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Morphometric Analysis of Gullies in Amire Ukiriki Watershed Benue State, Nigeria

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ABSTRACT :

Morphometric analysis of a watershed greatly enhances the understanding of how drainage morphometry influences landforms, their characteristics and gully development potential. This study sought to analysed morphometric of gullies in Amire Ukiriki watershed of Benue State, Nigeria, to inform erosion control strategies focusing on determining the geometry of gully channels, analyzing watershed morphometric parameters, and examining their interrelationships. The study employed field measurements, GIS, and remote sensing techniques to assess gully dimensions (length, depth, width, slope angle, cross-sectional area and volume of material removed) on 15 selected gullies and Watershed parameters (linear, geometric, aerial and relief aspects of the River Amire Ukiriki Watershed) were derived from Digital Elevation Models (DEMs) via GIS and remote sensing techniques. Pearson's Product Moment Correlation was employed to evaluate relationships. Results revealed gullies with lengths ranging from 46–82m, depths of 3.6–10.6m, and cross-sectional areas of 30.24–268.18m², with U-shaped forms predominant (46.7%), indicating mature erosion stages. The watershed, classified as a 7th-order dendritic system exhibited mean bifurcation ratio (5.53), high drainage density (3.83 km/km²), stream frequency (21.54 streams/km²), and an elongated shape (elongation ratio=0.44), suggesting prolonged runoff and erosion susceptibility where geological structures control the basin's shape. Strong positive correlations ($r>0.895$, $p<0.01$) were found between gully depth, width, cross-sectional area, and soil volume removed (total 34,700.42m³), while gully length positively correlated with bifurcation ratio ($r = 0.884$). Watershed parameters such as stream frequency, drainage density, bifurcation ratio, elevation and slope are closely interrelated and impact how water is distributed across the landscape, thereby influencing erosion potential. These findings underscore the influence of drainage network complexity and slope on gully development. The study recommended the need for implementation of integrated watershed management plan focusing on reducing peak runoff and enhancing infiltration, including vegetative stabilization and structural interventions to mitigate erosion and enhance environmental sustainability in the study area.

Keywords: Morphometric Analysis, Gully Erosion, Watershed Management, Soil Erosion, Geospatial Analysis, Land Degradation, GIS and Remote Sensing, Amire Ukiriki Watershed, Benue State, Nigeria.

Introduction

Gully erosion is a major ecological problem in Nigeria, particularly in the north central region, including Benue state. Gully erosion is a serious form of soil erosion with geometric attributes of length, depth and width not easily ameliorated by simple farming implements, and has the characteristics of a large amount of sediment delivery in the watershed. During gully erosion development, a large amount of sediment is carried away, resulting in serious soil and water loss. The sediment yield dominated by gullies accounts for 10~94% of the total sediment yield in the basin (Yang *et al.,* 2021). Gully erosion is a major cause of land degradation in many drought prone regions of the world, including Nigeria and accounts for a large portion of the total soil loss at the catchment scale (Poesen *et al.,* 2021). Geomorphic characterisation of gully channels is important for determining gully head expansion rates and sediment budgets. The morphology of gully cross-sections (GCs) can be characterised by size parameters (average top and bottom width, maximum and mean depth, and surface area (Li *et al.,* 2020) and proportionality parameters (e.g., the ratios of width to depth, average top width to maximum depth, and bottom width to top width.

Furthermore, upslope morphologic parameters significantly influence the threshold of gully formation (Poesen *et al.,* 2021). The morphological characteristics of gullies not only support the law of erosion and sediment yield, but also include process of gully development and evolution (Zhao, 2020). Research on gully morphology mainly includes the following aspects such as the relationship between the morphological parameters in terms of gully area, length, depth, density and volume (Yang *et al.,* 2021). This also includes the form assumed by gullies, direction of gully development and, the topographic and geomorphological characteristics of gully development at a drainage basin scale.

Morphometric analysis of drainage basin indicates the mathematical and geometrical analysis of land surface characteristics such as configuration, shape and dimension (Bogale, 2021). Morphometry also involves the quantitative measurement and analysis of various parameters, such as elevation, slope, and other attributes that define the shape and configuration of landforms (Patel, 2023). It provides valuable insights into the physical qualities of soil, erosional features, and land processes. Notably, a comprehensive understanding of river drainage morphometry is particularly important in studying and interpreting gully morphometric parameters.

The drainage or river basin is a fundamental component of the landscape where water and sediment collection and distribution occur. It is distinct from other landscape elements such as "division" or "interfluves" (Shamkhi *et al,* 2020). Morphometric analysis is successfully carried out by measuring the linear, relief, aerial, and geometric properties of the drainage basin. Morphometry of a drainage basin provides insightful information and characteristics of its geological, morphological, geomorphological, and hydrological processes as well as, the complex interrelationship between parameters (Kant *et al.*, 2022). It also provides information about the slope and relief characteristics, rock hardness or softness of the drainage basin. The morphometric parameters and their complex interrelationship provide information about flooding potentials, sediment movement, erosion capability, surface runoff, and infiltration of drainage basin (Sarkar *et al.,* 2020).

The watershed morphometric parameters reflect the hydrological behavior of the river basin and are useful in evaluating the hydrologic response of the basin. There are relationships between watershed morphometric parameters and gully development potential. For instance, higher drainage density indicates faster runoff and a more significant degree of channel abrasion for a given quantity of rainfall. Rivers and fluvial processes are the most dominant geomorphic systems of earth's surface responsible for morphometric changes in drainage basin or the watershed (Yang, 2021).

Understanding and analyzing these parameters can provide valuable insights into the behavior and characteristics of water flow within a basin. Morphometric analysis holds significant importance in categorizing watersheds, providing quantitative data on the stream network, and facilitating hydrological research. The stream network plays a crucial role in comprehending landform processes, physical soil characteristics, and the state of land degradation (Collins *et al.,* 2021). By considering the area, linear, and relief features of drainage basins, the morphometric analysis of the stream system can be improved (Van-Oost *et al.,* 2022). Thorough morphometric analysis of a catchment greatly enhances the understanding of how drainage morphometry influences landforms and their characteristics. It provides valuable insights into the relationships between the drainage network and the overall landscape, enabling researchers and land managers to make informed decisions regarding watershed management, land use planning, and environmental conservation.

Remote Sensing (RS) approaches have emerged as powerful techniques for capturing and expressing various aspects of the current climate, structural characteristics, geomorphology, and geology of watersheds (Shekar *et al.,* 2023). Moreso, Geographic Information System (GIS) applications have proven to be highly effective, efficient, and well-suited for spatial analysis. GIS provides a robust platform for manipulating and retrieving large databases, enabling the handling of complex problems in morphometric analysis. With the introduction of computer technology, GIS has undergone automation, allowing for the management of massive datasets and the resolution of numerous intricate problems. Moreover, it facilitates data retrieval and querying processes (Shekar and Mathew, 2023).

