Morphological Characterization and Spatial Variation of Permanent Gullies in Southern Gombe State, Nigeria: Implications for Erosion Hazard Management

Kalshidam Musa[1,]
musakalshidam@gmail.com
Phone: +2348021118190

Gideon Didams, [1,]
gdamsviva@gsu.edu.ng
Orcid: 0000000228460020
Phone: +2348035712204

[1]Department of Geography and Environmental Management,
Gombe State University, Tudun-Wada, Gombe,
Gombe State, Nigeria
Corresponding author: Didams Gideon (gdamsviva@gsu.edu.ng)

https://doi.org/10.56201/ijgem.vol.12.no10.2026.pg184.197

Abstract

Permanent gully erosion is a severe environmental problem in Southern Gombe State, Nigeria, destroying buildings, roads, bridges and agricultural lands. This study, characterizes morphologies and spatial variations of permanent gullies that dissect landscape of the area. Using Google Earth Pro imagery and detailed field measurement campaigns, 130 permanent gully locations were identified and thir morphometric parameters including length, top width, bed width, depth and surface area were measured every 20 m along gully channels. Permanent gullies were classified based on landscape position and morphology into continuous, discontinuous and bank gullies. Results show 130 permanent gullies affect 34,499.2 ha or 4.3% of study area. Continuous gullies dominate by area (46 gullies, 35% by count, 21,950.1 ha or 64% by area), followed by bank gullies (13 gullies, 10% by count, 8,624.5 ha or 25%) and discontinuous gullies (71 gullies, 55% by count, 3,924.3 ha or 11% by area). Morphometrically, gully depth ranges 0.9-12.2 m (exceptionally up to 20 m), width up to 68 m, length 99-10,857 m. Continuous gullies are largest (up to 20 m deep, 68 m wide, 10,857 m long) with trapezoidal cross-sections, occurring on gentle slopes along drainage paths with large contributing area, erodible soils from soft unconsolidated sedimentary rocks and poor vegetation cover. Bank gullies are large (up to 13.4 m deep, 43.1 m wide, 1,370 m long), less topographically controlled, originating from banks of streams and agricultural terraces, shaped by tension cracks, piping and mass movement. Discontinuous gullies are smaller (up to 3.2 m deep, 10.1 m wide, 915 m long), isolated on steep slopes with smaller contributing area and more stable shallow soils, characterized by abrupt headcut and alluvial fan at intersection with valley. Spatially, northern parts underlain by Gombe and Keri-Keri Formations show wide U-shaped active gullies lacking vegetation, while southern mountainous parts show narrow V-shaped partially stabilized gullies with vegetation but with falls indicating rejuvenation. Mechanisms include piping, tension crack development, dispersion, bank collapse and rill erosion initiation. The study recommends immediate zoning

of continuous gully systems as class 1 environmentally sensitive areas and implementation of differentiated interventions including check dams at gully mouths, gabion drops for headcut control, a 100 m ban on sand mining along gully banks, and establishment of an integrated remote sensing and field based monitoring system to support erosion control.

Keywords: *Gully morphology, Continuous gully, Discontinuous gully, Bank gully, Southern Gombe State, NEWMAP, Permanent gully*

Introduction

Gully erosion represents an advanced stage of water erosion in which concentrated runoff removes soil and weak bedrock, creating deep channels that cannot be eliminated through conventional tillage (Poesen et al., 2003; Valentin et al., 2005). Assessing gully morphology is an initial step in evaluating gully-forming processes because morphological characteristics reflect the processes responsible for gully development and support assessments of past, current, and future changes (Poesen et al., 2003). A clear understanding of morphology therefore enables projections of future gully behavior. Permanent gullies are channels incised into abandoned agricultural fields, rangelands, or shrublands. They commonly develop in unconsolidated slope deposits, particularly silt-clay materials and weathered soils, as a result of ephemeral runoff generated by rainstorms. These gullies are generally relatively narrow and deep, reaching depths of up to 25-30 m, and are difficult to cross or remove through tillage (Caraballo-Arias et al., 2016; Vanmaercke et al., 2016). Ephemeral gullies are linear erosion features produced by hydraulic action from overland flow. They have cross-sectional areas greater than one square foot, are temporary, can be removed through tillage, and tend to recur in the same locations (Foster, 1986; Nachtergaele et al., 2002). Ephemeral and permanent gullies differ in size and cross-sectional form. Ephemeral gullies are relatively wide and shallow, with poorly defined sidewalls and inconspicuous headcuts, whereas permanent gullies are relatively narrow and deep, have steep, distinct sidewalls, and exhibit headcuts that migrate upstream. They also differ in persistence, the former generally being temporary and the latter permanent; in eroded material, which ranges from soil removed to the depth reached by tillage to the full soil profile and soft bedrock; and in the processes responsible for detachment and transport. Ephemeral gullies are formed primarily by flowing water, while permanent gullies may involve flowing-water detachment, slumping of unstable banks, and headcut retreat (Vandaele et al., 1996).

