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ASSESSMENT OF SPATIO-TEMPORAL CHANGES IN THE GEOMETRIC CHARACTERISTICS OF A GULLY IN GOMBE METROPOLIS, GOMBE STATE NIGERIA

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Abstract

Gully erosion is a major ecological problem in Gombe town, it plays a crucial role in shaping landscapes of the town and is often associated with its land degradation processes. The problems of high rate of gully erosions expansion is of great concerns to the people in Gombe Metropolis due to the frequent loss of lives and properties it causes and the unsatisfactory efforts being made to control it. This study attempts assessment of the spatiotemporal changes of the geometric characteristics of Hayin Missau segment of Gombe/Yola road – Liji Quarters' gully. It is, also set to analyze the factors influencing the problem from 2000 to 2020 using Remote Sensing and GIS tools and techniques. Understanding the spatio-temporal changes in the geometric characteristics of gullies is essential for effective land management and erosion control strategies. The study locate, identify and determine the trends and extends of the gully, and suggests possible management strategies for controlling it. Landsat Satellite imageries and differential GPS, were used to capture the geometric characteristics of the gully at different epoch and for field measurements, verification, and validation respectively. Microsoft excel, Google Earth, and ArcGIS 10.3 software were used. The results shows that, the length of the gully is 3.98km, and the extent of the gully from 2005 to 2020 rises from 20.923 Ha in 2005 to 30.301 Ha in 2020. For sustainable mitigation and control of the gully erosion, this

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study recommends the strategic use of geospatial approach which include proper considerations of geometric characteristics and configuration in the design, and construction of erosion control structures.

Introduction

By a combination of natural (intense rainfall, steep slopes, erodibility of soils, drought that decimate vegetation) and human (misuse and or overuse of land) factors, landscapes become vulnerable to denudation by water and wind in a geological process that detaches, moves and deposits soil particles from upstream to downstream locations. Such process proceeds from the detachment of soil particles by raindrops (splash), their transportation by flowing water in thin sheets (sheet erosion), the concentration of runoff water into narrow channels (rill erosion), and the development of deep steep sided channels by concentrated water flow (gully erosion) (Amangabara, 2014; Balasubramanian, 2017). Nir, Knitter, Harold and Schutt, (2021) characterized gullies as linear channels that have a minimum depths of 30 cm or minimum cross-sectional areas of 930cm^2 and minimum volumes of 25 – 45m^3 . From these minimum values, very large gullies that are several kilometers in depths, widths and lengths develop and ravage the landscape.

The widespread incidence of gully erosion coupled with its diverse physical and socio economic effects (most of them negative) has made it one of the major ecological problems of the world. For instance, it is estimated that there are between 1.7 to 2 billion gully heads in the world, the major hotspots (> 50 gully heads/ km^2) being parts of China, Iran, Sahara Desert, the Andes and Madagasca (Vanmaercke, Chen, De Geeter, Poesen and Campforts, 2020). Gully erosion has also been reported in the USA, Australia, New Zealand, Ethiopia, Thailand, India, Brazil, arid and semi-arid areas (Valentin, Poesen, and Li, 2005; Aber and Aber, 2019). In Nigeria, virtually all parts of the country are affected by gully erosion. According Federal Government of Nigeria (2016), it is most serious in the South Eastern part of the country where there are about 3000 active gullies. Other most affected States are Ekiti, Gombe and Kogi. Because gully erosion leads to the loss of soil; a non- renewable resource that supports livelihood of man; it is recognized as a cancerous ecological disease with multi- faceted effects that threaten humanity. Among the consequences of gully erosion are dissection of the landscape, reduction in soil productivity (ten million square kilometers in the world), damage to property and infrastructure, increasing watershed sediment yield that negatively affects water quality, reducing the capacities of reservoirs and drainage networks by siltation which can increase runoff and sediment connectivity in the landscape, hence increasing the risk of flooding and catchment instability (Ionita, Fullen, Zgłobicki, and Poesen 2015; Hassen and Bantider 2020; Rahmati, Kalantari, Ferreira, Chen, Soleimanpour, Kapovi, Seifollahi-Aghmiunib,

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Ghajarniab and Kazemabadyi, 2022). Estimates of economic losses due to gully erosion in the world are put at USD 231 million annually (Zhang, Zhao, Yan, Qin and Miao, 2023). On the flip side, gullies provide interesting opportunities for educational purposes, as forested gully systems form attractive geo-touristic sites (Zgłobicki , Baran-Zgłobicka Gawrysiak, and Telecka 2015).

Gullies are dynamic features that undergo changes over time due to a multitude of factors, including climate variability, land use practices, vegetation cover, and geomorphic processes. Hence, their geometric characteristics (length, width, depth, and slope) vary over time and these variations are key indicators of changes in their shapes (V or U), stage of development (initiation, development, healing, and stabilization) and activity (active, inactive). Consequently, the geometry of gullies should be considered when control measures are contemplated, otherwise, they become waste of efforts and resources.

The landscape of Gombe metropolis is traversed by gullies of various sizes (Mbaya, 2017) because of which it is recognized among towns afflicted by gully erosion (Obateru, 2022). The negative effects of these gullies have necessitated the deployment of funds to control some of them using engineering methods. In 2022 alone, the sum of 4.5 Billion Naira was budgeted by the Gombe State government for gully erosion control (Periscope Nigeria June 2022). Expectedly, studies have been conducted about various aspects of the problem in the town. These include gully morphology and geotechnical assessment (Mbaya, Ayuba, and Abdullahi, 2012) gully erosion susceptibility mapping (Igwe, John, Solomon, Obinna, 2020), socio economic effects (Danladi and Ray), analysis of control measures (Mbaya, 2017).

