August as well as during Harmmatan periods of November to February due to Harmmatan effect. The area records four to five months of rainfall with an annual average of 620mm to 820mm concentrated mainly in the Months of July, August and September.

The soils found in Gombe metropolis are basically sandy Loam. The top soil is gritty, loose and non-plastic with low bulk density and low shear strength. The soils can be divided into two types which correspond to the geological formations from which they were derived. The soils are sandy and clay soils. The sandy soil is underlain by Keri-Keri formation found in the North western region of the metropolis, and has a depth that varies from 2.0cm to 20cm. The soils are mainly ferruginous soil, which is red and contains nodules of ironstone; It is marked by deposit of iron oxide pebbles and loose, very permeable and deficient in nutrients. The soils are derived from Pindiga formation or Gombe Sandstone. It is grey and moderately rich in organic matter and possesses significant swell shrink capacity as it goes through periods of wetting and drying. Both the two types of soil are characterized by exposed condition with little or no vegetative cover, adverse topography, long dry period and high temperature. The vegetation of Gombe metropolis is described as Sudan Savanna vegetation characterized by shrubs and scattered trees with some grass species. The predominant tree species include Parkia tree (*Parkia Clapper Tonia*), Baobab (*Adansonia Digitata*), Tamarind (*Tamarin dusindica*), Moringa (*Moringa Olifera*), Date palm (*Phonis Doctylifera*) and Neem (*Azandirach talndica*) The common grass species include those with short feathering type such as Barchuria Panicum (Igwe et'al., 2020).

Sampling Techniques

To effectively select gully sites for data collection in this study, two sampling techniques were employed. Firstly, the purposive sampling technique was used to select ten (10) gully catchments based on their observed magnitude and severe impacts on the environment for this study. The ten (10) gully catchments were purposely selected as thus: Tunfure (1 gully site), Arawa (1 gully site), Bolari East (1 gully site), Pantami (1 gully site), Liji (1 gully site), Bye Pass (1 gully site), Shamaki (1 gully site), Kagarawal (1 gully site), Mallam Inna area (1 gully site) and Barunde (1 gully site). Field observation and measurements in this study were done on gully variables and soil characteristics using quantitative research methods. Secondly, the systematic sampling technique was used to segment the selected gully channels at intervals of 20m for data collection on gully parameters.

Types and Sources of data

The data needed for this study was the dimensions of gully morphometric parameters from the ten gully catchments such as gully length (m), gully depth (m), gully top width (m), slope angle (degree), gully bed width (m), top width/depth ratio, top width/bed width ratio and cross sectional area (m²) in the study area. The data was collected through direct field measurements and observations using survey equipment such as 100m measuring tape, ranging poles and an Abney level.

Data Collection Procedures

To collect data, field measurements were done using some survey equipment as described below

(i) Gully length: This was measured using the 100m measuring tape, ranging poles and erosion pins, starting from the gully head. Preliminary survey showed that gullies in the study area with remarkable

removal of soil from their catchments range from 100m to above 300m in length. Therefore, the gullies were segmented at interval of 20m to determine their lengths and data collection on other gully parameters. Hence, 20m stretch was taken from the ranging pole that marked the end of the first stretch downstream, and this process continued to the mouth of the gully. This was done to determine the length of each gully channel under investigation. The 20m interval used in measuring gullies on the field was based on the fact that most gullies in the study area are moderate to large in size and length, and less sinuous to warrant smaller interval of measurements. Hence, with the 20m interval between each measurement it was easier to measure the gully characteristics and observe the processes occurring in the gully channels.

(ii) Bed width and Top width. These parameters were measured at each of the sampled points of the 20m intervals using erosion pins, measuring tape and ranging poles. At each of these points, the tape was stretched across the gully bed and shoulder to the opposite bank and readings in meters were obtained. The bed and shoulder widths are the major cross sectional variables of the gully system and therefore, help to determine the width at the top and bottom of the gully.

(iii) Gully depth: To measure the gully depth, the ranging poles and the linen tape were used. One of the poles was fixed at the deepest part of the gully bottom along the same line where bed and top widths were measured. The tape was stretched across the gully over the ranging pole. A third person standing near the ranging pole on the gully bottom was positioned to note where it met the tape. The pole was then removed and measured (from the ground up to the point where it met the tape) and the reading recorded as the depth. These measurements were done at intervals of 20m along the gully channels. The depth is essential in determining the extent to which the gully has been incised into the underlying geologic materials.

(iv) Slope angle: Slope angle was measured using an Abney level. Readings were taken at stretches of 20m interval. At each stretch, a reader stood in the middle of the pole to take readings both ways, focusing on the line in the Abney level, through the sight at the marked point on the pole. The difference in the two readings gave the angle of that particular stretch. The slope angle is insightful on the gradient along the gully side walls and the extent to which it has influenced sub-aerial processes in the gully system.

(v) Top width/bed width ratio: This was determined at all the sampled points by dividing the values of the top width by the bed width. The top width/bed width ratio is important for determining the gully form or adjustment between the two cross sectional variables (bed and top width) with the prevailing gully development mechanisms.

(vi) Top width/depth ratio: This was determined at all the sampled points by dividing the values of the top width by the depth of the gully system at those points. The top width/depth ratio helps in determining the developmental dimension of the gully system, in terms of widening and deepening in relation to the prevailing processes and mechanisms.

(vii) Gully cross sectional area: This was determined at all the sampled points by multiplying the top width at those points by the depth of the gully system at those points and expressed in m^2 . The cross-sectional area is imperative to determine the total area covered by the gully channel extending from the watershed to the extent to which it has been incised (Iorkua *et al.*, 2019).

Data analysis Techniques

The data collected was presented in tables for easy comprehension. Descriptive statistics such as mean and standard deviation were used to show variations in the data set. Inferential statistics such as Pearson's Product Moment correlation statistics was used to ascertain the nature and strength of the relationship between gully parameters in the study area with a view to determine their steady state of adjustments and the nature of sub-aerial processes taking place in the gully systems.