Based on landscape position, geomorphic processes, and developmental characteristics, permanent gullies are classified into three categories: continuous, discontinuous, and bank gullies (Poesen et al., 2003; Yibeltal et al., 2019). Continuous gullies, also called stream gullies (Billi & Dramis, 2003), consist of interconnected gully features. Their main channel is linked to numerous mature or immature branch gullies. They commonly begin high on a mountainside, where many small rills rapidly attain gully dimensions and then maintain an approximately uniform depth toward the mouth. Near the lowest segment, the depth decreases sharply, producing a shallower and wider channel that promotes greater sediment deposition. This configuration forms a networked gully system, which may comprise multiple-gully systems or several separate networks. Discontinuous gullies consist of isolated features that are not connected to one another and occur within ephemeral drainage systems on separate hillslopes. Their thalwegs commonly exhibit an abrupt headcut, with channel depth declining rapidly downstream, while the bed gradient becomes progressively gentler. The former valley floor may create an alluvial fan at the valley intersection (Le Roux & Sumner, 2012). A series of gullies can coalesce into one continuous network; however, if the fan is excessively steep, a new discontinuous gully may develop upslope through headcut advancement. As headcuts merge, they may produce or connect with a continuous network, although some gullies remain

entirely independent, resulting in a mixture of forms. Headcuts and mouths are critical locations in gully development. Bank gullies, also known as edge-of-field gullies, form when concentrated runoff crosses an earthen bank along roadcuts, terrace banks, riverbanks, or the banks of large gullies (Vandekerckhove et al., 2000). Their formation is associated with very steep local slopes, which promote rapid hydraulic erosion and piping, eventually followed by mass movement. After initiation, these gullies retreat through headcut migration into moderately sloping soil surfaces and may extend farther into rivers or agricultural terraces. During later stages, they can develop into discontinuous or continuous forms.

Gullying is a threshold-dependent phenomenon and represents one of the most severe forms of land degradation worldwide, resulting in soil loss, infrastructure destruction, and fatalities (Ionita et al., 2015). Nigeria is severely affected by soil erosion, with more than 6000 km2 impacted and approximately 3400 km2 highly vulnerable. The associated environmental damage is estimated to exceed US$1.5 billion annually, threatening the Federal Government's vision of positioning Nigeria among the world'Ugeni, 20 economies (Federal Government of Nigeria, 2012). In response, the Federal Government sought World Bank assistance through the Nigeria Erosion and Watershed Management Project (NEWMAP) to reduce vulnerability in selected sub-catchments, including those in Gombe State.

In Gombe State, the southern region is the most severely affected, characterized by dense, deeply incised gully networks that have created unsightly landscapes and destroyed buildings, roads, bridges and agricultural areas (Gombe State Ministry of Environment, 2017). The substantial risk posed by gullies to agricultural land and infrastructure, as well as the occurrence of fatal events, is evident. Although numerous studies worldwide have modeled gully susceptibility (Conforti et al., 2011; Rahmati et al., 2016; Saha et al., 2020; Amiri et al., 2019; Meliho et al., 2018; Angileri et al., 2016; Dewitte et al., 2015), to the best of our knowledge, no study has specifically characterized gully morphology in Southern Gombe State using geomorphological terrain-analysis techniques. Therefore, this study characterizes the morphology and spatial variation of permanent gullies dissecting the landscape of Southern Gombe State, Nigeria.

Description of Study Area

Southern Gombe State is situated approximately between latitudes 9°33'42.19" and 10°20'16.38" North and longitudes 10°41'52.61" and 11°57'52.75" East in Nigeria's North East region. Gombe State is one of Nigeria's 36 states and covers approximately 8,023.2 km^2 of its total landmass of 20,265.6 km2 (Google Earth, 2019). The study area is bordered by Borno State to the East, Yobe State to the North, Bauchi State to the West, and Adamawa and Taraba States to the South.

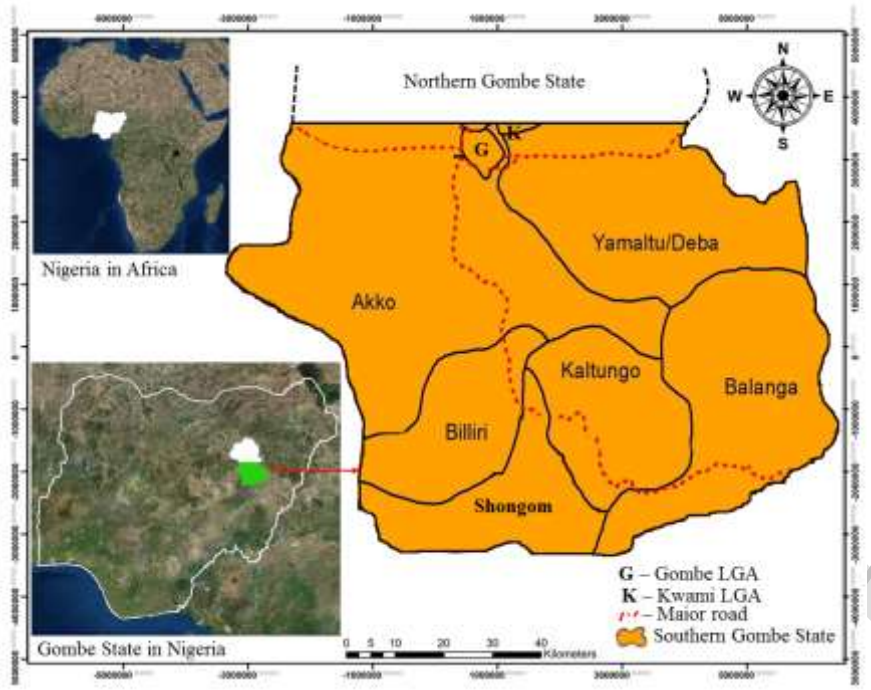


Figure.1: Location of Southern Gombe State
Source: Google Earth (2017)

The region has a semi-arid tropical continental climate classified as Aw. Rainfall occurs during a short season, is concentrated in a few events, and is often intense. Annual precipitation ranges from 800-1000 mm and generally increases southward, while the mean temperature is approximately 27°C. Climatic conditions are controlled primarily by the ITCZ/ITD. The area has a varied topography. Its northern section consists of undulating plains at elevations of approximately 400-500 m and is underlain by the Gombe and Keri-Keri Formations. The southern section is more mountainous, with elevations ranging from 700-1000 m and geology comprising the Basement Complex, Bima Sandstone, and volcanic plugs around Kaltungo.
The principal geological units include the Basement Complex around the Kaltungo hills, Bima Sandstone at Bambam, Gombe Sandstone near Kumo, and the Keri-Keri Formation. A volcanic plug occurs at Dogon Dutse. The geological cross-section (Figure 2) indicates alternating layers of soft, unconsolidated, and poorly consolidated sedimentary rocks that are highly susceptible to erosion. The major soil types are Lithosols, ferruginous tropical soils, vertisols, and hydromorphic soils. Drainage is dominated by the Gongola River system, which exhibits a dendritic pattern. Most streams are seasonal. Agriculture is the primary land use, and population density is relatively high. Large livestock commonly roam and forage across the area. Other activities include sand mining along gully banks and the use of shallow wells excavated in channel beds. Gully channels also occur within cultivated farmland.