It was observed that the hydraulic structures constructed to control some of the gullies are inadequate for their purposes; some overflow while others have collapsed. This suggests that the gullies and their geometries were not properly profiled for control. Field observations suggest that among these gullies, the *Hayin Misau* segment of the Gombe/Yola road- Liji quarters gully, is among the most prominent in size and destructive effects. Hence, the purpose of this paper is to examine the changes in geometric characteristics of the gully at five year intervals from 2005 to 2020. It is hoped that this will contribute in planning for the control and management of the gully. Data were collected from Landsat satellite images and field measurements. ArcGIS 10.7 and Civil 3D software packages were used for data processing, analysis and visualization.

Objectives:

The objectives of the paper are to;

- Measure the geometric characteristics of the gully
- Plot the profile of the gully
- Categorize the changes in the geometric characteristics of the gully

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The Study Area

The Gombe/Yola road- Liji quarters gully (Figure 1), is located between the southern by pass road and the Biu-Gombe road in Gombe metropolis the administrative capital of Gombe State, North Eastern Nigeria. The metropolis lies between Latitudes 11°11^{l} 20.4^{ll}N and 11°14^{l} 37.4^{ll} N and Longitudes 10°16^{l} 20.8^{ll} E and 10°19^{l} 16.0^{ll} E.

As at 2020, the area of the town is estimated at 44.105km^{2} (Abubakar, Ibrahim and Babayo, 2022). It has average annual rainfall of about 850mm, temperature range of 29°C to 35°C. High intensity rainfall associated with high run off, an average slope of -4% from western part to eastern part of the town, a Sudan savannah, consisting of open grassland, scattered shrubs and trees which dry up during the dry season (Igwe, John, Solomon, & Obinna, 2020) and loose porous sandy soils (Flayin and Udochukwu, 2022) predispose it to gully erosion.

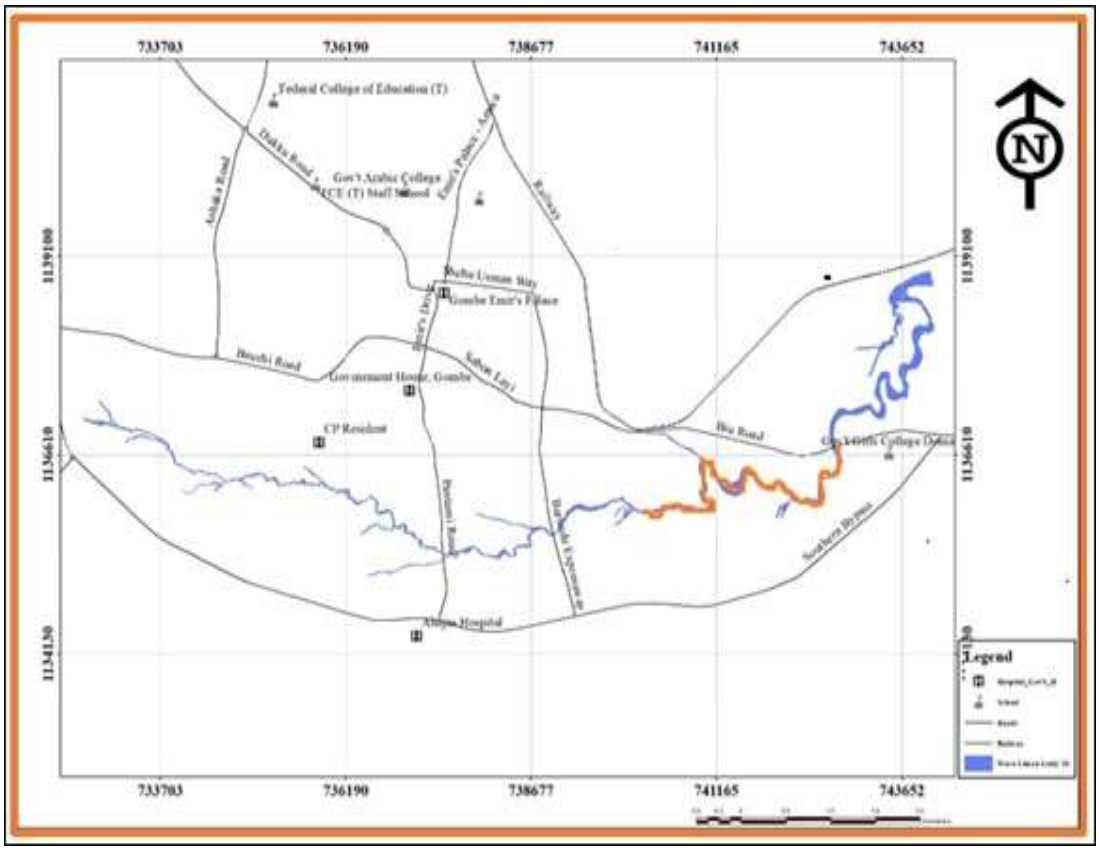


Figure 1: The Gombe/Yola Road- Liji Quarters Gully and Hayin Misau Segment. Source; Author

Like other gullies in the town, the gully begins from the western part of the town and terminates in River Dadinkowa in the eastern part, following the west east

orientation of the slope of the town. With a length of 14.3km, it traverses a significant part of the town, passing through parts of the GRA, Pantami, Wuro Liman, Manawashi, Hayin Misau, Bogo, Doma, and Liji wards. The Hayin Misau segment of the gully is 3.98km long (about 30% of the gully) and traverses Hayin Misau and Bogo wards. The coordinates of the start and end points of the gully and its segment studied (Hayin Misau) and the wards they traverse in the town are shown in Table 1.