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RESULTS AND DISCUSSION**Dimensions of Gully Morphometric Parameters in Gombe Metropolis**

Results on dimensions of gully morphometric parameters are contained in Tables 1 to 10.

Table 1: Shamaki Gully Catchment characteristics

Distance from gully head (m)	BW (m)	TW (m)	Gully Depth (m)	SA (degree)	TW/D ratio	TW/BW ratio	CSA (m ²)
0	8.3	17.9	5.4	5	3.31	2.16	96.66
20	7.9	15.9	3.7	3	4.3	2.01	58.83
40	7.4	9.4	4.6	3	2.04	1.27	43.24
60	7.6	12.9	4.4	2	2.93	1.7	56.76
80	6.4	20.6	5.7	4	3.61	3.22	117.42
100	7.9	18.1	4.4	3	4.11	2.29	79.64
120	7.6	16.8	4.7	2	3.57	2.21	78.96
140	7.9	9.8	3.8	4	2.58	1.24	37.24
160	6.6	12.4	5.3	3	2.34	1.88	65.72
180	6.9	19.6	5.7	3	3.44	2.84	111.72
Total	74.5	153.4	47.7	32	32.23	20.82	746.19
Mean	7.45	15.34	4.77	3.20	3.22	2.08	74.62

Source: Authors' field work, 2025

NOTE: BW (Bed width), TW (Top width), SA (Slope angle), TW/D (Top width/depth ratio), TW/BW (Top width/bed width ratio) and CSA (Cross sectional area).

According to the results in Table 1, Shamaki gully catchment has gully depth that varies from 3.7m to 5.7m with a mean of 4.77m, indicating an active and deep gully system. While the gully bed width ranges from 6.4m to 8.3m and top width of 9.4m to 20.6m with a mean value of 7.45m and 15.34m respectively. Top Width (TW) and Bed Width (BW) vary inconsistently along the gully length, with the widest top width (20.6m) recorded at 80 m from the gully head. The cross-sectional area fluctuates notably, from 37.24m² at 140m to 117.4 m² at 80m with a mean value of 74.62m². Larger CSA values usually correspond to sections where both TW and depth are higher. Frankl *et al.*, (2024) have shown that wider gullies with large CSA often indicate mature gully development phases where headward erosion slows while widening becomes dominant. This is consistent with results in Gombe metropolis where TW and CSA increase in the middle sections. The highest CSA and TW/D values appear around the middle segments (80m and 180m), which aligns with findings by Kumar *et al.* (2021) who reported

that mid-section gully segments often exhibit maximum cross-sectional development due to accumulated runoff and sediment transport dynamics.

Slope angle ranges from 2° to 5° with a mean value of 3.20°. In the current study it is observed that steeper slope angles enhances lateral recession and the largest CSAs occur at moderate slope angles (3°-4°), suggesting a balance between slope steepness and other factors such as soil type and vegetation cover. These findings also corroborates those of Ndabula *et al.* (2020) who emphasised that moderate slopes (3°-5°) contribute to higher sediment detachment rates, especially when soil cover is sparse. Higher TW/D and TW/BW ratios generally indicate wider and shallower gullies, suggesting potential for lateral erosion; hence it was observed in the present study that at 80m, TW/D was 3.61 and TW/BW was 3.22 among the highest values observed. Also, Borrelli *et al.* (2022) opined that higher TW/D and TW/BW ratios can indicate later-stage gully evolution, where width expansion overtakes depth growth.

Table 2: Mallam Inna Area Gully Catchment characteristics

Distance from gully head (m)	BW (m)	TW(m)	Gully Depth (m)	SA (degree)	TW/D ratio	TW/BW ratio	CSA (m ²)
0	33.6	70.2	15.3	12	4.59	2.09	1074.06
20	24.3	64.3	14.7	11	4.37	2.65	945.21
40	25.6	73.4	15.6	9	4.71	2.87	1145.04
60	24.8	74.2	17.4	7	4.26	2.99	1291.08
80	21.3	72.5	17.8	9	4.07	3.40	1290.5
100	21.8	72.7	17.7	8	4.11	3.33	1286.79
120	32.1	75.4	17.6	5	4.28	2.35	1327.04
140	34.6	73.2	17.9	6	4.09	2.12	1310.28
160	22.5	72.5	16.7	7	4.34	3.22	1210.75
180	23.6	74.3	14.4	9	5.16	3.15	1069.92
200	24.4	73.6	18.9	10	3.89	3.02	1391.04
220	22.3	71.6	16.8	8	4.26	3.21	1202.88
240	20.9	74.7	17.5	7	4.27	3.57	1307.25
260	30.1	76.5	14.6	5	5.24	2.54	1116.9
Total	361.9	1019.1	232.9	113	61.64	40.51	16968.7
Mean	25.85	72.79	16.64	8.07	4.40	2.89	1212.05

Source: Authors' field work, 2025

Table 2 contains information on Mallam Inna gully parameters and it shows characteristics of both active and mature gully stages along its length. The gully depth varies from 14.4m to 18.9m with a mean of 16.64m, indicating severe erosion in urbanised areas, likely driven by concentrated runoff from impervious surfaces (Eze *et al.*, 2024). There is increasing cross-sectional area values ranging from 945.21m² to 1391.04m² with a mean value of 1212.05m², generally increasing with distance from the gully head up to around 200 meters. This suggests ongoing gully expansion and evolution along the channel. These findings agreed with those of Frankl *et al.* (2021) who noted that urban expansion and land-use changes increase runoff, contributing to varied patterns of gully development. Extreme CSA values at Mallam Inna correlate with high runoff volumes in densely populated urban areas,

where drainage systems are overloaded by intense rainfall events, and thereby enhancing soil erosion (FAO, 2022).