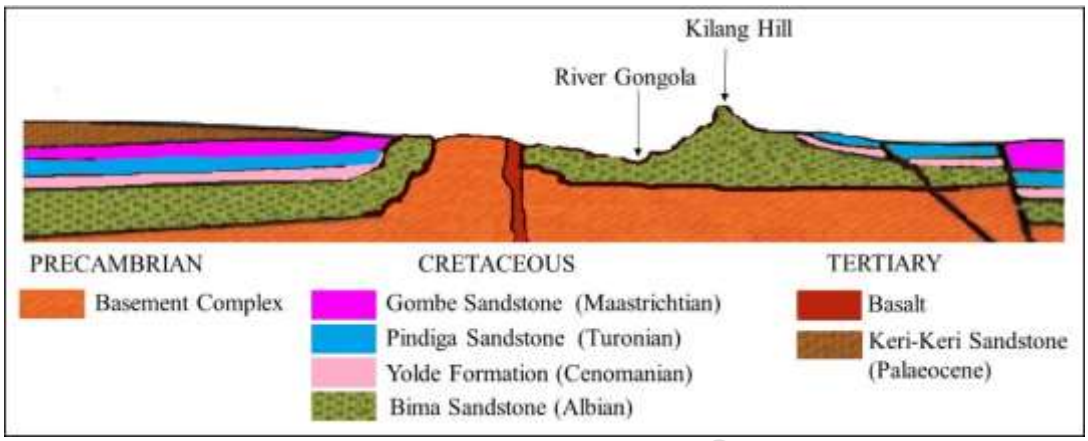


Figure 2: Geological Cross-section of Southern Gombe State

Methodology

The study focused on permanent gully channels that are sufficiently large to be visible on satellite imagery, deep enough to obstruct land development, and potentially capable of causing harmful consequences for the environment and people. The Square-foot, landscape position, and morphological criteria were used to identify and distinguish permanent gullies from other linear erosional channels. A generic nominal classification scheme was adopted, in which permanent gully erosion features were primarily categorized as continuous, discontinuous, or bank gullies.

Both primary and secondary data were used. Primary data comprised direct field observations and measurements, digital elevation model (DEM) data, locations of previously identified gully features. Secondary data were obtained from the Nigeria Geological Survey Agency (NGSA), the Federal Department of Agriculthe roadLand Resources (FDALR), Abuja, the Nigerian Meteorological Agency (NiMet), NEWMAP, and the Gombe State Ministry of Land Survey. These data included information on geology, soil texture, rainfall, temperature, gully distribution, and land use. Field equipment consisted of a handheld Garmin 12XL GPS receiver, a surveyor's measuring tape measuring 100m with a 1 cm scale, ranging poles, an Abney level, a digital camera, and computer systems, including a laptop, desktop, scanner, and printer. The GPS was used for recording the geographical coordinate of permanent gully locations, while the 100m measuring tape was used to determine gully parameters, including length, width, and depth. Nine sheets of Nigerian topographic maps at a scale of 1:50,000, comprising sheets 151NE Akko, 152NE Gombe, 152NW Gombe, 152SE Gombe, 152SW Gombe, 173NE Kaltungo, 173NW Kaltungo, 173SE Kaltungo, and 173SW Kaltungo, covering the study area and used for field operations and DEM generation. Software and remote-sensing materials included Landsat 8 imagery archived by the USGS, three DigitalGlobe images archived in Google Earth, Landsat 8 for land-use analysis, and Google Earth imagery for identifying and extracting gully features. GIS-based analysis was conducted with ArcGIS 10.1. Gully length was defined as the longitudinal distance from the gully headcut to the mouth along the channel. The channel was divided into 20 m segments, and lengths were measured accordingly. Abrupt changes in the channel profile, from the headcut to the outlet, were also identified using a 100 m tape. The mean length of all measured segments was taken as the gully length and calculated. Gully width was determined as the horizontal distance between the left and right banks of the channel. Measurements included the top width and bed width, obtained by stretching a measuring tape vertically across the gully from one bank to the other at 20 m intervals. Measurements were repeated at all selected points along the channel, and the mean values for top width and bed width were used to represent gully width. Gully depth was measured vertically across the channel cross-section. A measuring tape was positioned at

ground level and stretched across the channel, while a third person held a ranging pole at the deepest point of the gully floor. The reading on the ranging pole where it contacted the stretched measuring tape was recorded, and gully depth was computed. Gully surface area was measured as the area of the study covered by gullies and expressed in hectares (ha). The surface area of each gully channel or system was derived from the DEM using standard GIS techniques. These values were then summed to determine the total gullied area within the study.

Interpretation of satellite imagery:

During field surveys, time limitations and difficult terrain permitted only partial local measurements of gully morphology. Some gullies may have remained undetected because vegetation obscured them, while documenting their dimensions was particularly challenging where gullies were large and extended across expansive mountainous landscapes. Consequently, field observations alone provided limited information. Given the historical significance of gully erosion, remote sensing (RS) was used to obtain measurements of such gullies. Google Earth Pro data provided planimetric and altimetric accuracy at the submeter level. Locations of control points were established in Google Earth, and field recordings from Garmin GPS devices were used to evaluate accuracy.