Table 1: Coordinates of the Gully and its Hayin Misau Segment

Gully/segment of gully	Start Point		End Point		Length (km)	Areas Traversed
	Northings	Eastings	Easthings	Northings		
Gombe/Yola road – Liji Quarters	7326819	1137065	743826	1138796	14.3	GRA, Pantami, Wuro Liman, Manawashi, Barunde, Hayin Misau, Bogo, Doma, Liji Quarters
Hayin Misau segment of the gully	740645	1135937	742545.	1136162	3.98	Hayin Misau, Bogo

Methodology

Among the gullies in Gombe, the *Hayin Misau* segment of the Gombe/Yola road – Liji Quarter's gully was purposely chosen after reconnaissance, which indicated that it is among the prominent areas afflicted by erosion. Landsat images of the gully at five-year intervals from 2000 to 2015 (2000, 2010, 2015) were downloaded at same scale and altitude of capture using Google Earth. ArcGIS 10.7 software was used to enhance and multi-band classify the satellite images to aid structural interpretation. The images were validated after ground-truthing and geo-referenced to a Universal Transverse Mercator (UTM) grid, using coordinates of

control points proximal to the gully. The coordinates of the controls were obtained from the Gombe State Ministry of Lands and Survey.

The boundaries of the Hayin Misau segment of the gully were delineated from the Landsat images of the respective years of interest. The coordinates of points along the boundaries where changes of alignment were observed were extracted. The differences and were used to determine changes in the geometric attributes of the gully for each of the study periods. The union overlay tool of the ArcGIS 10.7 software was used.

To complement the satellite data, a differential GPS instrument was used to measure the geometric characteristics of the length, width, and depth of the gully in 2020. This was done by measuring their cross-sectional values at 25m intervals and at points where the change in gradient was observed from the start of the concerned segment of the gully to its end. The field data were used to produce the cross-sectional profiles (start, middle, and end) of the study site using Civil 3D software.

To determine the five-year changes in the geometry of the gully, three layers were compared at a time: 2005 to 2010, 2010-2015, and 2015-2020. The total change was obtained by comparing the values of 2005 and 2020. The results of the union overlay analysis were used to attribute parts of the gully into two categories whose areas were determined: erosion (where the gully increased), and accretion (where the gully receded).

Limitations of Methodology

The use of remote sensing images in measuring the geometric variables of gullies is limited by the impossibility of obtaining gully depth and the difficulty and imprecision of determining width (Casali, Gimenez, and Campo-Bescos, 2015; Golosov, *et al,* 2018 in Zhang, Han, Cruse, Zhang, Hu, Yan, and Guo, 2022). Thus, data about the depths of the gully from the satellite images were not included while caution was taken in delineating the widths of the gully. The depth of the gully was determined from field measurements made in 2020 and the accuracy depends on the limitations of the instrument used and the ability of the researchers.

Results and Discussion

The Temporal Geometric Characteristics of the Gully

The results of measurements in respect of the geometric characteristics are presented in Table 2. From the table, as at 2000, and subsequent years, the length of the gully under study is 3.98 km. The average width of the gully increased from

53.4m in 2005 to 94.8m in 2010, (an increase of 41.4 m). The average of increase is 8.28m annually.

Similarly, it was found that the area of the gully increased by 3.293 hectares from 20.923 hectares in 2005 to 24.216 hectares in 2010. This suggest mean increase of 0.6586 hectares every year. The -1.7% average slope value of the gully in 2005, and 2010 remain constant .

Year	Length (M)	Width (M)	Area (HA)	Slope (%)	Remark
2005	3980	53.4	20.923	- 1.7	
2010	3980	94.8	24.216	-1.7	
2005-2010		41.4	3.293	0	No changes
2015	3980	113.6	26.925	-1.9%	
2010-2015		18.8	2.709	-0.2%	Change
2020	3980	138.6	30.301	-1.9%	Same change as 2015
2015-2020		25.0	3.376	0	No changes
2005-2020		85.2	9.378	-0.2	Same Change as 2010 - 2015

In a similar trend, the values of the average width of the gully increased by 18.8m between 2010 and 2015, averaging 3.76m annually. The spatial extent of the gully increased by 2.709 hectares, implying yearly increase of 0.5418 hectares. Average slope increased by -0.2% from -1.7% in 2010 to -1.9% in 2015. From 2015 to 2020, average width increased by 5m annually from 113.6m to 138.6m while the area increased at the rate of 0.6752 hectares every year from 26.925 hectares to 30.301 hectares. There was stability in slope at -1.9% in the 2015-2020 study period.

The highest increase in the average width of the gully (41.4m) was witnessed in the 2005 to 2010 study epoch while its area increased the most (3.376 hectares) from 2015 to 2020. On the whole, within the temporal scope of the study, the average width of the gully increased by 85.2m, the area by 9.378 hectares, and the slope by -0.2%. The average area of land lost to erosion within the study epoch approximates to 0.6252 hectares annually.

The spatial profiles of the gully in the respective years of study are depicted in Figures 2a, b, c, and d respectively.

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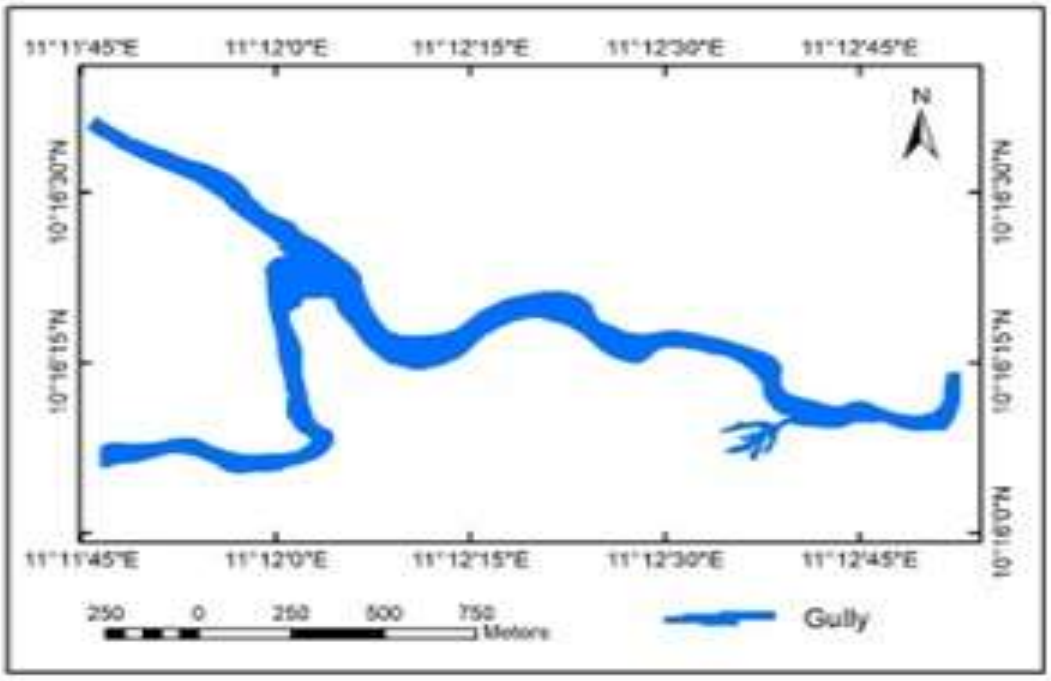