In the year 2022, there has been a surge of research focusing on morphometric analysis utilizing GIS and RS. These studies have explored various applications of these technologies, highlighting their effectiveness in capturing, storing, analyzing and manipulating morphometric parameters. Examples of such works include those conducted by Caleb *et al.,* (2020), Shekar and Mathew (2022), Kandekar *et al.,* (2021), Sutradhar and Mondal (2022). The combination of GIS and RS in morphometric analysis allows for the comprehensive assessment of watershed characteristics.

These technologies provide a wealth of spatial data, enabling researchers to analyze and interpret the complex interactions between landforms, hydrological processes, and environmental factors. By leveraging the capabilities of GIS and RS, researchers can gain valuable insights into the morphology and behavior of watersheds, supporting informed decision-making in various disciplines related to water resources, land management, and environmental planning. Hence, studies of this nature cannot be overemphsised due to its importance in providing information needed to mitigate the impact of gully erosion in Amire Ukiriki watershed for analyzing morphometric parameters and enhanced environmental sustainability.

Gully morphometry analysis in watersheds is a critical aspect of understanding erosion dynamics and landscape evolution. Various studies have explored the relationships between gully morphology, watershed characteristics, and erosion processes. The key findings include: Gully dimensions (length, width, depth, volume) are strongly influenced by watershed topography, soil properties, and hydrological processes. High drainage density, slope gradient, and stream frequency increase gully formation risks.

Studies use morphometric indices such as bifurcation ratio, elongation ratio, and relief ratio to assess gully-prone areas. Satellite imagery and Digital Elevation Models (DEMs) have improved gully mapping and morphometric analysis. GIS-based models, such as the Revised Universal Soil Loss Equation (RUSLE) and Soil and Water Assessment Tool (SWAT), help in gully erosion prediction. Watershed hydrology plays a crucial role in gully development, with peak runoff and flow accumulation accelerating gully incision. Sediment yield from gullies significantly contributes to downstream sedimentation, impacting river systems and reservoirs. Changes in land cover (e.g., deforestation, agriculture expansion) influence gully evolution by altering runoff and infiltration. Climate variability, especially extreme rainfall events, exacerbates gully headward erosion and lateral expansion.

Most studies provide snapshots of gully morphometry rather than long-term monitoring, there is a need for time-series analysis to understand the progression of gully development under different climatic and land-use conditions. Many morphometric studies do not incorporate hydrological modeling to simulate runoff and sediment transport in watersheds. Coupling morphometric parameters with process-based models can improve predictions of gully erosion risks. While land-use changes are acknowledged, there is limited research quantifying the direct human impact (e.g., road construction, mining) on gully morphometry. More studies should assess how infrastructure development alters watershed hydrology and gully formation. Variations in data sources, measurement techniques, and classification schemes create inconsistencies in gully morphometry research. Standardized protocols for gully mapping and classification are needed for better comparisons across different watersheds. This clearly shows that there is dealt of literature in the aspect of gully morphometry in the Amire Ukiriki watershed. This study therefore seeks to fill the gap that exists in literature.

A. Problem Statement

Gully erosion is a serious environmental problem in different parts of the world, and it has been observed to pose significant risk to lives and properties in Amire Ukiriki watershed of Benue State, Nigeria. It has caused the destruction of farmlands, roads, buildings, infrastructure and animal death in the area; which rendered many households homeless, lost properties and made some of the roads impassable, thereby creating transportation challenges in the area (Ahile, 2019).

Studies have been carried out by researchers in several watersheds in relation to the study of gully erosion and drainage basin morphometric analysis. Bunmi *et al.* (2017) used DEM to analyze the morphometry of Asa and Oyun River Basins, North Central Nigeria focusing on quantifying morphometric parameters of the basin and reported that the basin was highly dissected and circular in nature which allowed runoff to be quickly removed from the watershed, thereby causing soil erosion downslope. Songu (2019) analysed morphometric parameters of the Kereke watershed in Benue State using GIS data and techniques and reported that the basin had moderate drainage density and length of overland flow which were found to have impacted the initiation of gully erosion in the area.

Aper and Hundu (2018) analysed Katsina-Ala watershed, using GIS data and techniques reported a strong influence of drainage dissection on fluvial processes in the watershed. Adelalu *et al*., (2019) investigated river Donga to characterise the watershed and assess its impact on fluvial processes such as soil erosion and flooding. They reported that the drainage basin was elongated and characterised with low runoff and longer duration of flow peaks, with minimal positive feedbacks on gully initiation in the watershed. In spite of the importance of assessing gully morphometry and drainage basin parameters, little or no attention has been given to study of gully morphometry in Amire Ukiriki watershed of Benue State, thereby creating paucity of data in literature. Better still, the processes operating in the gully channels resulting to the adjustments of the gully morphological parameters in the watershed which ought to be useful for gully control measures are also deficient in literature.

Moreover, the relationship between gully geometry and basin morphometric parameters of Amire Ukiriki which is helpful in understanding the dynamics of basin control on gully initiation at a drainage basin scale is also lacking in literature. It is against this backdrop that this study sought to analyse gully morphometry in Amire Ukiriki watershed with the purpose of providing information needed to bridge the observed gaps in literature and enhance gully control and sustainable environmental management in the study area.

The following research questions were used to summarize the research problems.

i. What is the geometry of gully channels in Amire Ukiriki watershed?
ii. What is the nature of the morphometric parameters of Amire Ukiriki watershed?
iii. What is the nature of the relationship between gully geometry and Amire Ukiriki watershed parameters?

B. Objective

The aim of the study is to analyse gully morphometry in Amire Ukiriki watershed of Benue State, North Central Nigeria. The aim was achieved through the following specific objectives to:

i. Determine the geometry of gully channels in Amire Ukiriki watershed.
ii. Analyse the morphometric parameters of Amire Ukiriki watershed.
iii. Examine the relationship between geometry of gully channels and Amire Ukiriki watershed parameters.

This research covers the entire river Amire Ukiriki watershed within Kwande and Ushongo Local Government Area of Benue State, North Central Nigeria. It treats the aspect of geometry of Gully catchment (Gully length, top width, bed width, depth nature, cross sectional area, gully slope angle and volume of material removed), Morphometric parameters of the watershed (stream order, stream number, stream length, stream length ratio (Rl), bifurcation ratio (Rb), drainage pattern, watershed area, drainage density (Dd), form factor (Rf), relief ratio (Rh) and basin Relief). Also, the relationship between dimensions of gully morphological parameters and Aamire Ukiriki watershed parameters were evaluated to ascertain the influence of the watershed parameters on gully development in the area. The research was conducted during September, 2024 to February, 2025 in order to measure the nature of morphological parameters of gullies in the catchment area.