Types and Percentage Proportions of Permanent Gullies

The study was based on the understanding that field investigations were guided by the basic principles of geomorphology and that the occurrence and distribution of gully erosion in Southern Gombe resulted from interactions among geo-environmental factors and fluvial geomorphological processes that operated in the past. Various types of permanent gullies had developed in the intensely affected areas. Field observations showed that piping, tension-crack development, dispersion, bank collapse, and rill-erosion development were the most important mechanisms responsible for gully initiation and development in the study area. The increasing extent and intensity of gully erosion underscore the importance of addressing this issue and the need to consolidate relevant management guidelines.

Interpretation of Google Earth imagery enabled the identification and extraction of 130 critical permanent gully locations. Based on their landscape position, morphological, and hydraulic geometry characteristics, the identified gullies were classified into three principal types: continuous, discontinuous, and bank gullies, each exhibiting distinct morphological characteristics. Together, these gullies covered 34,499.2 ha, representing 4.3% of the study area. Table 1 shows that 46 gullies were classified as continuous, 71 as discontinuous, and 13 as bank gullies. In terms of percentage distribution.

Table 1: Types of permanent gullies in Southern Gombe State

Gully type	No. gullies	Gully (%)	Area (ha)	Area (%)
Continuous	46	35	21,950.1	64
Discontinuous	71	55	3,924.3	11
Bank	13	10	8,624.8	25
Total	**130**	**100**	**34,499.2**	**100**

Results from digital analysis and field observations indicated that continuous gullies represent the largest gully-erosion features dissecting the landscape, covering 21,950.1 ha, or 64%, of Southern Gombe. They are readily identifiable by their pronounced morphology, reaching depths of up to 20 m, widths of up to 68 m, and lengths of up to 10,857 m, with a typical trapezoidal cross-sectional profile. Field observations further indicated that these gullies occur predominantly in areas with gentle slopes, saturation along drainage paths, large contributing areas, erodible soils, soft unconsolidated or poorly consolidated sedimentary rocks, and sparse

vegetation cover. Additional observations of the processes shaping these gullies suggested that headward, waterfall, and lateral erosion promote the undercutting of slope banks, while gully-bank collapse is primarily driven by gravity. The continuous gullies described here correspond to those reported by Le Roux & Sumner (2012) in Eastern Cape Province, South Africa, where continuous gullies likewise predominate on gentle, saturated slopes.

Bank gullies are also relatively extensive, covering 8,624.8 ha, or 25%, and reaching depths of up to 13.4 m, widths of up to 43.1 m, and lengths of up to 1,370 m. However, their development is less strongly controlled by topographic conditions. The erosion processes observed in association with these gullies include the formation of tension cracks, piping or tunneling, and mass-movement processes such as slumping and soil falls. In the field, a few bank gullies were observed to occur as offshoots originating from bank streams and agricultural terraces. This finding is consistent with Fernandes et al. (2017), who recorded a large number of bank gullies occurring in agricultural terraces in Adorigo, Portugal.

Results for the discontinuous types showed that they were smaller, covering 3,924.3 ha, or 11%, and reaching depths of up to 3.2 m, widths of up to 10.1 m, and lengths of up to 915 m. They occurred primarily on steep slopes where the surface was less saturated and the contributing area was smaller, and where soils were more stable and shallower. This result confirms the discontinuous gullies reported in Eastern Cape Province, South Africa, by Le Roux & Summer, (2012). Discontinuous gullies were the most numerous (55% by count) but occupied the smallest area (11%), indicating that they represent an early stage of gully development and may merge into a continuous network if the fan is too steep. New discontinuous gullies may form upslope as headcuts advance, while headcuts may merge discontinuous gullies to form or connect with continuous gullies; however, some remain fully independent. This mixture highlights the importance of headcut and mouth locations in gully development.

Morphometric Characteristics

A fundamental understanding of morphology is necessary for assessing gully processes. Such assessment, in turn, enables projections of future gully behavior because gully morphology reflects the processes responsible for its formation and can therefore support evaluations of past, present, and potential future development. In general, permanent gully features occur in areas marked by incisions with predominantly near-vertical banks and are generally large. Gully depth varies from 0.9-12.2 m, less commonly reaching 20 m and, in exceptional cases, exceeding this value. Maximum lengths are 10,857 m for continuous gullies, 497.2 m for discontinuous gullies, and 1,092.3 m for bank gullies based on earlier measurements; however, field observations recorded bank gullies reaching up to 1,370 m.

The cross-sections are predominantly U-shaped, although V-shaped gullies are also present. Spatial observations indicate that the northern parts of the study area, where the Gombe and Keri-Keri geologic formations are extensively exposed, contain mostly broad, U-shaped gully channels with little or no vegetation cover on their side slopes, indicating an active stage of gullying. In contrast, the mountainous southern part commonly contains narrow, V-shaped gullies, with some vegetation established on the slopes, suggesting stabilization. Nevertheless, the occurrence of falls in some channels indicates that gully rejuvenation is taking place.

Table 2 shows that the 130 permanent gullies collectively affect approximately 34,499.2 ha, representing 4.3% of the study area. A detailed examination of the tables indicates that the 46 continuous gullies cover 21,950.1 ha, or 64% of the affected area, whereas bank gullies cover 8,624.5 ha, or 25%. In contrast, discontinuous gullies are numerically predominant, with 71 occurrences, but account for only 11% of the affected area.