Figure 2a: Profile of the gully in 2005 Source; Author

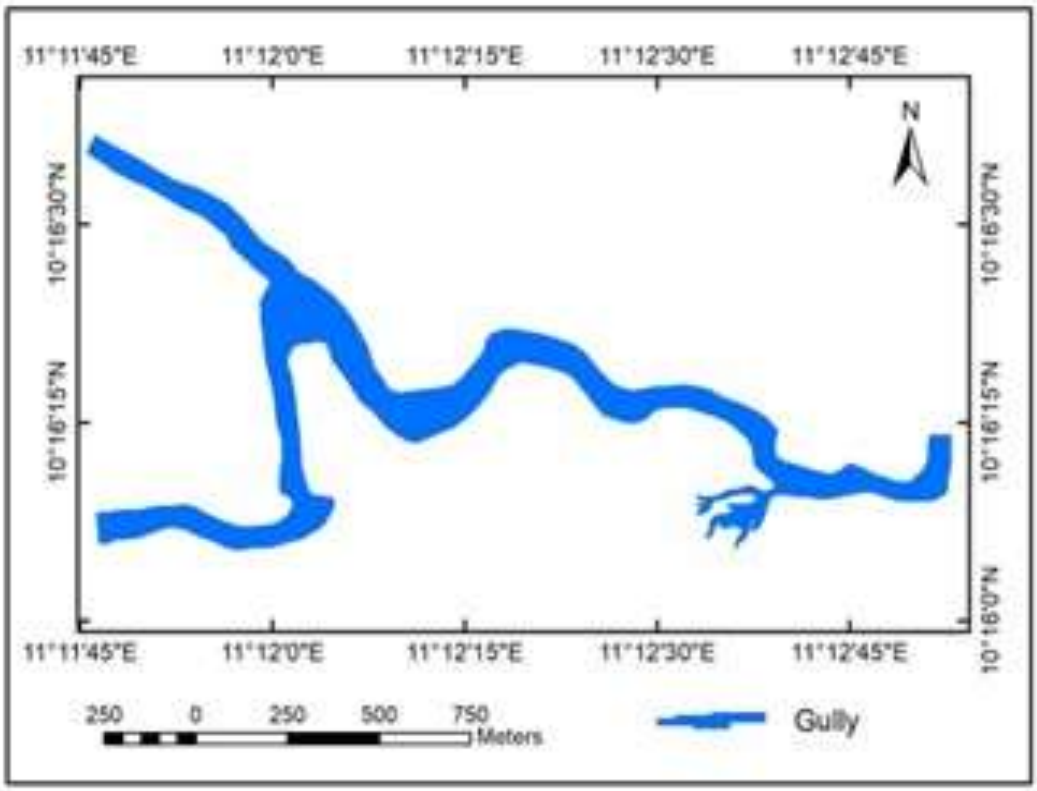


Figure 2b: Profile of the gully in 2010 Source; Author

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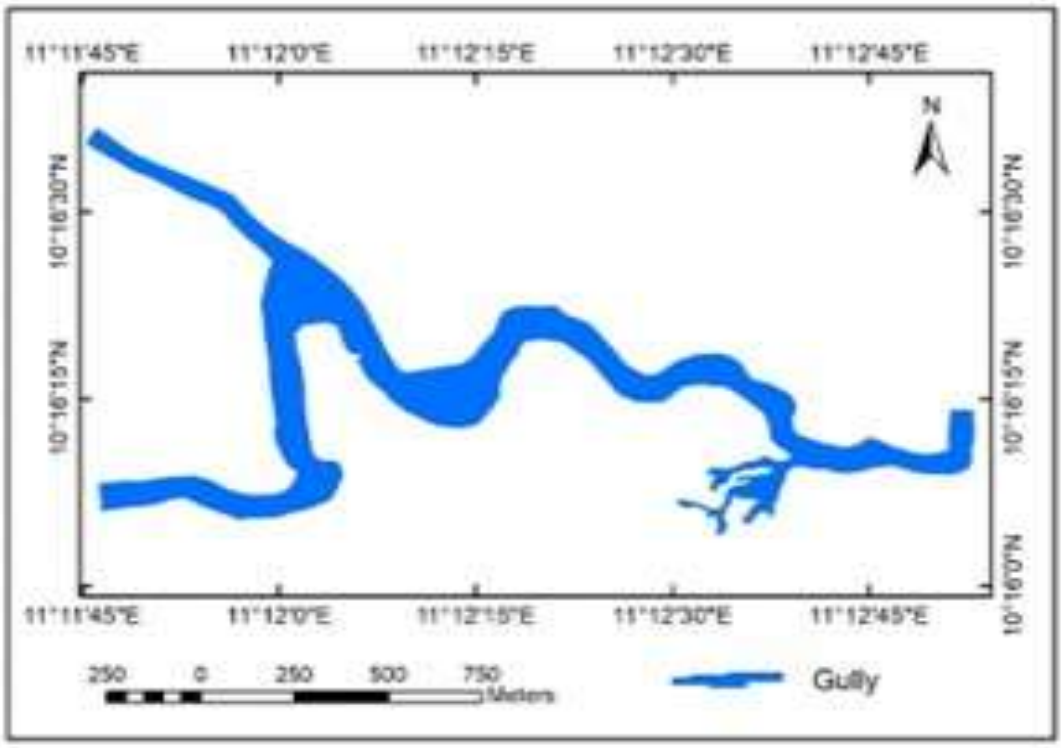