This study on the analysis of gully morphometry in the Amire Ukiriki watershed of Benue State, North Central Nigeria, involves examining the physical characteristics and behaviour of gullies in the study area. Gullies are channels or grooves that are formed by the erosion of the land surface, typically as a result of water flow. By analyzing the morphometry of gullies, researchers can gain insights into the processes that contribute to their formation and evolution, the extent of the environmental impacts caused by gully erosion, such as the loss of fertile topsoil, the destruction of habitats, and the contamination of water sources as well as the factors that influence their behaviour over time.

The findings of the study would help identify areas that are at high risk of erosion. This information can be used to develop targeted conservation measures to protect these areas and prevent further erosion. The study can also provide valuable insights for land-use planning, as gully erosion can make certain areas unsuitable for agriculture or other land uses. By understanding the morphometry of gullies in the Amire Ukiriki watershed, this information can then be used to develop strategies for mitigating these impacts and protecting the study area's natural resources.

In addition, Gully morphometry helps in understanding the processes and factors contributing to gully erosion in the study area, the study will provides baseline data on the physical characteristics of gullies, such as their shapes, and distribution, understanding how they influence surface runoff, groundwater recharge, and sediment transport, which are crucial for water resource management and also improve the socio-economic well-being of local communities.

Moreover, this research is also expected to contribute to the development of sustainable land management practices and erosion control measures tailored to the specific conditions of the Amire Ukiriki watershed. Furthermore, the study will emphasize the need for integrated approaches that consider both natural and anthropogenic factors in order to develop effective erosion control and mitigation strategies for sustainable land management in the watershed and for future research on detailed morphological, geological and climatological investigation among others in the study area. Finally, the study will provide useful information that will improve the depth of literature on the subject matter and future studies.

Methodology

This section discusses the study area in terms of the location, climate, relief, drainage, rainfall, economic activities, population, soil, vegetation and land use. It also describes the data sources, method of data collection and the techniques used for data analysis. In order to meet objectives of the study, the methodology followed and the materials used are discussed in this chapter.

A. Study Area

The River Amire Ukiriki watershed extended to cover Kwande and Ushongo Local Government Area of Benue State, north central Nigeria. It is located between Latitude $6^{0}44'52''$N to $7^{0}5'35''$N and Longitude $9^{0}12'62''$E to $9^{0}22'31''$E. The River Basin is bounded to the North by Buruku and Katsina-ala L.G.A, to the West by Mbayegh District (Ushongo) L.G.A, to the East by Ikov District and kwande L.G.A and to the South by Kwande L.G.A. River Amire Ukiriki catchment is occupying a total land area of about 352.4422square kilometres. Figure 1 shows the map of the study area.

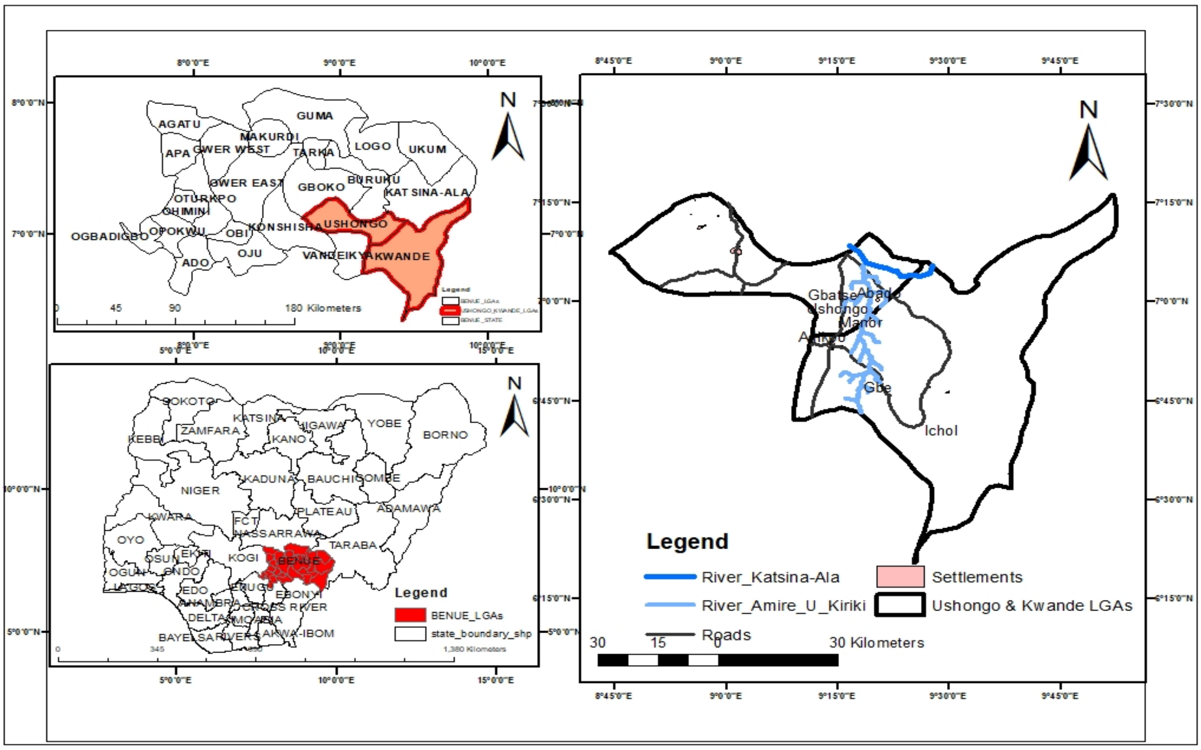

Figure 1: Study Area

The study area experiences tropical wet and dry climate classified as tropical savannah climate (Aw) under the Koppen's classification system. The watershed experiences two major seasons; rainy and dry. The wet season extends from April to October, characterized by significant rainfall, with average annual precipitation ranging between 100cm-200cm. The dry season spans from November to March, marked by minimal rainfall and lower humidity levels. The seasonal rainfall distribution in the area is uni-modal with the highest rainfall occurring in August and September (Tarhemba, 2019). Temperature of the area is generally high during the day throughout the year. Temperature fluctuations throughout the year are notable, with average temperatures ranging from 23°C to 38°C. The hottest months are typically March and April, while the coolest temperatures are observed in July and August. The relative humidity experienced in the area is higher during wet seasons and low during dry season. The study area receives abundant sunlight due to its location in the tropics. This also influences the conventional type of rainfall experienced in the area. Figure 2 shows the drainage map of the river Amire Ukiriki watershed.