Table 2: Morphometric characteristics of studied permanent gullies (n=130)

Gully type	Length (m)			Width (m)			Depth (m)			Gullied area (ha)	Gully area (%)
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean		
Cont.	2097	10857	5550.7	6.4	68	31.4	1.4	20	12.2	21950.1	64
Bank	777	1370	1092.3	4	43.1	6	0.9	13.4	1.8	8624.8	25
Discount.	99.2	915	494.2	3.1	10.1	15.4	0.9	3.2	4.9	3924.3	11
Total										**34499.2**	**100**

The observed morphology reflects the products of gully-forming processes (Poesen et al., 2003). In the north, broad, U-shaped gullies with little vegetation indicate an active gullying stage associated with erodible duplex soils, extensive contributing areas, saturation along drainage pathways, and inadequate vegetation cover. The Gombe and Keri-Keri Formations are extensively exposed and consist of soft, unconsolidated or poorly consolidated sedimentary rocks. In the south, narrow, V-shaped gullies with vegetation on some slopes suggest partial stabilization; however, their falls indicate renewed activity resulting from tectonic uplift or changes in base level. Near-vertical banks, tension cracks, piping, dispersion, bank collapse, and rill erosion contribute to gully initiation and development. The increasing intensity and expansion of gullying highlight the need for greater attention to and consolidation of management guidelines. U-shaped cross-sections indicate that bank collapse and mass movement are more influential than channel downcutting, whereas V-shaped cross-sections indicate that downcutting predominates in the more resistant Basement Complex of the southern mountainous region.

Field observations further indicated that continuous gullies generally develop on gentle slopes where saturation occurs along drainage pathways, contributing areas are extensive, soils are erodible, the underlying sedimentary rocks are soft or poorly consolidated, and vegetation cover is sparse. These conditions promote erosion processes such as headward extension, waterfall formation, and lateral erosion, which undercut slopes and banks, triggering collapse under gravitational forces, consistent with the findings of Le Roux & Sumner (2012) in the Eastern Cape. Bank gullies are less strongly governed by topographic conditions and may develop away from drainage lines, originating along stream banks, agricultural terraces, tension cracks, piping and tunneling features, or areas affected by mass movement, slumping, and soil falls, as reported by Fernandes et al. (2017) for the numerous bank gullies on agricultural terraces in Adorigo, Portugal. Discontinuous gullies are smaller and commonly occur on steeper slopes with less-saturated surfaces, smaller contributing areas, more stable soils, shallower and more abrupt headcuts, and gentler gradients at the base where the original valley floor intersects an alluvial fan. Along a valley, individual gullies may merge into a single continuous network; however, if the fan is excessively steep, a new discontinuous gully may develop upslope as the headcut advances. These headcuts may eventually merge, converting discontinuous gullies into continuous forms or causing them to join an existing network, although some remain entirely independent. This mixture is particularly evident at critical locations near the headcut mouth, which is important for gully development and supports the conclusions of Le Roux & Summer (2012).

Spatial variation in occurrence of permanent gullies

Analysis of the spatial distribution of gully features revealed distinct spatial variation (figure 3) governed by geo-environmental factors. The northern part of Southern Gombe State (Akko, Yamaltu Deba, southern Kwami, and northern Balanga), underlain by the Gombe Sandstone

and Keri-Keri Formation, is characterized by wide, U-shaped gullies; large, continuous forms; active erosion; limited vegetation cover on side slopes; high drainage density; proximity to streams and roads; poor vegetation cover; gentle slopes of 5-15°; and saturation zones.