Figure 2c: Profile of the gully in 2015 Source; Author

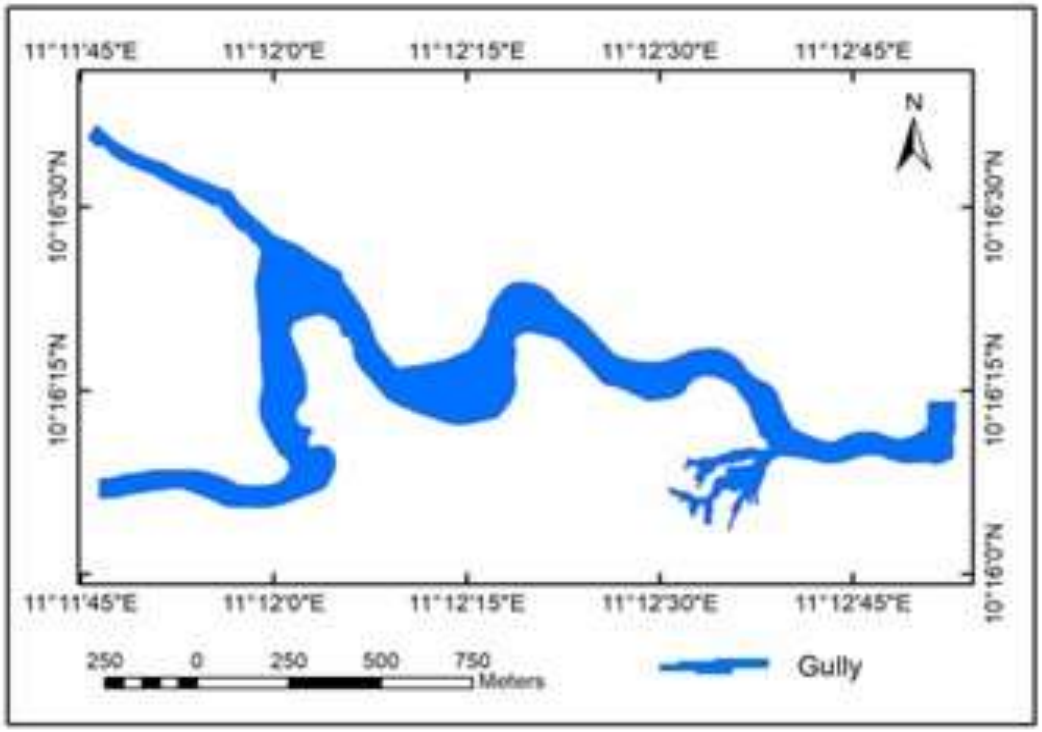


Figure 2d: Profile of the gully in 2020 Source; Author

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The Cross Profile of the Gully

The cross profiles of the gully at 0 + 000m, 2 + 000m, and 3+980m are presented in Figures 3a, b, and c respectively. The average depth and width of the gully were found to be 2.5m and 138.6m respectively. The profiles indicate that the gully has greater width than depth, implying greater lateral than vertical erosion, hence the trapezoidal shape of the gully.

Similar findings were reported for gullies in town by Mbaya, Ayuba and Abdullahi (2012), and Flayin and Udochukwu (2022). Elsewhere, the trend was reported by Vandekerekhove, Poesen, Oostwoud, Gyssels, Beuselinck, and Deluna, (2000) in South East Spain, Oparaku and Iwar (2018) in Idah-Ankpa, North Central Nigeria, and Yazie, Mekonnen and Derebe (2021) in Northwest Ethiopia. This situation is the outcome of geomorphological processes that undercut the gully walls making them slough on to the gully floors as sediments that raise the gully floors (Oparaku and Iwar, 2018). The relative stability of the slope of the gully may be the combined consequence of the greater lateral erosion and the raising of the gully floor by the sloughing of the gully walls on the floor.