The TW/D fluctuates from 3.89 to 5.24 with a mean of 4.40 indicating a wider, more stable gullies, while lower values can indicate deeper incision or active headcut migration. This also reflects gully widening due to sidewall collapse, exacerbated by poorly consolidated sediments (Eze *et al.*, 2024). Slope angle decreased from 12° at the gully head scarp to 5° and 7° at distances beyond 120m with a mean of 8.07m. This suggest that such slope flattening indicates mature gully stages and reduced erosive power downstream. Top Width/Bed Width ratios ranged from 2.09 to 3.57; thereby supporting the findings of Frankl *et al.* (2021) and Nyssen *et al.* (2022) who reported that higher TW/BW ratios suggest widening processes influenced by lateral erosion along gully banks, indicating adjustments in form and processes taking place in the gully channel.

Table 3: Bolari East Gully Catchment characteristics

Distance from gully head (m)	BW (m)	TW (m)	Gully Depth (m)	SA (degree)	TW/D ratio	TW/BW ratio	CSA (m ²)
0	24.3	58.2	6.5	6	8.95	2.40	378.3
20	28.2	59.7	5.6	5	10.66	2.12	334.32
40	28.1	57.9	6.0	7	9.65	2.06	347.4
60	27.2	57.6	8.3	3	6.94	2.12	478.08
80	22.1	56.8	10.4	6	5.46	2.57	590.72
100	16.8	56.9	10.5	8	5.42	3.39	597.45
120	20.1	58.1	10.3	9	5.64	2.89	598.43
140	24.2	57.3	7.3	6	7.85	2.37	418.29
160	20.4	57.4	5.2	5	11.04	2.81	298.48
180	31.7	52.4	6.2	7	8.45	1.65	324.88
200	22.5	56.2	5.5	3	10.22	2.50	309.1
220	27.2	57.7	8.6	6	6.71	2.12	496.22
240	28.5	56.7	6.7	8	8.46	1.99	379.89
260	26.1	54.8	8.7	6	6.30	2.10	476.76
280	24.1	55.8	9.4	5	5.94	2.32	524.52
300	18.6	57.4	10.6	7	5.42	3.09	608.44
320	20.5	58.6	9.8	8	5.98	2.86	574.28
340	23.2	56.8	8.3	6	6.84	2.45	471.44
360	21.5	56.2	5.9	8	9.53	2.61	331.58
380	30.7	51.3	5.2	5	9.87	1.67	266.76
Total	486	1133.8	155	124	155.33	48.09	8805.34
Mean	24.3	56.69	7.75	6.2	7.77	2.40	440.27

Source: Authors' field work, 2025

It is observed in Table 3 that Bolari east gully catchment characteristics varied in width, depth, and cross-sectional area along the gully catchment. The gully has a length of over 380m and the gully depth ranges from 5.2m to 10.6m with a mean value of 7.75m, supporting the findings of Hou *et al.* (2023)

on gully head migration and enlargement phases, where mid-sections often exhibit maximum incision. TW/D ratio varies from 5.42 to 11.04 with a mean value of 7.77 showing instability; and lower value of 5.42 at 100 m and 300m signaling bank undercutting and collapse risk. These findings aligned with those of Ogbonnaya *et al.* (2021) who reported that narrower top width relative to depth signifies active incision phases with V-shaped valley, rather than lateral expansion. TW/BW ratio ranges from 1.65 to 3.39, revealing channel shape evolution where low ratio of 1.65 at 180 m indicate V-shaped gullies, common in headcuts or resistant layers. While high ratios of 3.39 at 100m reflect a U-shaped section, suggesting bank collapse or lateral widening at certain points, consistent with the findings of Castillo *et al.* (2020) who reported that increased top width/depth ratios indicating gully stabilisation or matured stage. Moreso, the slope angle varied between 3° and 9°, reflecting its role in influencing flow velocity and sediment transport capacity. The study by Zhu *et al.* (2024) confirmed that moderate slope angles (5-8°) often correspond with enhanced runoff energy capable of deepening gullies, aligning with areas showing greater depth and CSA in Table 3. Steeper slopes of 9° at 120m correlate with shallower depths (10.3m) but wider tops (TW = 58.1m), implying sediment deposition at slope breaks. Gentle slopes (e.g 3° at 60m) coincide with maximum depth (8.3m), supporting focused down cutting in low-gradient zones.

The Cross-Sectional Area (CSA) varied from 266.76m² to 608.44m² with a mean value of 440.27m² and exhibiting peak values at 100–120m and 300m. This suggests active erosion zones where flow energy concentrates, likely due to steeper slopes or softer sediments typical in semi-arid regions with intense runoff (Poesen, 2024). Additionally, CSA increased notably in the middle section (200m - 320m), indicating zones of higher erosive potential. Similar trends were documented by Wu *et al.* (2022) in East African gully systems, highlighting middle segments as focal points for sediment yield. A rising CSA from 378.3m² at 0m to a peak of 608.44m² at 300m suggested an increasing erosional force downstream until a possible stabilisation point beyond that. These findings corroborated those of Kidanemariam and Roca (2025), who documented similar CSA evolution in Ethiopian gully systems linked to catchment runoff patterns and vegetation cover. The Bolari East Gully exhibits classic erosion patterns driven by hydraulic gradients and material resistance. Its matured state (mean TW/BW = 2.40) and high cross sectional area (CSA= 8,805.34 m²) is capable generating high sediment yield and this underscore urgent conservation needs, aligning with global observations that gully erosion dominates sediment budgets in degraded catchments (Poesen, 2022).