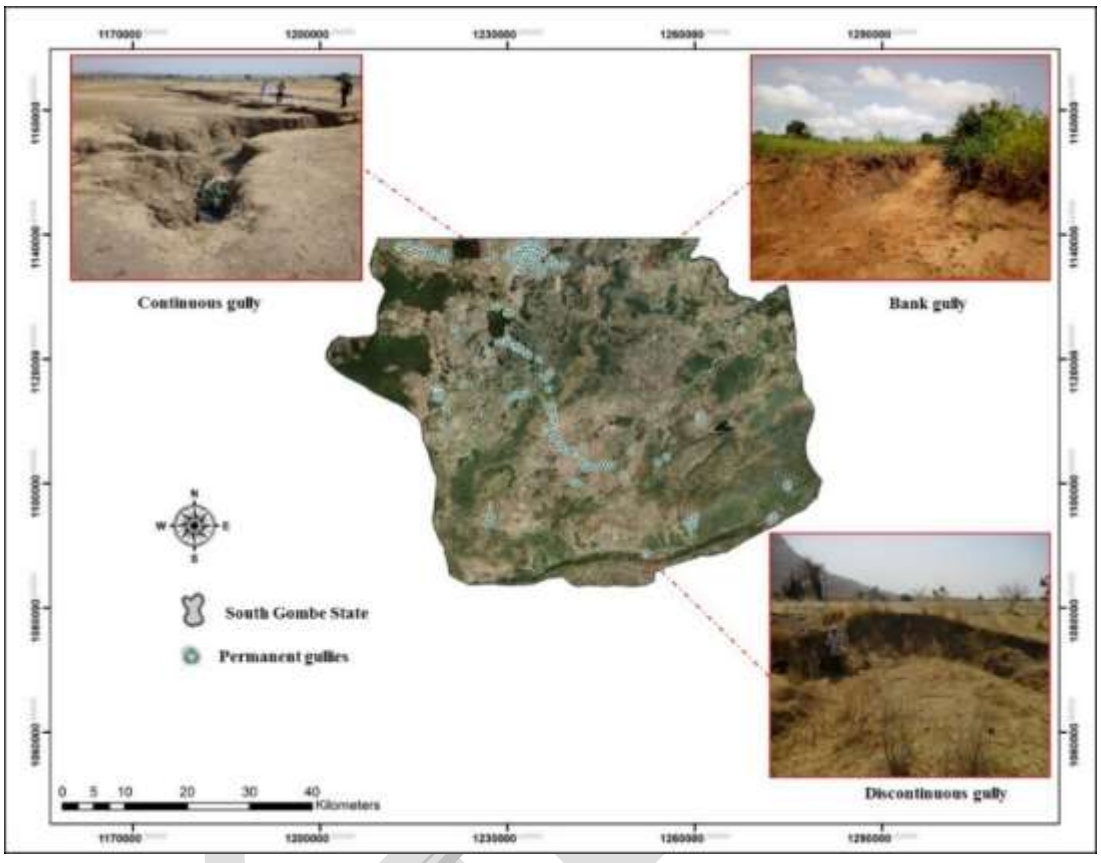


Figure 3: Spatial distribution of permanent gullies affecting the study area

Southern mountainous part (Kaltungo, Shongom, Billiri), is characterized by narrow, V-shaped gullies, along with smaller discontinuous and bank-type gullies. Vegetation has partially stabilized the slopes, which are steep (>25°) and underlain by Basement Complex outcrops, Bima Sandstone, and volcanic plugs. Waterfalls indicate renewed incision, while the gullies are generally distant from roads but close to streams that cut along fault lines. Although vegetation stabilization suggests reduced current activity, the presence of waterfalls indicates rejuvenation associated with base-level lowering or human activities, including sand mining and the excavation of shallow wells in channel beds.

The central transitional zone contains a mixture of gully types. The spatial variation in erosion mechanisms can be explained through geomorphological principles. Geological structure is a dominant control on landform evolution, as reflected in the works of Thornbury (1968) and Oguchi (2019). In this context, structure refers not only to rock features such as folds, faults, and unconformities but also to the general physical and chemical characteristics of the earth materials from which landforms are carved. This concept considers the susceptibility of an area, its geological structure, the effects of deformation, and the geomorphic processes operating within it. Consequently, the geological setting of the entire Southern Gombe State constitutes the dominant control on susceptibility to gully erosion. To a large extent, relief is shaped by Earth-surface processes because geomorphic processes operate at different rates. Differences in the rates at which these processes act, together with varying degrees of resistance within the Earth's surface, produce distinct landscape features. These variations result from differences in lithology and structural characteristics, which control deformation and

consequently alter relief. Thus, the occurrence of diverse and changing relief within gully catchments is inevitable. In the current study area, susceptibility mapping is required to examine the existing and changing relief of the land.

Geomorphic processes leave distinctive imprints on landforms, with each process generating its own characteristic assemblage. This concept demonstrates that landforms do not develop randomly; rather, each geomorphic process produces particular landform types that preserve evidence of its operation. Such imprints make it possible to distinguish erosional features from depositional ones, including aeolian and fluvial forms (Thornbury, 1968; Oguchi, 2019). This concept provides the basis for the genetic classification of landforms and offers a suitable framework for identifying and inferring how landforms originated. It is therefore a useful tool for identifying the permanent gully-erosion features examined in this study. Although geomorphology is primarily concerned with present-day landscapes, its usefulness is maximized when the concept is extended historically. This perspective highlights the need for historical approaches to morphogenic interpretations of landforms and provides a complementary concept to the principle of uniformitarianism. Together, these form a fundamental basis for current and future assessments of terrain susceptibility to gully erosion in Southern Gombe and throughout Gombe State.

Rainfall variability across space also exerts control. In the semi-arid climate, rainfall is concentrated in a few short-duration, high-intensity events, which contributes to the intensification of gully erosion. Zhang et al. (2019) identified a relationship between rainfall and gully erosion, with rainfall in all classes positively associated with the probability of gully erosion. The likelihood of gully occurrence at any location increases with the amount of rainfall received there. This is evident when gully-location data are overlaid on a rainfall map, as most gullies are situated in areas receiving more than 1000 mm of rainfall. This result agrees with the findings of Conforti et al. (2011) in the Turbolo catchment, Italy; Rahmati et al. (2016) in the Chavar region, Iran; and Makaya et al. (2019) in upper uMgeni, South Africa.

Distance from roads was the most important factor in the subsequent modeling. Distance from roads, drainage density, distance from streams, SPI, TWI, slope aspect, and rainfall were the most influential factors associated with gully-erosion occurrence. In contrast, slope gradient, slope length, and land use had moderate effects, whereas geology, soil texture, elevation, and plan curvature were the least important and had the weakest influence. However, geology and soil texture are critical to morphological characterization, as Gombe and Keri-Keri contain erodible duplex soils and extensive contributing areas. Land use such as armlands within gully channels, large livestock populations that roam and forage, sand mining along gully banks, and shallow wells in channel beds accelerate erosion, and population density, areas with high population density experience more bank gullies because of roadcuts and terrace banks. Thus, the spatial variation is not random but is controlled by interactions among geo-environmental factors and fluvial geomorphological processes that operated in the past.

Implications for Hazard Management

Evidence from geomorphological interpretations of satellite imagery and field surveys indicates that permanent gullies have expanded beyond their previously documented boundaries within the study area. The extent of this expansion has reached alarming proportions, with gullies now occupying nearly 24% of the study area, which is highly to extremely susceptible to additional gully development. Unless immediate action is taken to halt this trend, the gullies will continue to multiply and intensify the already severe problems associated with existing erosion. The spatial extent and scale of the affected areas therefore require reassessment through further research. In addition to the factors observed in this study, gully erosion may have been accelerated in certain locations and may also occur in areas previously considered relatively safe or less susceptible.

The findings are applicable to gully erosion monitoring at the catchment scale. The study provides an important resource for planners, decision-makers, and engineers, enabling them to make cost-effective, rapid, and rational decisions to reduce or prevent the damage caused by existing and future gullies. Highly to extremely susceptible locations should be avoided, and appropriate preventive and mitigation measures should be implemented. A similar methodology may also be applied in other regions with comparable physiographic and topographical characteristics. The study identified the precise locations of existing permanent gully erosion features and their associated morphometric properties. This can provide baseline information for further assessments of gully erosion hazard and for geomorphologically related studies within the study area.