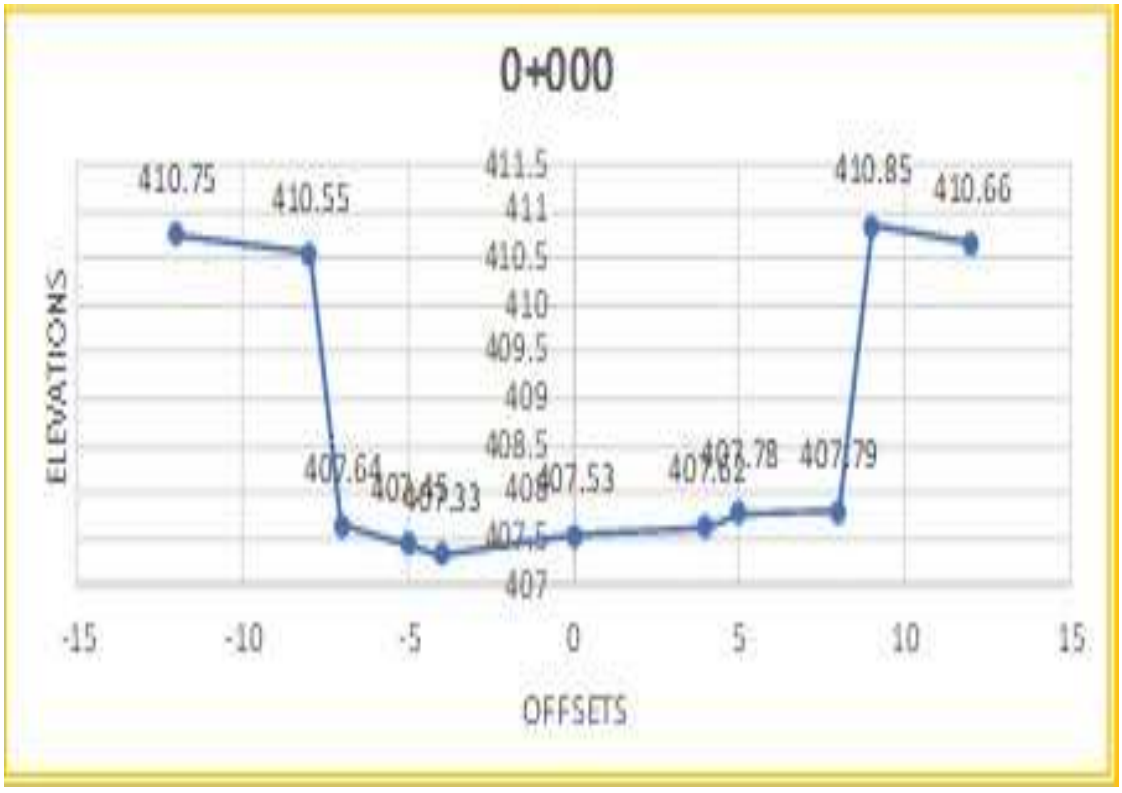


Figure 3a: Cross Profile of the Gully at 0 + 000 Source; Author

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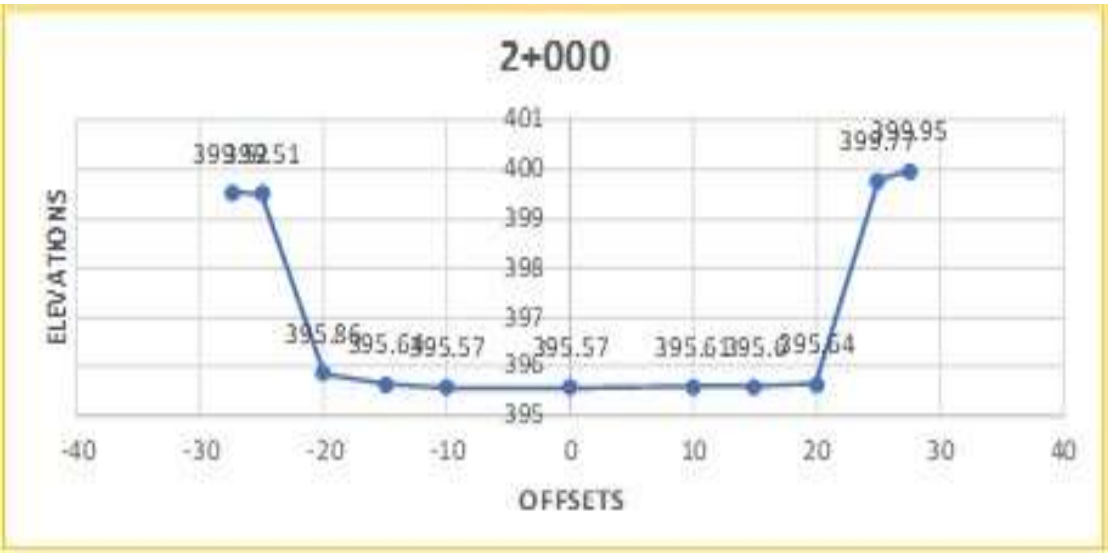


Figure 3b: Cross Profile of the Gully at 2 + 000 Source; Author



Figure 3c: Cross Profile of the Gully at 3 + 980 Source; Author

The greater lateral erosion also suggests the undercutting of buildings contiguous with the gully and the destruction valuable land that would have been used for urban land uses, essentially, residential. For instance, at an average plot size of 15m * 15m, the 9.378 hectares of land eroded within the study period would have accommodated 416 residential plots. In addition, the increasing width of the gully imply decreasing contiguity of hitherto proximal areas with attendant difficulty of access. It is reported that the gully destroyed about 200 houses, a complete primary school of six (6) block classrooms, and all hydraulic structures constructed to control it (Plates 1 and 2).

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Plate 1: Retaining wall collapsed by Hayin Misau gully. Source; Author



Plate 2: Houses destroyed by Hayin Misau gully. Source; Author

Danladi and Ray (2014) reported the destruction of 239 houses, 19 roads, 22 culverts and bridges, 103 plots, the displacement of 20125 people, and the loss of 15 persons due to gully erosion in Gombe between 1996 and 2011.The trapezoidal shape of the gully is also indicative of the uniform susceptibility of the surface and subsurface soil layers to erosion. Flayin and Okechukwu (2022) reported the dominance of sand in the soil layers of the area.

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Categories of the Changes in the Geometry of the Gully

Gullies are dynamic geomorphological structures that under changes as responses to variations in local conditions relevant to their initiation and development. Thus, there is a coexistence of erosional and depositional processes which vary in dominance spatially and temporally in gully channels. The characterization of the geometric characteristics of gullies help to understand the spatial and temporal dynamics of the erosion and deposition processes acting in gully channels (Zhang, Zhao, Yan, Qin, and Miao, 2023). The coexistence of erosion and deposition in gully channels results in a give and take situation with erosion wearing away the soil and deposition accumulating of sediments (thus leading to accretion).

A coexistence of erosion and deposition were observed in the study site within the study epoch. Quantification of erosion and accretion, represented in Figure 4, reveal that 7.473 hectares of land were eroded while accretion amounted to 1.905 hectares. This indicates the dominance of erosion over accretion by 5.368 hectares, equivalent to 400%. This result is similar to those of Roux, Morake, Hedding, Waal, and Anderson (2022) and Zhang, *et.al* (2023).