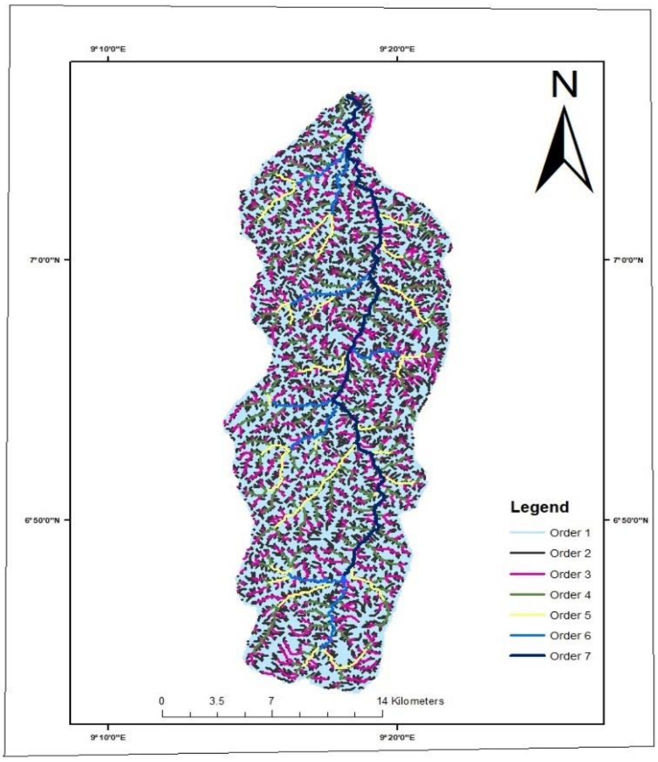

Figure 2: Drainage Map of River Amire Ukiriki Watershed

According to Ahile (2019), Amire Ukiriki watershed falls within the Ikyogen and Ushongo highland complex comprising ancient igneous, metamorphic and sedimentary rocks. This is a complex unit where there are angular plains with deeply incised valleys and a high relief. These sediments have undergone varying degrees of metamorphism and these sedimentary are underlined at variable depth by basement complex rocks. It is an area of basement complex rocks comprises of granites, porphyritic granites, migmatites, diorites, pegmatites, gneisses and fluoride salt. The geology of the area warranted soil of lithosols with thin layers of less than 10cm thick cover hard rocks that occur in the hilly terrain areas of steep slopes. These occur on the hills of Ushongo, and Mata hills respectively. Sedimentary materials are also found in downhill sides in the low-lying areas as well as fadama soils, smaller rivers, which develop in alluvial deposits of major streams flood plains of Amire Ukiriki, among others. The soil consists of various thin layers of sediments of different texture or particles derived from varied parent materials (comprising an assortment of clays, sand, gravels, and pebbles). This is seen in the flood plains of Umanor, Akenge, Uavande, Barazor, Uchor and Baa streams.

The study area lies within Ushongo and Kwande LGAs, the area is divided into two parts namely High areas and low land. Generally, the high terrain is characterised by steep and deep valleys with the gradient gently rising towards the hills in the south, west and eastern side ranging from 400m-1500m above sea level. The geology of the area is dominated by basement complex rocks, which are believed to have escaped the marine transgression of the cretaceous glaciations (Ahile, 2019). The low land consists of mostly of sand and alluvium that made up of the flood plain. River Amire Ukiriki is one of the promising tributaries of River katsina-ala in Benue State. This river transport rainwater with huge amounts of sediments through to river katsina-ala. River Amire Ukiriki took its source from the Sankwara hills in Obudu, Cross River State. It flows northward direction to other parts of the area with a volumetric flow remaining considerable even in the low water period. The tributary streams to the river catchment include Umanor, Akenge, Uavande, Barazor, Uchor, Baa and many other small streams that traverse the area and drain into river Amire Ukiriki. This makes these area water resources potential for socio-economic activities such as fishing, domestic purposes and irrigation agriculture.

The volume of water in this river and its tributaries is affected by the seasons with their full region obtained during the wet season, reaching their peaks in the months of August and September which often results to periodic flash floods. The volume of water drops with the setting in of dry season often leading to complete drying up of smaller streams. Surface draining is generally good and the flood plains found around the river form ideal sites for Fadama farming together with the ponds created by rivers. Also, the permanent water table in many parts of the study area is very low, due to thick overlying permeable sediments and the great depth to which weathering has reached. The drainage is deterministic of the cost of transportation and other land use in the area (Ahile, 2019).

The soils in the study area are mainly oxisols and ultisols (tropical ferruginous), which vary over space concerning texture, drainage, gravel content, etc. A typical profile is highly weathered with sandy surface layer overlying mottled clay subsoil. The varieties of soil types which vary from sandy to clay with lateralized surface or extensive duricrust sediments of clay and fine grained of coarse loosed sands which occur in the valleys and low plains. These soils because they develop on Precambrian rock which is known to be generally rich in clay, both the surface and in the sub-surface soil are generally sticky (Ahile, 2019). Along the flood plains of River Amire Ukiriki and its tributaries are very fertile soil reach in marine sediments that encourage rice cultivation. Lateritic ironstone is common everywhere except on the alluvium of the river flood plains. The soil of the area also varies significantly with altitude and on slopes. The soil materials are alluvium leaving shallow soil on the upper slopes. Soil usually found in valleys or depressions are better owing primarily to slope and water table. Thus, the pattern of soil distribution in this area shows a top sequence or catenaries' effect and soil parent materials. The agronomic significance of this subsoil crust is that it often produces a perched water table which is an important source of capillary water, which keeps the surface moist long after the end of the rainy season (Ahile, 2019).

The study area lies in the southern guinea savannah of Nigeria. Persistent clearance of the vegetation has led to re-growth of vegetation at various levels of seral development and more importantly parklands with grasses ideal for animal grazing during their early growth. These succulent grasses can be cut with machinery, dried and baled for dry season livestock feeding the grasses, however, grow very tall, coarse, and tough on maturity (Ahile, 2019). This vegetation although constitutes of both natural and man-made plants, the chunk of it particularly trees are natural, the scattered trees are mainly of economic value and include locust bean, shear butter, mango, silk cotton, African iron, Isoberlina, cashew, oil palm, oliveri, and gmelina. These trees produce valuable fruits, wood, and fibers which can be utilized for small scale cottage industries. Forest trees such as mahogany, obeche, and iroko are used as timbers. Other economic trees include African pear, bamboo, raffia palm, oranges and coconut (Ahile, 2019).