Table 4: Kagarawal Gully catchment characteristics

Distance from gully head (m)	BW (m)	TW(m)	Gully Depth (m)	SA (degree)	TW/D ratio	TW/BW ratio	CSA (m ²)
0	10.8	14.8	2.1	3	7.05	1.37	31.08
20	8.5	14.9	2.0	5	7.45	1.75	29.8
40	8.1	14.5	2.5	5	5.80	1.79	36.25
60	12.2	14.7	2.2	6	6.68	1.20	32.34
80	8.3	14.2	3.4	5	4.18	1.71	48.28
100	6.2	13.7	4.5	4	3.04	2.21	61.65
120	11.5	13.8	2.1	5	6.57	1.20	28.98
140	9.5	12.9	3.0	6	4.30	1.36	38.7
160	7.1	14.8	2.8	5	5.29	2.08	41.44
180	11.5	13.5	2.7	4	5.00	1.17	36.45
200	9.3	14.6	3.9	5	3.74	1.57	56.94
220	6.2	12.5	4.1	6	3.05	2.02	51.25
Total	109.2	168.9	35.3	59	62.15	19.43	493.16
Mean	9.1	14.08	2.94	4.92	5.18	1.62	41.10

Source: Authors' field work, 2025

The results presented in Table 4 on Kagarawal Gully catchment shows that the TW/BW Ratio ranges from 1.17 to 2.21 with a mean of 1.61 indicating variable bank steepness. Higher ratios of 2.21 at 100m suggest vertical bank collapse or seepage erosion, aligning with studies linking high TW/BW to piping or saturation-driven bank failure (see Poesen, 2020). The TW/BW values >1.5 (e.g., 2.21 at 100m) signal bank undercutting or toe erosion, consistent with gullies in sandy-loam soils as reported by Castillo *et al.*, (2022). The TW/D ratio decreased downstream from 7.05 to 3.04, reflecting a shift from vertical to lateral erosion. This is in line with global observations where headcut migration dominates upstream, while downstream segments widen (Bennett & Wells, 2019). TW/D < 4 (e.g., 3.04 at 100m) indicates unstable banks prone to mass failure. This aligns with field experiments showing ratios <5 correlating with high sediment yields (Li *et al.*, 2022). TW/D >5 upstream suggests recovery potential, while low ratios downstream imply ongoing degradation matching stability indices from gullies developed under semi-humid regions of the world (Guerra *et al.*, 2023). The maximum depth of 4.5 m and CSA value of 61.65 m² at 100m correlated with the steepest slope (6°) and lowest TW/D (3.04), indicating the potential for adjustments of the gully morphological parameters to a steady state of dynamic equilibrium with the prevailing environmental conditions.

The second peak at 220m (CSA 51.25 m², slope 6°) suggests recurring erosion where slopes exceed critical angles (>5°) (Guerra *et al.*, 2023). All slopes angles are gentle ranging from 3° to 6° yet drive significant erosion and this corroborated the findings of Vanmaercke *et al.*, (2023) who emphasized that even low-gradient slopes become erosive under intense rainfall or disturbed vegetation, as also observed in Gombe metropolis.

By implication, peak erosion at 80 to 100m and 220m suggests high-energy flow events. Recent

models tie such patterns to extreme rainfall increasing gully activity by 15–40% in semi-arid regions (Intergovernmental Panel on Climate Change (IPCC), 2022). Lack of vegetation or tillage practices may explain abrupt width/depth changes (e.g., BW drop from 12.2m to 6.2m between 60 to 100m), as observed in Ethiopian highlands (Adediji *et al.*, 2023). The Kagarawal gully characteristics reflect a state of dynamic erosion processes driven by slope, flow concentration, and likely human disturbances within the watershed. Downstream of the gully increases in depth and CSA align with global trends of gully maturation under climate stressors. Therefore, prioritising stabilisation at high CSA segments (80m to 100m, 220m), and using soil-bioengineering techniques such as check dams and grass planting are critical in stabilising the gullies (Bai *et al.*, 2024).

Table 5: Barunde Gully Catchment characteristics

Distance from gully head (m)	BW(m)	TW (m)	Gully Depth (m)	SA (degree)	TW/D ratio	TW/BW ratio	CSA (m)
0	14.8	31.6	4.6	4	6.87	2.14	145.36
20	20.5	29.7	5.4	5	5.50	1.45	160.38
40	22.3	30.3	5.7	6	5.32	1.36	172.71
60	20.7	30.4	6.2	4	4.90	1.47	188.48
80	19.8	32.5	7.8	4	4.17	1.64	253.5
100	16.2	25.6	6.7	3	3.82	1.58	171.52
120	13.8	30.7	5.6	5	5.48	2.22	171.92
140	21.6	26.7	5.8	4	4.60	1.24	154.86
160	23.3	31.3	4.7	3	6.66	1.34	147.11
180	21.7	29.4	6.6	6	4.45	1.35	194.04
200	20.8	31.5	7.2	4	4.38	1.51	226.8
220	15.2	26.6	6.2	3	4.29	1.75	164.92
Total	230.7	356.3	72.5	51	60.44	19.05	2151.6
Mean	19.23	29.69	6.04	4.25	5.04	1.59	179.30

Source: Authors' field work, 2025

The results in Table 5 shows at Barunde gully catchment has a mean depth of 6.04m, mean bed width of 19.23m, mean top width of 29.69m, mean slope angle of 4.25°, mean shoulder width/depth ratio of 5.04m, mean shoulder width/bed width ratio of 1.59m and mean cross sectional area of 179.30m². The top width/depth ratio decreases downstream from 6.87 at head to 3.82 with a mean of 5.04m, indicating a shift from widening-dominated to deepening-dominated erosion. The mean TW/D ratio (5.04) consistently exceeds the typical stability threshold of 3 to 4 (Frankl *et al.*, 2013), with a peak value at 6.87 (0m) and 6.66 (160m) signaling severe bank collapse and slumping of earth materials. This widening relative to depth is a classic indicator of active lateral erosion and mass failure (Castillo and Gómez, 2016). Interestingly, Bai *et al.* (2024) reported that, high TW/D ratios point to bank collapse as a key process, driven by soil saturation, piping, or tension cracks. Fluctuating CSA/depth suggest headcut retreat and knick point migration are also significant and typical drivers in evolving gullies. These findings aligned with those of Zhou *et al.* (2021), who found that headcut migration dominated initial stages, while downstream sections experience vertical incision due to concentrated flow. The variability observed in the gully processes suggest localised controls such as soil pipes or seepage, and this is consistent with the findings of Zhang *et al.* (2023) on subsurface flow which drives abrupt

morphology changes.