Implications for policy and practice: Nigeria faces a severe soil-erosion problem driven by both natural and human causes. Approximately 6000 km^2 of land is affected by erosion, while about 3400 km^2 is highly exposed. The devastating effects of erosion affect many people's lives, destroy essential infrastructure, impede economic development and poverty alleviation, and create environmental problems. Gully erosion alone causes damage estimated at over $100 million annually nationwide, undermining economic growth and threatening the Federal Government's goal of positioning Nigeria among the first 20 economies in the world. A recent assessment of the situation by the FGN confirmed that the magnitude of the problem exceeds the capacity of communities, LGAs, States and the Federal Government to address without assistance from development partners. Consequently, the FGN requested support from the World Bank to address Nigeria's long-standing and worsening erosion problem and degraded watersheds through the Nigeria Erosion Watershed Management Project (NEWMAP). The development objective of NEWMAP is to reduce susceptibility to soil erosion in targeted sub-catchments, including Gombe State. Accordingly, accurate, fine-scale mapping of existing and potential gully-erosion locations across the landscape is essential for sustainable land management and gully-erosion control. Such mapping would also provide a database for improving current knowledge of the relationship between influencing factors and the distribution of gully erosion. This study examined Southern Gombe State, where widespread gully erosion is evident, and successfully characterized gully landforms and identified the most important influencing factors that influence gully erosion in Southern Gombe State. Consequently, the information presented in this study offers broader insights and perspectives on gully erosion, enhancing the study's usefulness to NEWMAP, which was established to address this issue.

Conclusion

This study presents a comprehensive geomorphological terrain-analysis characterization of permanent gullies in Southern Gombe State, establishing that gully morphology is a direct imprint of forming processes and a predictor of future behavior. The mapping of 130 permanent gullies covering 34,499.2 ha confirms three distinct genetic types with contrasting morphometry and landscape position. Continuous gullies constitute the major hazard by area (64%) with depths up to 20 m and lengths over 10 km, formed by headward, waterfall and lateral erosion with bank collapse on gentle, saturated, erodible duplex soils of the Gombe and Keri-Keri Formations. Bank gullies (25%) are associated with tension cracks, piping and mass movement along roadcuts and agricultural terraces. Discontinuous gullies (55% by count, 11% by area) are early-stage forms on steep slopes that may coalesce into continuous networks through headcut advancement.

The spatial contrast between broad, U-shaped, vegetation-free active gullies in the north indicating active gullying dominated by bank collapse, and narrow, V-shaped, partially vegetated gullies in the south indicating stabilization with renewed incision dominated by downcutting, reflects geological control as the dominant factor in Thornbury's concept of

structure. This is modulated by topographic, hydrological and anthropogenic factors. The alignment with rainfall concentration in few intense events, high drainage density, TWI and proximity to roads corroborates studies by Conforti et al. (2011), Rahmati et al. (2016) and Le Roux & Sumner (2012). The evidence of expansion and the identification of 24% of the landscape as highly susceptible underscores that current intervention capacity is exceeded. The dataset provides precise locations and morphometric properties essential for catchment-scale susceptibility modeling and cost-effective decision making. The methodology combining sub-meter Google Earth Pro imagery with field GPS validation is transferable to other regions with comparable physiographic settings.

Recommendations

Based on the evidence of expansion beyond previously documented boundaries and the identification of 24% of Southern Gombe State as highly susceptible to further gully development, immediate prioritization and zoning is recommended. The 46 continuous gully systems covering 21,950 ha in the northern Akko, Yamaltu-Deba, southern Kwami and northern Balanga axis, underlain by the soft, unconsolidated Gombe and Keri-Keri Formations, should be designated as Class I Environmentally Sensitive Areas where new infrastructure, road construction and settlement expansion are avoided, while the entire susceptible area should be re-mapped at 1:10,000 scale by the Gombe State Ministry of Environment and the Nigeria Erosion and Watershed Management Project. This should be complemented by differentiated engineering intervention according to gully type and morphometry. For the broad, U-shaped, active continuous gullies in the north, where bank collapse and mass movement dominate over downcutting and where saturation occurs along drainage pathways with large contributing areas, check dams should be installed at the lower segments where depth decreases sharply to promote sediment deposition and reduce stream power, combined with vegetative stabilization of near-vertical side slopes using Vetiver grass and Leucaena. For the narrow, V-shaped discontinuous gullies predominant in the southern mountainous zone of Kaltungo, Shongom and Billiri, which represent early-stage forms on steep slopes greater than 25 degrees underlain by Basement Complex and volcanic plugs, priority should be given to headcut treatment using gabion drop structures and diversion channels to prevent their coalescence into continuous networks, while bank gullies associated with roadcuts and agricultural terraces require immediate stabilization with retaining walls and proper culvert design. To address the anthropogenic factors that accelerate gully erosion, a 100-meter buffer ban on sand mining along gully banks should be enforced, particularly in Kaltungo and Billiri where field observations recorded excavation along banks and shallow wells in channel beds that trigger piping, tunneling and rejuvenation indicated by waterfall features, alongside community-based livestock control and regulation of farmland encroachment into gully channels.

References

Amiri, M., Pourghasemi, H. R., Ghanbarian, G. A., & Afzali, S. F. (2019). Assessment of the importance of gully erosion effective factors using Boruta algorithm and its application for gully erosion modeling. Environmental Earth Sciences, 78(5), 1-17.

Angileri, S. E., Conoscenti, C., Hochschild, V., Märker, M., Rotigliano, E., & Agnesi, V. (2016). Water erosion susceptibility mapping by applying Stochastic Gradient Treeboost to the Imera Meridionale River Basin (Sicily, Italy). Geomorphology, 262, 61-76.