The area is most widely developed as farm lands characterized by scattered matured trees and undergrowth of shrubs and grasses, ideal for animal grazing during their early growth. The grasses however grow very tall, coarse and tough upon maturity; some of the species of grasses which are luxuriant such as gamba grass, spear grass, and elephant grass. These grasses have the ability to regenerate during the rainy season (Tarhemba, 2019). Around the hilly area, dense canopy vegetation occurs looking much like a tropical rainforest in terms of tree concentration and content. This heavy vegetation owes to the high incidence of rainfall in the area. This thick vegetation cover coupled with the rough terrain of this area can be investigated into ascertaining the infiltration level of this area (Tarhemba, 2019). This vegetation is of economic value to the dwellers in the area where the trees are used for fuel, raw materials, food and medicinal purpose housing construction and as well as hunting. Some of the forests have the following characteristics, vegetal diversity, ever green trees, dark and undergrowth interspersed with clearings, scanty litter (organic matter settling on the ground), presence of "strangler" creepers, presence of "buttresses" (that is, large wigged ribs at the base of trunks) and spindly roots in trees living in often-flooded areas (Ahile, 2019).

Population constitutes a vital component of the resource and development potential of any community, the size, rate of growth, spatial distribution, democratic structure and quality determine on the pattern of development. In 2006, the populations of Kwande and Ushongo local government areas were 248,697 and 188,341 peoples respectively. The figure increased to 359,000 and 277,100 (NPC, 2022). The figure is projected based on the 2006 population figure to be 387,228 and 298,528 in 2025 (NPC, 2025). The dominant tribe is the Tiv speaking people who are mostly farmers while Igbo and Hausa are business men. Table 1 shows the population size of Kwande and Ushongo LGAs with their projections. Source: National Population Commission (2006) and Projection (2020, 2025).

Table 1: Population

LGA	2006	2020 Projection	2025 Projection
Kwande	248,697	359,000	387,228
Ushongo	188,341	277,100	298,528
Total	**439,044**	**636,100**	**685,756**

The study area is occupied by the Tiv people and hence the soil in the forest zone is most productive, the inhabitant here involves in agricultural activities, which serve as a major source of food to the entire community and also in fishing because of the presence of river Amire Ukiriki. Agriculture practice is the dominant in the study area; the people are almost totally dependent on the cultivation of land as a means of livelihood, the fact that about 80% of the total populations of the study area make their living by farming (Ahile, 2019).

The type of agriculture practice in the area is dual in nature which means that the inhabitant practice both commercial and subsistence type of agriculture where they cultivate crop on the large scale for consumption and for sale to enable them cater for the other aspect of living which include buying cloths, payment of children's fees, kitchen ingredients, bathing soap as well as paying medical bills where possible (Ahile, 2019). The people of the area cultivate variety of crops some on the large scale and others on a relatively small scale. Some of the crops cultivated in the area on a large scale include; Ground nut, tomatoes, pepper, maize, sweet potatoes, yam, guinea corn, millets, rice and cassava. On the small scale, the people of the area cultivate the following crops on the small scale; Banana, plantain, greens, as well as some tree crops such as mangoes, orchard farm, Cashew nut and Pawpaw owing to the fertile land and favourable climatic conditions (Ahile, 2019). The presence of both river and streams which most of the inhabitant involve in fishing and hunting of animals in their nearby riparian forests as well as trading around road side.

In the study area, there are ideal markets that have their fixed days (5days) of operation that aid buying and selling of goods and services include Adikpo, Akerior, Ushongo, Ikyogen, Chor, Manor, Sati, Abado market among others. Traders come from different places to patronize the market with variety of goods, which is mostly patronized by the local communities. There are also road side shops that usually operate by the road side which people patronize them on daily bases. They are usually not organised but operate in patches of isolate site, which is mostly patronize by travelers. The pattern of settlement is a dispersed settlement that the people mostly settle in isolated homes while in the rural towns such as Adikpo, Akerior and Ushongo has nucleated settlements. Those living within the hilly areas of Ushongo hill engaged in quarrying of granites rocks and selling to aim their living. The people live a social life and they welcome every visitor at the community sometimes, offer a piece of land to people willing to settle temporary at the community (Ahile, 2019).

B. Research Design

The research design adopted in this study is quantitative research method with emphasis on field measurements and use of GIS and remote sensing techniques. In order to have general information about the morphometric parameters, a reconnaissance was conducted on the study area. Accordingly, three major stages of the river Amire Ukiriki watershed (upper, middle and the lower course) were selected based on areas affected by gully erosion.

Data Types and Sources

i. To achieve objective one, data needed is information on dimensions of gully parameters such as gully length (m), gully depth (m), gully shoulder width (m), slope angle (degree), gully bed width (m), shoulder width/depth ratio, shoulder width/bed width ratio, cross-sectional area (m^2) and volume of material removed by the gully catchment. The data was sourced from field measurements using survey equipment such as measuring tape, leveling staff and ranging poles.

ii. To achieve objective two, data required are quantitative information on morphometric parameters of Amire Ukiriki watershed such as local relief (m), relief ratio, total stream length (km), basin area (km^2), form factor, circularity ratio, elongation ratio, bifurcation ratio, basin length (m), basin slope gradient (degree), drainage intensity, drainage density (km^{-1}), drainage frequency and length of overland flow (km). This data was sourced from analyzing satellite imageries of the study area using GIS techniques. The DEM imageries were downloaded from USGS Earth Explorer website.

iii. To achieve objective three, data needed is information on the relationship between geometry of gully channels contained in objective (i) and Amire Ukiriki watershed parameters contained in objective (ii). The data was sourced from filed work, GIS techniques and the use of Pearson's Product Moment Correlation statistics.

The study sample comprises of 15 gullies selected among the 23 gullies in the watershed. Stratified sampling technique was considered to select 15 out of the 23 gullies within the watershed, 7 gullies from Ushongo and 8 gullies from Kwande Local Government Areas. Purposive sampling technique was then used to select four (4) gullies from each of the considered functional units of the catchment on the basis of the most intensive gullies identified during reconnaissance making up the sum of fifteen (15) gullies in the study area. Field method design and systematic sampling procedure was therefore used to collect data on the gully characteristics. The gully parameters like shoulder width, bed width, length, slope gradient, depth, and cross-sectional area were measured from the field using required survey equipment along each of the selected gullies.

To achieve objective one, data was being collected as follows: Gully Length was measured using the linen tape and ranging poles, starting from the gully head. It was measured at 20m interval. Another 20m stretch was taken from the ranging pole that marked the end of the first stretch, downstream the gully, again at the most center. This process continued to the mouth of the gully. This was done to determine the length of the gully channel.

Bed width and shoulder width were measured at each of the sampled points. 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 process was repeated at all the 15 sampled points. 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.

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 shoulder 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 noted where it met the tape. The pole was removed and measured (from the ground up to the point where it met the tape) and the reading recorded as the depth. The depth is essential in determining the extent to which the gully has been incised into the underlying geological materials.