The TW/BW Values ranged from 1.24 to 2.22 with a mean of 1.59, reflecting irregular bank collapse. High ratios (2.22) correlate with Vanmaercke *et al.* (2021) findings that sandy-loam banks collapse frequently, and widen gullies during intense rainfall. Also, TW/BW Ratio (Mean 1.59) values were consistently >1 , confirming a trapezoidal cross-sectional gully. The TW/BW ratios were observed to high where top width widens dramatically relative to the bed, suggesting intense overhanging and collapse (Zgłobicki *et al.*, 2021). This shape is typical of actively eroding gullies in unconsolidated materials. The trapezoidal shape and high TW/D suggest that the gully is erosive and cohesionless soils (e.g., sands, loams) are prevalent, thereby enhancing runoff generation from all sides of the gully banks. Fluctuations likely reflect variations in soil texture, stratigraphy, or compaction. Concentrated flow pathways (e.g., runoff convergence at 80m, 200m) are probable triggers for peak erosion zones (Teshome *et al.*, 2021). Cross-Sectional Area (CSA) increased from 145.36m² at 0m to a peak of 253.5m² at 80m, followed by fluctuations but an overall increasing trend to 226.8 m² at 200m. This indicated a substantial amount of soil loss and sediment production, especially in the middle sections (60m-100m, 180m-200m). The large CSAs (mean 179.3 m², total 2151.6 m² over 220m) indicated intense erosion. This aligns with previous studies showing that gullies contribute disproportionately (often $>50\%$) to catchment sediment yields, degrading land and water resources pollution (Poesen *et al.*, 2024; Borrelli *et al.*, 2021).

Poesen (2024) linked such hotspots to slope reductions ($<5^\circ$) or anthropogenic barriers. Initial CSA surge (0–40 m) reflects headward migration, exacerbated by recent extreme rainfall events (IPCC AR6, 2021, 20% increase in tropical storm intensity). The low slopes (3° – 6°) yet high erosion as reported by Guerra *et al.* (2023) attributed this to preferential flow in vertisols (common in tropical catchments) which undercuts bank and upstream deforestation intensifies and runoff, thereby accelerating incision even on gentle slopes. The slope angle ranges from 3° to 6° (mean 4.25°), with slightly steeper slopes (e.g., 5° – 6°) at 20m, 40m, 120m and 180m, correlating with locally increased depth or CSA. These findings corroborated those of Nwanchukwu *et al.* (2024) and Vanmaercke *et al.* (2023) who reported that steeper local slopes increase flow velocity and erosive power, accelerating downcutting and headcut retreat Parameters (BW, TW, Depth, CSA). In Gombe metropolis, there is an observed fluctuation along the 220m gully profile (e.g., TW ranges 25.6m–32.5m, depth, 4.6m–7.8m). This reflects heterogeneity in soil properties, subsurface flow paths and vegetation cover, or past management practices. This is consistent with previous findings that gully development is highly sensitive to local conditions (Vanmaercke *et al.*, 2023).

The gully catchment depicts an active, unstable gully characterised by significant downstream enlargement (especially 60m to 100m), severe bank collapse (evident in high TW/D ratios), and a classic trapezoidal shape indicative of ongoing lateral erosion. The spatial variability in gully form highlights the influence of localised factors. These findings indicated that gullies of this magnitude are major sediment sources requiring integrated stabilisation measures targeting both headcuts and banks, while managing upstream runoff. The results provide a clear baseline for prioritising intervention zones (e.g., 60m to 100m, 180m to 220m) and designing context-specific rehabilitation strategies.

Table 6: Ligi Gully catchment characteristics

Distance from gully head (m)	BW(m)	TW(m)	Gully depth (m)	SA (degree)	TW/D ratio	TW/BW ratio	CSA (m ²)
0	17.4	34.3	9.7	7	3.54	1.971	332.71
20	17.6	34.5	11.5	6	3.00	1.960	396.75
40	18.4	32.4	10.9	7	2.97	1.761	353.16
60	11.8	26.3	9.6	5	2.74	2.229	252.48
80	12.2	24.2	10.2	8	2.37	1.984	246.84
100	12.8	27.7	12.4	9	2.23	2.164	343.48
120	11.2	25.6	12.3	8	2.08	2.286	314.88
140	16.4	33.5	10.7	6	3.13	2.043	358.45
160	15.6	32.5	12.5	7	2.60	2.083	406.25
180	17.4	30.7	11.2	8	2.74	1.764	343.84
200	12.6	25.3	10.3	6	2.46	2.008	260.59
220	12.9	22.6	10.4	4	2.17	1.752	235.04
240	11.8	28.7	11.4	7	2.52	2.432	327.18
260	12.6	24.6	11.1	6	2.22	1.952	273.06
Total	200.7	402.9	154.2	94	36.77	28.389	4444.71
Mean	14.34	28.78	11.01	6.71	2.63	2.03	317.48

Source: Authors' field work, 2025

Results contained in Table 6 shows that the gully characteristics in Ligi varies in depth from 9.7m to 12.5m with a mean of 11.01m exceeding thresholds for "mega-gullies" (Poesen, 2020), signaling advanced land degradation. Depths >10m often require engineered interventions for stabilisation (Frankl *et al.*, 2021). The TW/BW Ratios varies from 1.75 to 2.43 with mean value of 2.03 reflecting active sidewall collapse and gully widening. Ratios >2.0 (e.g., 2.43 at 240m) align with areas of intense bank undercutting and tension cracking (Zglobicki *et al.*, 2021). TW/D Ratios ranges from 2.08 to 3.54 with a mean of 2.63. The lower value of 2.08 at 120m indicates unstable, near-vertical walls prone to mass failure, while higher ratios of 3.54 at gully head suggest deposition or gentle slopes (Dube *et al.*, 2023). High TW/D (3.54) and steep slope (7°) suggest ongoing headward retreat a critical process driving gully expansion (Li *et al.*, 2023). Also, the mean slope angle of 6.71 falls within the highest-risk category for gully initiation (5–8°), especially under intense rainfall (Zglobicki *et al.*, 2021). Slopes >6° (e.g., 9° at 100 m) accelerates runoff energy, increasing incision rates (Dube *et al.*, 2023). Steeper slopes and large volumes suggest intensified erosion from high-intensity rainfall events consistent with climate-driven erosion trends (Li *et al.*, 2023).