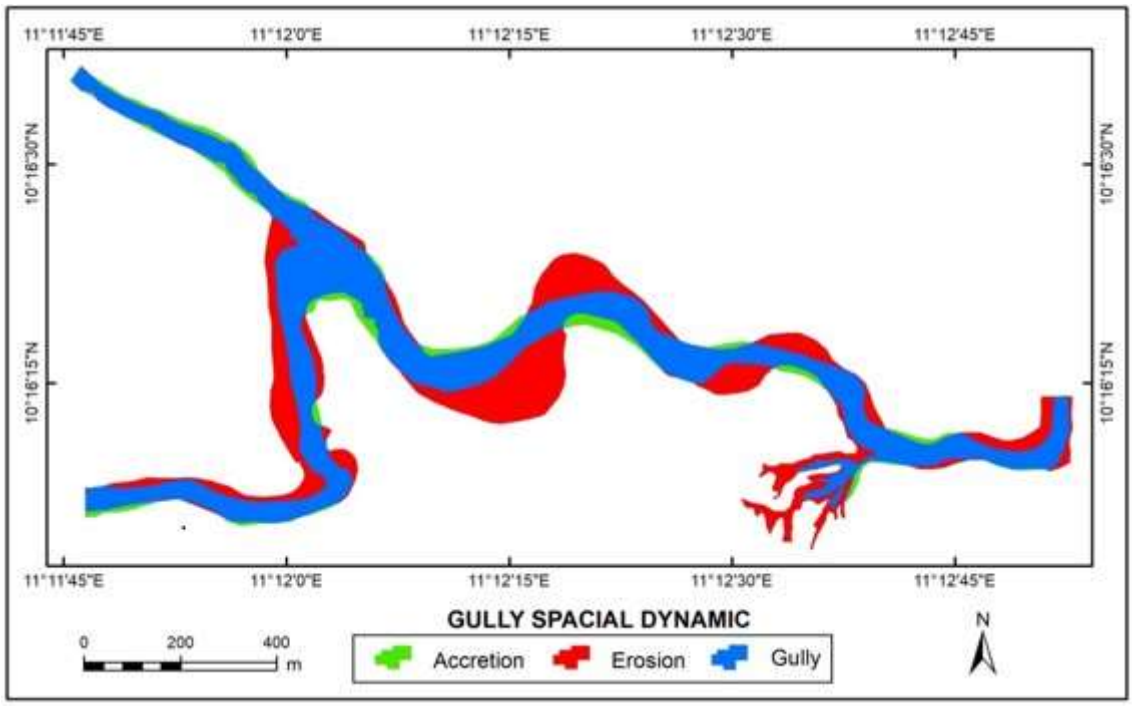


Figure 4: Erosion and Accretion in the Study Site, Source; Author

From Figure 4, it can be observed that erosion and accretion occur on opposite sides of the meanders of the gully. While erosion happened on the outside,

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accretion happened on the inside of the meanders. However, in all meanders, there was more of erosion than accretion. This can be attributed to the dominance of the predisposing factors of erosion in the town highlighted earlier. The incidence of accretion can be attributed to the stable gentle slope in the study segment and its wide nature, factors that slow down the erosive power of runoff. While the areas of accretion may become stable and even support the growth of vegetation, it is postulated that high rainfall/ runoff events can wash them away, thus, making them temporary (Roux, 2022). Also, the incidence of accretion is indicative of the possibility of the siltation of hydraulic structures that may be constructed to control the gully.

Conclusion

This study examined the changes in the geometric variables of the *Hayin Misau* segment of the Gombe/Yola road – Liji Quarters gully in Gombe metropolis from 2005 to 2020. The results obtained from remote sensing images and field observations, shows that the gully, which has a trapezoidal shape, has increased in width and aerial extents within the study period. Similarly it shows that erosion and accretion processes have taken place with erosion dominating over accretion by about 400%.

To address the problem of erosion, the following are recommended;

i) Erosion is site specific therefore the design and construction of engineering structures meant to control the gullies should incorporated appropriate geometric variables data. Therefore it is recommended that field measurements to ascertain the real situation be carried out first prior to the design and commencement of the constructions process. The government agencies responsible for the design and control gullies are encourage to ensure appropriate actions are taken in this respect

ii) It is shown that erosion and accretion occur on opposite sides of the meanders of the study gully. Thus the dynamic characteristics of the gully requires regular monitoring and evaluation in its geometric conditions. Therefore regular monitoring and evaluation of the gullies should be part of strategies for all-inclusive management of the gully. The Ministry of Environment and agencies responsible environmental protection agencies are ensure placement of adequate monitoring strategies in the area

iii) The loss of lives and properties occasioned by the widening of the gullies especially during raining season calls for imposition of stringent development control on either sides of the gully. Therefore the agencies responsible for planning and issuance of development permit should ensure that no buildings development are allow to take place within the area identified as gully vulnerable or prone areas.