Slope angles were measured using Abney level and leveling staff. 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.

The Shoulder width/bed Width Ratio was determined at all sampled points by dividing the values of the shoulder width by the bed width. The shoulder width/bed width ratio is important for determining the adjustment between the two cross sectional variables (bed and shoulder width) with the prevailing gully development mechanisms. Similarly, the Shoulder width/depth Ratio was determined at all sampled points by dividing the values of the shoulder width by the depth of the gully system at those points. The shoulder 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.

The Cross Sectional Area of the gully catchment was determined using a formula adopted by Ofomata (2000) in South Eastern Nigeria. The formula is given as:

$$A = w \times d \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eqn\ 1.$$

Where, A = Cross Sectional Area (m^2), w = shoulder width of the gully (m), d = depth of the gully (m).

The second objective was achieved by collecting data from satellite imageries using GIS techniques. Digital Elevation Model (DEM) was acquired directly from the USGS Earth Explorer website (link: https://earthexplorer.usgs.gov/). DEM provides more advantages in topographic data delineation.

To achieve objective three, data in objective one and two above were used to generate a correlation matrix using Pearson's Product Moment correlation statistics. This was used to evaluate the nature and strength of the relationship between the two variables and inferences was made.

Data Processing and Analysis

Data obtained was coded for analysis using Statistical Package for Social Science (SPSS), Microsoft Excel 2010 and ArcGIS 10.7.1. The objectives of the study were achieved as follow: the first objective was achieved through analysis using descriptive statistics (i.e. mean, standard deviation (S.D) and coefficient of variation to ascertain variation in the data set and the results were presented using tables. Mean was determined using the formula in Eqn 2, where $\sum \quad x$ is the sum of all the observation and n is the number of observations.

$$\sum \frac{x}{n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eqn\ 2.$$

Standard deviation was determined using the formula:

$$\sigma = \sqrt{\frac{\sum \quad (x_i - \mu)^2}{N}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eqn\ 3.$$

Where x_i is individual observation, μ is the mean and N is the number of observations.

Coefficient of variation was determined by dividing mean by standard deviation and multiplying by 100 as thus: CV=SD/μ×100

Where, CV is coefficient of variation, **μ**, is mean SD, standard deviation.

The second objective was achieved using the Geographic Information System (GIS) Techniques. The watershed boundary of river Amire Ukiriki and the stream network were automatically extracted from DEM using Hydrology tools of ArcMap 10.7.1 software. The morphometric parameters of linear, geometric, basin texture (aerial), relief characteristics are processed using spatial analysis tools and calculated by predetermined mathematical formulas. Automatic extraction techniques have been used for evaluating the morphometric parameters of the basin, that is, extraction of watershed boundary and extraction of drainage network of River Amire Ukiriki watershed. The Digital elevation model is the first input for morphometric analysis. The tiles of the elevation raster (DEM) has been extracted using data management function of Arc-tool box in ArcGIS 10.7.1 and the generated data was transformed from geographic coordinate system to projected coordinate system World Mercator. To ascertain compatibility, the catchment map of Nigeria, and political map of the catchment area were georeferenced to WGS1984 World Mercator. The shape-file of the basin was extracted from the Nigeria political catchment map through digitizing and was used to clip out the study area from the DEM to actual boundary limit and shape. The depression in the DEM was filled using the fill tool and was used to create the flow direction grid of the Basin. Flow direction grid holds values in its cells that indicate the direction of the steepest descent from each cell. This value determines the direction water will flow from each cell based on the underlying topography of the landscape. The Flow Accumulation Grid was processed to create the Stream Definition Grid. A threshold of the volume of flow (number of accumulating cells) that defines a stream in the project area was set. This helped in proper definition of the stream segments. The idea here is that the grid cells that accumulate runoff from a specified number of cells are considered to be the stream (flow route) cells. Strahler's system of classification designates a segment with no tributaries as a first-order stream. Where two first-order stream segments join, they form a second-order stream segment and so on. The sum of the length, and total number of the streams (linear aspect) were calculated with the help calculate geometry module of Arc GIS 10.7.1

The last objective was achieved using the inferential statistics such as Pearson's Product Moment Correlation Coefficient (PPMCC) analysis to examine the strength of the linear relationship between dimensions of gully parameters and Amire Ukiriki morphometric parameters. The correlation coefficient (r) is measured on a scale that varies from +1 through 0 to -1. When (r) is greater than zero, it indicates a positive relationship, while values less the zero signify a negative relationship. A positive relationship indicates that when the value of one variable increases, the value of the other also tend to increase while a negative relationship signifies that when the value of one variable increases, the value of the other variable tends to decrease. The Pearson's product moment correlation coefficient was determined using the formula:

$$r = \frac{\sum \quad (x_i - \underline{x})(y_i - \underline{y})}{\sqrt{\sum \quad (x_i - \underline{x})^2 \sum \quad (y_i - \underline{y})^2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . Eqn\ 4.$$

Where r = correlation coefficient, x_i = values of the **x**-variable in a sample, $\underline{x}$ = mean of the values of the **x**-variable, y_i = values of the **y**-variable in a sample, $\underline{y}$ = mean of the values of the **y**-variable.

Results and Discussion

This section presents the results obtained from the field and discussion with respects to the aim and objectives of the research work and linked with the literature reviewed.

A. Morphometry/Geometrical Parameters of Gully Catchments in Amire Ukiriki Watershed

In assessing the morphometric parameters of the gullies, field surveys measurements of gully morphology and hydraulic variables were carried out by the researcher using Global Positioning System (GPS), measuring tape, ranging pole, among others. The results presented in Table 2, and Figure 3 were obtained from river Amire Ukiriki watershed while Table 2 depicts the geographical coordinates of the fifteen (15) gullies locations within river Amire Ukiriki watershed and figure 3 shows the distribution of gullies within the watershed. Table 3 shows the morphometric of gullies obtained from the watershed based on the gully's location. Table 3 presents the morphometric characteristics of gullies assessed across fifteen distinct locations in river Amire Ukiriki watershed. The parameters evaluated include gully length (L), depth (D), bed width (BW), shoulder width (SW), slope angle (SA), derived morphometric ratios, and calculated values for cross-sectional area and volume of soil material removed. The results reveal significant variability across sites, indicating the complex nature of gully erosion processes.