The cross-sectional area varies from 235.04m² to 406.25m² with a mean value of 317.48m² over 260m of gully length, indicated a pulsed sediment delivery to downstream systems, exacerbating gully siltation and water quality issues (Poesen, 2020). Recent studies by Vanmaercke *et al.*, (2021); Li *et al.*, (2023) confirmed that gullies of this scale dominate sediment yield in catchments, contributing 50% to 80% of total soil loss in degraded watersheds, and thereby contributing to disrupt agricultural

practices, infrastructure, and buildings in such areas. CSA peak of 406.25m² at 160 m with a depth of 12.5m and width of 32.5m indicated that the gully is at its matured stage. This correlated with steeper slopes (7° to 9°) and aligns with models showing flow convergence and amplifying erosion at mid-slope as reported by Castillo *et al.*(2022). Ligi gully represents a highly active, large-scale matured erosion system with significant sediment production. Its U-shaped morphology (high TW/BW, variable TW/D) and slope angles (mean 6.71°) suggests that such a gully is a primary contributor to land degradation in the area, as such the spatial erosion pattern observed intensifying mid-slope underscores the need for targeted stabilisation.

Table 7: Pantami gully catchment characteristics

Distance from gully head (m)	BW (m)	TW(m)	Gully depth (m)	SA (degree)	TW/D ratio	TW/BW ratio	CSA (m ³)
0	14.0	23.2	7.6	4	3.053	1.66	176.32
20	14.3	20.7	8.2	5	2.524	1.45	169.74
40	13.4	22.6	15.2	6	1.487	1.69	343.52
60	13.2	22.4	15.4	8	1.455	1.70	344.96
80	10.1	18.3	10.9	6	1.679	1.81	199.47
100	13.5	22.6	8.6	5	2.628	1.67	194.36
120	12.3	21.7	8.7	5	2.494	1.76	188.79
140	13.6	20.6	14.2	7	1.451	1.51	292.52
160	12.2	23.4	13.4	5	1.746	1.92	313.56
180	10.5	19.2	10.6	5	1.811	1.83	203.52
Total	127.1	214.7	112.8	56	20.328	17	2426.76
Mean	12.71	21.47	11.28	5.60	2.03	1.70	242.68

Source: Authors' field work, 2025

Table 7 shows that Pantami gully channel depth ranges from 7.6m to 15.4m with a mean of 11.28m indicating severe erosion processes as confirmed by Poesen (2020) and Li *et al.*, (2023) that gullies exceeding 5m depth often represent advanced stage and difficult to reverse land degradation stages. Such gullies also causes significant soil loss and sediment pollution, as well as severe impacts on the existing infrastructures. The TW/BW ratio of 1.51 to 1.92 with mean value of 1.70 shows that top width is 70% wider than the bed. This is typical of actively widening gullies undergoing sidewall collapse (Zglobicki *et al.*, 2021). Higher ratios (1.92 at 160m) suggest intense sidewall mass movement at specific points culminating into a trapezoidal shaped gully. The higher CSA (>340 m³) and lower TW/D ratio (<1.5) at 40m and 60m highlights a major erosion hotspot. This aligns with the findings of Castillo *et al.*, (2022) that gully erosion often intensifies at mid-slope due to concentrated flow energy and potentially weaker subsurface materials. Low TW/D ratios (1.49 at 40m, 1.46 at 60m and 140m) signifies steep, unstable walls highly prone to mass failure (collapsing), a key process in gully widening noted by Frankl *et al.* (2021).

The CSA ranges from 169.74 m³ to 343.52 m³, reflecting the complex interplay of slope, material resistance, and flow hydraulics along the gully, consistent with high-resolution monitoring studies (Castillo *et al.*, 2022). Total CSA of 2426.76m³ at 180m signifies enormous soil removal. Recent studies quantify gully erosion as a dominant sediment source, often exceeding sheet/rill erosion by

orders of magnitude in affected catchments (Vanmaercke *et al.*, 2021; Li *et al.*, 2023). The measured SA from 4° to 8° and mean value of 5.6° falls within the critical range where gully initiation and growth are highly sensitive. The studies by Zglobicki *et al.* (2021) and Dube *et al.*, (2023) demonstrated that slopes between 3° and 8° are particularly vulnerable to gulying when combined with other factors such as intense rainfall or human disturbances. The Pantami gully exhibited characteristics of severe, active erosion, particularly pronounced in its mid-section (40m to 60m from head). The deep profile (>15m), steep unstable walls (low TW/D), significant sediment volumes (high CSA), and vulnerable slope angles (mean 5.6°) highlighted its status as a major land degradation hotspot. These findings underscore the disproportionate role of large gullies in soil loss and the critical need for targeted stabilisation efforts in such high-severity sections to mitigate ongoing damage and sediment production.