REFERENCES

Aber, J. S., Marzolff, I., Ries, J. B., & Aber, S. E. W. (2019). Gully-Erosion Monitoring. *Small-Format Aerial Photography and UAS Imagery*, 259–271. https://doi.org/10.1016/B978-0-12-812942-5.00014-8

Abubakar M.B. , Dike E. F. C., Obaje N. G., Wehner H. and Jauro A (2008) Petroleum prospectively of cretaceous formations in the gongola basin, upper Benue trough, Nigeria: an organic geochemical perspective on a migrated oil controversy. *Journal of Petroleum Geology* 31(4): 387-408

Amangabara, G.T. (2014) Understanding effective gully control measures in Imo State. *Canadian Open Soil and Erosion Journal* 1(1):1-9

Alfonso-Toreno, A., Gomez-Gutierrez, A. and Schnabel, S. (2021) Dynamics of Erosion and Deposition in a Partially Restored Valley Bottom Gully. *Land* 10(1): 62

Balasubramanian, A., & Balasubramanian, P. A. (2017). *Soil Erosion-Causes and Effects*. https://doi.org/10.13140/RG.2.2.26247.39841

Casali, J., Gimenez, R.J. AND Campo-Bescos, M.A. (2015) Gully Geometry: What are we measuring? *Soil* 1(2015): 509-513

Danladi A. & Ray H. H. (2020). Socio Economic Effect of Gully Erosion on land use in Gombe Metropolis, Gombe State, Nigeria. *Journal of Geography and Regional Planning*. http//www.academicjournals.org/JGRP

Flayin, M.J. and Udochukwu, M.O. (2022) Soil assessment and mitigation of flash flood erosion using Ipomoe Carnea in Gombe town, Gombe State, Nigeria. *Technology audit and production reserves* 6(3): 15-23

Hassen, G., & Bantider, A. (2020). Assessment of drivers and dynamics of gully erosion in case of Tabota Koromo and Koromo Danshe watersheds, South Central Ethiopia. *Geoenvironmental Disasters*, *7*(1). https://doi.org/10.1186/s40677-019-0138-4

Ionita, I., Fullen, M.A., Zgłobicki, W., Poesen, J. (2015) Gully erosion as a natural and human-induced hazard. *Nat Hazards* (2015) 79:S1–S5 DOI 10.1007/s11069-015-1935-z

Igwe, O., John, U. I., Solomon, O., & Obinna, O. (2020). GIS-based gully erosion susceptibility modeling, adapting bivariate statistical method and AHP approach in Gombe town and environs Northeast Nigeria. *Geoenvironmental Disasters*, *7*(1). https://doi.org/10.1186/s40677-020-00166-8

Mbaya, L.A. (2017) Spatial Analysis of Gully Erosion Control Measures in Gombe Town, Gombe State, Nigeria. *Advances in Image and Video Processing* 5(4): 17-26

Mbaya L A, Ayuba H. K., Abdullahi J. (2012) An Assessment of Gully Erosion in Gombe Town, Gombe State, Nigeria Journal of Geography and Geology Vol. 4 No. 3 Canadian Center of Science and Education

Nir, N., Knitter, D., Hardt, J., & Schutt, B. (2021). Human movement and gully erosion: Investigating feedback mechanisms using Frequency Ratio and Least Cost Path analysis in Tigray, Ethiopia. *PLoS ONE*, *16*(2 February). https://doi.org/10.1371/journal.pone.0245248

EDITOR-IN-CHIEF
Prof. W. F. HILL [MALAWI]

Obateru, R. O. (2022) Assessing Gully Erosion in Nigeria: A Review. The Nigerian Geographical Journal 16(1): 81-95

Oparaku, L.A. and Iwar, R.T. (2018) Relationships between Average Gully Depths and Widths on Geological Sediments Underlying the Idah-Ankpa Plateau of the North Central Nigeria. *International Soil and Water Conservation Research* 6(1): 43-50

Rahmati, O., Kalantari, Z., Ferreira, C S., Chen, W., Soleimanpour, S. M., Kapovi, M., Seifollahi-Aghmiunib, S., Ghajarniab , N., Kazemabadyi, N.K. (2022) Contribution of physical and anthropogenic factors to gully erosion initiation. *Catena* (Cremlingen. Print), 210: 105925-105925 https://doi.org/10.1016/j.catena.2021.105925

Roux, J., Morake, L. and Hedding D. W. (2022) Intra Gully Mapping of the Largest Documented Gully Network in South Africa using UAV Photogrammetry: Implications for Restoration Strategies. Progress in Physical Geography, Earth and Environment 46(5):772-789

Valentin, C., Poesen, J., & Li, Y. (2005). Gully erosion: Impacts, factors and control. *Catena*, 63(2–3), 132–153. https://doi.org/10.1016/j.catena.2005.06.001

Vandkerekhove, I., Poeson, J., Oostwound, D., Gyssels, G., Beuselinck, I. and Deluna, E. (2000) Characteristics and Controlling Factors of Bank Gullies in two Semi-arid Mediterranean Environments. Geomorphology 3(1-2): 17-58

Vanmaercke, M., Chen, Y., De Geeter, S., Poesen, J. and Campforts, B. (2020) A first data driven gully head density map of the world. EGU General Assembly 2020, Online, 4-8 May2020 https://doi.org/10.5194/egusphere-egu2020-9285, 2020

Yazie, T., Mekonnen, M. Derebe, A. (2021) Gully Erosion and its Impacts on Soil Loss and Crop Yield in three Decades, Northwest Ethiopia. *Modelling Earth Systems and Environment* 7(4): 1-10

Zaborski P., Ugodulunwa F., Idomigie A., Nnabo P., Ibe K. (1997)
Stratigraphy and structure of the Cretaceous Gongola Basin, northeast Nigeria
Bulletin des Centres de Recherches Exploration-Production Elf Aquitaine, Vol.21, No.1, 153-185, 1997

Zgłobicki, W. Baran-Zgłobicka, B., Gawrysiak, L. and Telecka, M. (2015) The impact of permanent gullies on present-day land use and agriculture in loess areas (E. Poland). *Catena* 126:28–36

Zhang, G., Zhao, W., Yan, T., Qin, W. and Miao, X. (2023) Estimation of gully growth rate and erosion amount using UAV and Worldview-3 images in Yimeng mountain area, China. Remote sensing 15(1): 233

Zhang, S., Han, X., Cruse, R.M., Zhang, X., Hu, W., Yan, Y. and Guo, M. (2022) Morpholgical Characteristics and Influencing Factors of Permanent Gully and its Contribution to Regional Soil Loss based on Field Investigation in Mollisols Region of Northeast China. *Catena* 2(17) 106467