Table 2: Coordinate Position of Gullies Locations within river Amire Ukiriki watershed

S/N	Gully Locations	Latitude (N)	Longitude (E)
1	Tse Baka	7.088835^{0}N	9.305156^{0}E
2	Gbinde	7.039529^{0}N	9.259631^{0}E
3	Ikpa-Jov	7.029681^{0}N	9.322678^{0}E
4	Tyotsar	6.981287^{0}N	9.323846^{0}E
5	Genger	7.024031^{0}N	9.289997^{0}E
6	Abado	6.966238^{0}N	9.345811^{0}E
7	Ityov	6.977429^{0}N	9.281666^{0}E
8	Manor	6.926259^{0}N	9.300976^{0}E
9	Usambe	6.907614^{0}N	9.265648^{0}E
10	Kuhe	6.813918^{0}N	9.329532^{0}E
11	Ichol	6.862325^{0}N	9.348197^{0}E
12	Gbe	6.842557^{0}N	9.293944^{0}E
13	Ada	6.794146^{0}N	9.284955^{0}E
14	Koti	6.783341^{0}N	9.258319^{0}E
15	Acha	6.783111^{0}N	9.324653^{0}E

Based on the result in Table 3, the gully lengths varied from 46 m (Manor) to 82 m (Abado), with a mean length of 60.27 m, suggesting moderate spatial development. Gully depths ranged between 3.6 m (Ikpa-Jov) and 10.6 m (Tyotsar) with a mean of 5.43m (>2m), while bed widths spanned from 3.4 m (Gbe) to 16.2 m (Tyotsar) with a mean of 5.82m (>3-5m), indicating significant variability geomorphological perspective showing active and advanced erosion. Figure 4 further explain the dimension of gullies across the study area. With the gully length ranging between 46-82m and the cross-sectional area ranging between 30.24-268.18m^2, Abado having the highest length of gully (82m) followed by Gbinde and Ityov (73m) and (73m) respectively. The shortest gully length was captured in Manor (46m), Tse Baka (47m) and Koti (48m) respectively. This reflects differences in erosion intensity likely governed by a combination of soil type, slope, vegetation cover, and land use practices, consistent with findings by Ahmed *et al*. (2022) and Eze & Okeke (2021) who identify the primary causes of gully erosion as land use change, climatic factors, geology, soil properties, vegetation and human activities. Tyotsar distinctly showed extreme gully development with the highest depth, bed width, and material removal (11,848.68 m^3), marking it as a hotspot of degradation.

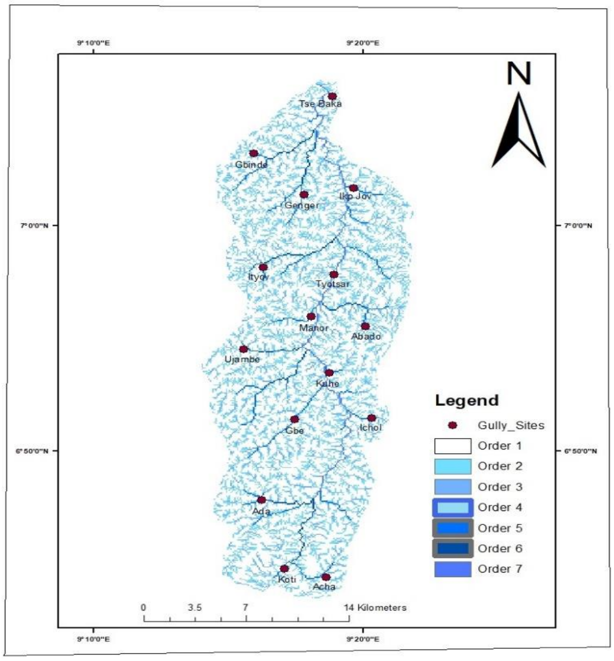

Figure 3: Watershed of River Amire Ukiriki Showing Locations of Sampled Gullies

Table 3: Morphometry of the Studied Gullies Based on Selected Locations.

S/N	Gully Site Location	Gully Length (GL) (m)	Gully Depth (GD) (m)	Bed Width (BW) (m)	Shoulder Width (SW) (m)	Slope Angle (SA) (0^0)	Shoulder Width/ Depth Ratio	Shoulder Width/ Bed Ratio	Cross Sectional Area SW×D (m^2)	Volume of Soil Material Removed GL×GD×BW (m^3)
1	Tse Baka	47	5.3	4.8	12.3	5	2.32	2.56	65.19	**1195.68**
2	Gbinde	73	5.2	3.7	9.5	4	1.83	2.57	49.40	**1404.52**
3	Ikpa-Jov	56	3.6	4.5	8.4	4	2.33	1.87	30.24	**907.20**
4	Tyotsar	69	10.6	16.2	25.3	8	2.39	1.56	268.18	**11848.68**
5	Genger	52	4.7	6.4	12.7	4	2.70	1.98	59.69	**1564.16**
6	Abado	82	7.2	8.6	13.7	6	1.90	1.59	98.64	**5077.44**
7	Ityov	73	6.3	6.2	10.4	3	1.65	1.68	65.52	**2851.38**
8	Manor	46	4.3	6.4	14.6	4	3.40	2.28	62.78	**1265.92**
9	Usambe	70	4.4	3.8	9.5	5	2.16	2.50	41.80	**1170.40**
10	Kuhe	49	4.7	3.5	8.2	1	1.74	2.34	38.54	**806.05**
11	Ichol	67	5.2	4.2	9.2	5	1.77	2.19	47.84	**1463.28**
12	Gbe	55	5.1	3.4	9.3	1	1.82	2.74	47.43	**953.70**
13	Ada	62	4.9	4.3	9.6	2	1.96	2.23	47.04	**1306.34**
14	Koti	48	5.4	7.6	12.5	6	2.31	1.64	67.50	**1969.92**
15	Acha	55	4.5	3.7	11.6	5	2.58	1.64	52.20	**915.75**
Total		904	81.4	87.3	176.8	63	32.87	31.39	1041.99	**34700.42**
Mean			5.43	5.82	11.79	4.20	2.19	2.09	69.47	**2313.36**
S. D			1.66	3.29	4.23	1.90	0.46	0.41	57.28	**2851.04**
CV%			30.66	56.52	35.87	45.18	21.22	19.46	82.46	**123.24**

Key: GL = Gully Length, GD = Gully Depth, BW = Bed Width, SW = Shoulder Width, SA = Slope Angle, 0^0= Degree,
SD = Standard Deviation, CV% = Coefficient of variation.