Table 8: Arawa Gully catchment Characteristics

Distance from gully head (m)	BW (m)	TW(m)	Gully depth (m)	SA (degree)	TW/D ratio	TW/BW ratio	CSA (m ²)
0	13.5	25.7	10.7	9	2.40	1.90	274.99
20	10.7	32.3	11.3	7	2.86	3.02	364.99
40	12.4	31.5	14.5	6	2.17	2.54	456.75
60	19.6	35.2	14.7	7	2.39	1.80	517.44
80	10.4	25.4	11.5	4	2.21	2.44	292.1
100	9.8	22.7	11.3	6	2.01	2.32	256.51
120	12.5	24.7	11.8	3	2.09	1.98	291.46
140	11.7	31.3	12.3	6	2.54	2.68	384.99
160	11.4	30.5	13.5	7	2.26	2.68	411.75
180	19.8	36.2	14.2	6	2.55	1.83	514.04
200	10.5	23.6	12.5	6	1.89	2.25	295.0
220	8.6	21.7	11.6	4	1.87	2.52	251.72
Total	150.9	340.8	149.9	71	27.24	27.96	4311.74
Mean	12.58	28.40	12.49	5.92	2.27	2.33	359.31

Source: Authors' field work, 2025

Table 8 contain results on Arawa gully catchment. The gully has a depth that ranges from 10.7m to 14.7m with average value of 12.49m and CSA of 251.72 m² to 517.44 m² with average mean of 359.31m². These results are in line with those reported by Osadebe and Ezezika (2023) and Amalu *et al.* (2022), that gullies with depths over 10m and CSA values greater than 300m² are classified as mega gullies contributing to high sediment yield potential, increased risk of infrastructural damage if located near settlements or roads, as also highlighted by Adedeji *et al.* (2023). TW/D ratio of 1.87 to 2.86 with a mean value of 2.27 and TW/BW ratio of 1.80 to 3.02 and average of 2.33 indicates a U-shaped gully profile common in stable but expansive gullies (Bai *et al.*, 2024). This also connotes a significant lateral expansion, consistent with gully systems influenced by urban or peri-urban land uses (Chen *et al.*, 2025). The slope angle ranges from 4° to 9° with average value of 5.92° suggesting moderately steep terrain as noted by Nwachukwu *et al.* (2024) that slope angles between 5° to 10° often accelerate gully headcut migration, particularly when compounded by upstream land-use changes such as deforestation or construction.

Table 9: Bye pass Gully catchment characteristics

Distance from gully head (m)	BW(m)	TW(m)	Gully depth (m)	SA (degree)	TW/D ratio	TW/BW ratio	CSA (m ²)
0	3.2	11.5	4.6	3	2.50	3.59	52.9
20	3.4	8.2	4.8	4	1.71	2.41	39.36
40	3.5	7.6	4.7	2	1.62	2.17	35.72
60	2.9	5.6	3.9	5	1.44	1.93	21.84
80	3.7	9.2	5.1	3	1.80	2.49	46.92
100	3.2	7.3	4.9	3	1.49	2.28	35.77
120	3.4	10.5	3.6	2	2.92	3.09	37.8
140	3.4	7.2	4.2	4	1.71	2.12	30.24
160	2.8	7.9	3.7	3	2.14	2.82	29.23
180	2.5	6.6	3.5	4	1.89	2.64	23.1
200	3.2	8.5	4.1	2	2.07	2.66	34.85
220	3.1	6.3	4.4	2	1.43	2.03	27.72
Total	38.3	96.4	51.5	37	22.72	30.23	415.45
Mean	3.19	8.03	4.29	3.08	1.89	2.52	34.62

Source: Authors' field work, 2025

The results in Table 9 on Bye Pass gully catchment reveals a high TW/BW ratios, averaging 2.52 as also reported by Chen *et al.* (2025) is an indicator of instability and potential sidewall collapse, while TW/D ratio of 1.89 indicates a V-shaped gully form, with significant broad top width and narrow bottom (bed width). The results also revealed that gully depth ranges from 3.5m to 4.9m with average value of 4.29m indicating an active and deep gully system as supported by Oke and Ezenwaji (2021), who suggested that gullies with depths exceeding 4m and CSA above 30m², exhibit high sediment transport capacity. As emphasised by Bai *et al.* (2024) gullies with mean depths above 4m in urban or semi-urban environments are particularly sensitive to storm water surges. This reflects the Bye Pass gully profile, with mean depth value of 4.29m. The mean slope angle of 3.08° shows relatively gentle slope combined with high TW/BW ratio aligns with patterns observed in urban gullies in developing regions (Amalu *et al.*, 2022). These characteristics often result from runoff concentration due to impervious surfaces such as roads and rooftops. Bye Pass gully channel exhibits a matured stage gully profile, according to classifications in Osadebe and Ezezika (2023). This is evidenced by deep channels, broad top widths and high cross-sectional areas. This gully has over the years threatened the existence of the major bye-pass road in Gombe State due to its head ward retreat and significant soil loss from the gully catchment as revealed in plate 1.

Table 10: Tunfure Gully catchment characteristics



Plate 1: Bye-pass road in Gombe threatened by head ward retreat of gully erosion in the area

Source: Authors' field work, 2025

Distance from gully head (m)	BW(m)	TW (m)	Gully depth (m)	SA (degree)	TW/D ratio	TW/BW ratio	CSA(m ²)
0	7.2	12.5	2.3	3	5.43	1.74	28.75
20	3.5	4.7	2.5	2	1.88	1.34	11.75
40	8.4	12.3	1.8	3	6.83	1.46	22.14
60	6.7	10.3	1.3	2	7.92	1.54	13.39
80	7.2	13.1	1.4	2	9.36	1.82	18.34
100	6.2	9.3	2.0	3	4.65	1.50	18.6
120	7.0	8.0	2.1	3	3.81	1.14	16.8
140	6.2	11.5	2.7	4	4.26	1.85	31.05
160	3.6	5.7	2.2	2	2.59	1.58	12.54
180	7.4	11.3	2.5	3	4.52	1.53	28.25
200	7.7	10.6	1.7	1	6.24	1.38	18.02
220	7.8	12.1	1.3	3	9.31	1.55	15.73
240	6.5	11.3	2.1	3	5.38	1.74	23.73
260	6.8	8.3	1.9	2	4.37	1.22	15.77
Total	92.2	141	27.8	36	76.55	21.39	274.86
Mean	6.59	10.07	1.99	2.57	5.47	1.53	19.63

Source: Authors' field work, 2025

NOTE: BW (Bed width), TW (Top width), SA (Slope angle), TW/D (Top width/depth ratio), TW/BW (Top width/bed width ratio) and CSA (Cross sectional area).