Arabameri, A., Pradhan, B., & Rezaei, K. (2019). Gully erosion zonation mapping using integrated geographically weighted regression with certainty factor and random forest models in GIS. Journal of Environmental Management, 232, 928-942.

Billi, P., & Dramis, F. (2003). Geomorphological investigation on gully erosion in the Rift Valley and the northern highlands of Ethiopia. Catena, 50(2-4), 353-368.

Brice, J. (1966). Erosion and deposition in the loess-mantled Great Plains. US Geological Survey Professional Paper, 352-H.

Caraballo-Arias, N. A., Conoscenti, C., Di Stefano, C., & Ferro, V. (2016). A new empirical model for estimating calanchi and permanent gully erosion in Sicily, Italy. Geomorphology, 265, 113-120.

Conforti, M., Aucelli, P. P., Robustelli, G., & Scarciglia, F. (2011). Geomorphology and GIS analysis for mapping gully erosion susceptibility in the Turbolo catchment (Northern Calabria, Italy). Natural Hazards, 56(3), 881-898.

Dewitte, O., Daoudi, M., Bosco, C., & Van Den Eeckhaut, M. (2015). Predicting the susceptibility to gully initiation in data-poor regions. Geomorphology, 228, 101-115.

Federal Government of Nigeria. (2012). Nigeria Erosion and Watershed Management Project (NEWMAP) Project Appraisal Document. World Bank.

Fernandes, J., Bateira, C., Soares, L., Faria, A., Oliveira, A., Hermenegildo, C., ... & Teixeira, M. (2017). SIMWE model application for bank gully erosion modelling in Douro region (NW Portugal). Geophysical Research Abstracts, 19.

Foster, G. R. (1986). Understanding ephemeral gully erosion. Soil Conservation Society of America.

Heede, B. H. (1970). Morphology of gullies in the Colorado Rocky Mountains. Bulletin of International Association of Scientific Hydrology, 15, 79-89.

Imeson, A. C., & Kwaad, F. J. P. M. (1980). Gully types and gully prediction. KNAG Geografisch Tijdschrift, 14(5), 430-441.

Ionita, I., Niacsu, L., Petrovici, G., & Blebea-Apostu, A. M. (2015). Gully development in Eastern Romania. Carpathian Journal of Earth and Environmental Sciences, 10(4), 225-236.

Le Roux, J. J., & Sumner, P. D. (2012). Factors controlling gully development: Comparing continuous and discontinuous gullies. Land Degradation & Development, 23(5), 440-449.

Makaya, N. P., Zewdu, F., & Tegegne, M. (2019). Gully erosion susceptibility mapping in upper uMgeni catchment, South Africa. Journal of African Earth Sciences, 150, 1-12.

Meliho, M., Khattabi, A., & Mhammdi, N. (2018). Spatial assessment of gully erosion susceptibility using frequency ratio method in Ourika watershed, Morocco. Soil and Water Research, 13(4), 207-216.

Nachtergaele, J., Poesen, J., & Van Wesemael, B. (2002). Gravel mulching in vineyards of southern Switzerland. Soil and Tillage Research, 64(1-2), 147-156.

Oguchi, T. (2019). Principles of geomorphology: Thornbury revisited. Geomorphological Research, 58, 1-10.

Poesen, J., Nachtergaele, J., Verstraeten, G., & Valentin, C. (2003). Gully erosion and environmental change: importance and research needs. Catena, 50(2-4), 91-133.

Poesen, J. (1993). Gully typology and gully control measures. Soil erosion and conservation.

Poesen, J., Vandekerckhove, L., Nachtergaele, J., Oostwoud Wijdenes, D., Verstraeten, G., & van Wesemael, B. (2002). Gully erosion in dryland environments. In Bull, L. J., & Kirkby, M. J. (Eds.), Dryland Rivers: Hydrology and Geomorphology of Semi-arid Channels (pp. 229-262). Wiley.

Rahmati, O., Haghizadeh, A., Pourghasemi, H. R., & Noormohamadi, F. (2016). Gully erosion susceptibility mapping: the role of GIS-based bivariate statistical models and their comparison. Natural Hazards, 82(2), 1231-1258.

Saha, S., Roy, J., Arabameri, A., Blaschke, T., & Tien Bui, D. (2020). Machine learning-based gully erosion susceptibility mapping: A comparison among models. Remote Sensing, 12(3), 437.

Thornbury, W. D. (1968). Principles of Geomorphology. John Wiley & Sons.

Valentin, C., Poesen, J., & Li, Y. (2005). Gully erosion: Impacts, factors and control. Catena, 63(2-3), 132-153.

Vandaele, K., Poesen, J., Govers, G., & van Wesemael, B. (1996). Geomorphic threshold conditions for ephemeral gully incision. Geomorphology, 16(2), 161-173.

Vandekerckhove, L., Poesen, J., Oostwoud Wijdenes, D., Nachtergaele, J., Kosmas, C., Roxo, M. J., & de Figueiredo, T. (2000). Thresholds for gully initiation and sedimentation in Mediterranean Europe. Earth Surface Processes and Landforms, 25(11), 1201-1220.

Vanmaercke, M., Poesen, J., Van Mele, B., Demuzere, M., Bruynseels, A., Golosov, V., ... & Yermolaev, O. (2016). How fast do gully headcuts retreat? Earth-Science Reviews, 154, 336-355.

Yibeltal, M., Tsunekawa, A., Haregeweyn, N., Adgo, E., Meshesha, D. T., Akir, A. A., ... & Fenta, A. A. (2019). Morphological and empirical analysis of gully erosion features. International Soil and Water Conservation Research, 7(3), 258-267.

Zhang, X., et al. (2019). Rainfall intensity and gully erosion in semi-arid regions. Journal of Hydrology, 574, 1-12.