Table 10 shows that the gully depth in Tunfure gully catchment ranges from 1.3m to 2.7m with a mean of 1.99 m, while top width ranges from 4.7m to 12.5m with a mean value of 10.07m. The bed width ranges from 3.5m to 8.4m with a mean of 6.59m. This heterogeneity indicates a V-shaped gully form, which aligns with patterns described by Bai *et al.* (2024), where human activities and local hydrology alter gully geometry along its course. Studies such as Amalu *et al.* (2022) emphasised that a TW/D ratio greater than 3 often indicates moderate to severe gully erosion. The mean TW/D ratio is 5.47, suggesting pronounced gully expansion. The mean ratio of TW/BW in Table 10 is 1.53m, supporting the classification by Oladosu *et al.* (2022) who stated that a TW/BW ratio close to or above 1.5 is typical for matured gullies with wider upper sections due to headward erosion and sidewall collapse. On the other hand, the slope angle ranges from 1° to 4° with a mean of 2.57° showing that Tunfure gully falls within the low-to-moderate slope category. These findings corroborated those of Nwachukwu *et al.* (2024) who noted that such slope angles contribute to a gradual but persistent gully expansion rather than rapid incision.

Relationship between Gully Morphological parameters in the study area

The results on nature of the relationship between gully morphological parameters are contained in Table 11. Results of the correlation analysis revealed that there is strong positive relationship between the gullies' top widths and bed widths ($r = 0.89$), indicating a concurrent adjustment between the two properties. This relationship indicates that as the gullies' top or shoulder widths increases, the bed widths also increase. This shows a fine adjustment to forms and the processes (e.g. lateral recession) at work; given some of the gullies U-shape form. This is due to the almost concurrent degrading of the top and bed widths. The relationship is a clear situation of co-variation of two variables which are both controlled by other factors; in this case discharge or runoff and the nature of gully valley slope gradient and floor materials which are predominantly sandy materials. There is also a moderately strong relationship between bed width and depth ($r = 0.54$). One conclusion that can be drawn from this relationship is that the retreat of gully side takes place at rates proportional to the rate of gully deepening. This could be attributed to processes taking place in the bed and side walls. Also, it was observed that there is a weak negative correlation between the distance from gully head (Length) and top width/depth ratio ($r = -0.12$). This implied that as the distance from gully head increased, the gullies' top width and depths decreased. The lengths of the gullies are therefore negatively predictive of gully deepening and widening.

Table 11: Correlation matrix of gully characteristics in the study area

	D	BW	TW	SA	TW/D	TW/BW	CSA	L
D	1.00							
BW	0.54	1.00						
TW	0.68	0.89	1.00					
SA	0.71	0.57	0.65	1.00				
TW/D	-0.15	0.53	0.48	0.13	1.00			
TW/BW	-0.16	-0.15	-0.01	-0.18	-0.26	1.00		
CSA	0.84	0.71	0.89	0.66	0.14	0.02	1.00	
L	0.05	0.16	0.19	0.02	0.12	0.08	0.11	1.00

Level of significance: 0.05

Source: Authors' data analysis, 2025

Note: D is gully depth. BW is Bed width. TW is Top width. SA is Slope angle. TW/D is Top width-depth ratio. TW/BW is Top width-Bed width ratio. CSA is Cross sectional area. L is length.

The transporting capacity of gully channels depends largely on slope gradient along the gully beds and the widths of the gullies. Gullies with moderately to large widths are likely to experience longer peak flows during rainfall and deposition along the gully floor and thereby reducing their depths. The implication is that lateral recession acting on the gully sides and slumping of materials at different points along the gully channel will be pronounced; a situation that is common among gullies in the study area.

Notably, there are strong and positive correlations between the slope angles of gullies and most of the other gully attributes. The relationship between slope angle and depth ($r = 0.71$), slope angle and bed width ($r = 0.57$), slope angle and top width (0.65) are very strong. These shows that the nature of the gully side slope gradients has significant influence on gully depths and widths as the gullies increase in size. The slope gradient correlations also, predicts that the gully shearing and transporting capacity is affected by other factors such as buildings, refuse dumping on gully banks and lack of drains which are likely to enhance high rate of surface runoff in the area, capable of influencing gully initiation in the study area. The findings of this study corroborated with those of Wu *et al.* (2022) who reported in their study that areal erosion rates increased over time, due to the influence of steep gradients along gully banks which reinforced gully bank erosion at different rates and gully development dynamics among the three regions were influenced by land use, slope, and topographic factors.

Worthy of note is that, some of the gullies in the study area are ephemeral in nature, and so they contain water and enhance channel flow and sediment entrainment in some parts of the year. This hydrological property of the gullies increase their destructive role in the development of badland topography in the area through gully bank erosion, traction and mass wasting, which culminates in the destruction of nearby buildings and roads as shown in plate 1. However, there are ongoing efforts by Gombe State government to control the incipient and developed gullies in the study area, through engineering construction of side wall embankments and drainages that could contain the excess runoff in the area. Hence, most of the onsite gully assessment was done in areas where the gullies are yet to be controlled for observations on the fluvial processes taking place in the gully catchments and field measurements.

CONCLUSION AND RECOMMENDATIONS

The morphological characteristics of gully channels were assessed in Gombe metropolis and it was observed that the gully channels in the study area are large in size and have developed to a disastrous level and currently serves as a destructive agent to roads, houses and capable of causing road accidents in many parts of the town. The development of gully erosion in the study area has been exacerbated by anthropogenic activities such as indiscriminate disposal of solid waste and building of houses on waterways, that affects surface runoff. It is hereby concluded that gully erosion in Gombe metropolis has caused a lot of havocs to the inhabitants and if left unabated will continue to be inimical to the development of the area. It is therefore recommended that the Gombe State government should carry out gully stabilisation process using engineering methods such as building concrete wall embankments and storm drains to control the development of gullies in the study area for enhance environmental sustainability. Also, the Gombe State government and Non-Governmental organisations should engage

in landscape management by planting trees around the gully sites, to help stabilise the gully banks and reclaim the gully sites.

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