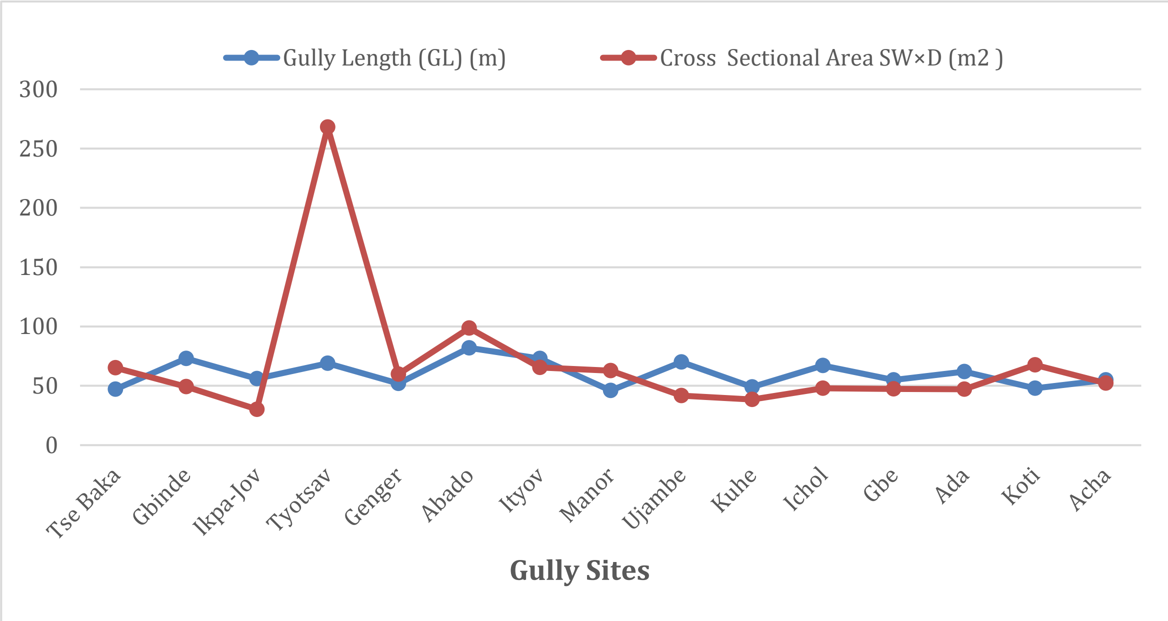

Figure 4: Gully Length and Cross-Sectional Area

The high standard deviation (SD = 3.29 for BW and 2851.04 for soil material removed) and coefficients of variation (CV% = 56.52% for BW; 123.24% for volume) confirm the heterogeneity of gully erosion across the landscape. The findings align with Nugroho *et al.* (2023), who emphasize that variability in geomorphic and hydrologic factors plays a dominant role in erosion patterns. These patterns also confirm and the findings from Zhou *et al.* (2022) and Ogbonna *et al.* (2021), who documented similar spatial heterogeneity in gully development due to topography, lithology, and anthropogenic influences. The high standard deviations and coefficients of variation (CV %), especially in material removed (CV = 123.24%), confirm the non-uniform and site-specific nature of gully development. This supports the assertion by Nasiri *et al.* (2021) that gully evolution is often driven by a mix of climatic, geomorphic, and land-use factors. Additionally, Chauhan *et al.* (2020), put it that the depth and width of gullies are closely linked to rainfall intensity and land disturbance, which accelerate subsurface flow and head cut migration. The substantial volume of material removed, exceeding 34,700 m^3, aligns with the work of Hou *et al.* (2023), who showed that gully heads are dominant sediment sources in severely degraded catchments.

B. Morphometric Ratios and Implications

The shoulder width-to-depth ratio (SW/D) and shoulder width-to-bed width ratio (SW/BW) provide insight into gully cross-sectional shape and stability. A higher SW/D ratio often suggests mature or stabilized gullies with lateral expansion, whereas lower ratios are indicative of active incision. The mean SW/D ratio of 2.19 and SW/BW ratio of 2.09 (Table 3) reflect intermediate development stages, consistent with Billi and Dramis (2021) who described transitional gully systems as those undergoing both vertical and lateral erosion. It also indicates that, on average, gullies are relatively wide compared to their depth, suggesting semi-stable or laterally expanding systems as described by Mensah and Appiah (2020). Zhao *et al.* (2023) found similar morphometric profiles in loess regions of China, where intermediate ratios were associated with moderate erosion risk and evolving gully morphology. Sites like Manor (SW/D = 3.40) exhibited wide, shallow profiles, potentially indicating mature or stabilized channels, while Kuhe (SW/D = 1.74) reflected an active erosive phase, supporting the theory proposed by Nyssen *et al*. (2020) that evolving gullies tend to deepen faster before widening. Table 4 shows the Gully Form and Magnitudes.

Table 4: Gull Form and Magnitude

S/N	Gully Site Location	Gully Form	Magnitude
1	Tse Baka	V and U Shape	Large
2	Gbinde	V Shape	Medium
3	Ikpa-Jov	V and U Shape	Small
4	Tyotsar	U Shape	Large
5	Genger	U Shape	Large
6	Abado	U Shape	Large
7	Ityov	U Shape	Large
8	Manor	U Shape	Medium
9	Usambe	V Shape	Small
10	Kuhe	V Shape	Small
11	Ichol	V Shape	Medium
12	Gbe	V Shape	Small
13	Ada	U Shape	Medium
14	Koti	U Shape	Large
15	Acha	V Shape	Large

From the results presented in the Table 4, and appendix (7) it was observed that gullies in the study area are characterised with U-shape, V-shape or V and U-shape cross sections, majority of gullies in the study area were U-shaped gullies. Explicitly, a total of 7 gullies in the study area were U-shaped gullies which indicates more mature erosion, where both vertical and lateral erosion have occurred, implying more matured degradation usually in wider valleys or areas with gentler slopes. Moreso, the results Table 4 revealed the presence of V-shaped gullies which generally signify active incision with minimal lateral erosion, often found in areas with high relief and poor vegetation cover, leading to deep, narrow cuts. Mixed profiles (V and U), as observed in Tse Baka and Ikpa-Jov, may indicate transitional phases, affected by temporal and spatial variability in rainfall and land use.

This discovery is in line with the work of Amare *et al.* (2022), who report that, gully cross-sections are shaped by underlying soil structure, slope gradient, vegetation, and land use. Tyotsar through Manor predominantly exhibit U-shaped profiles, supporting the idea of sustained erosional activity and possible anthropogenic influences (e.g., farming, overgrazing). U-shaped gullies often result from prolonged erosion processes, while V-shapes may indicate recent, aggressive channel incision. V-shaped gullies generally signify active incision with minimal lateral erosion, often found in areas with high relief and poor vegetation cover, leading to deep, narrow cuts. V-shapes at sites like Gbinde, Usambe, Kuhe, Ichol, Gbe, and Acha point to younger, actively deepening gullies. As supported by Nyssen *et al.* (2020), the shape of gully cross-sections is heavily influenced by slope gradient, soil cohesiveness, and

human disturbances such as deforestation and overgrazing. U-shaped gullies often develop in clay-rich soils where sidewall collapse increases lateral widening.

Similarly, the data present in (Table 4) shows that the magnitude of gullies found are small, medium or large gullies. It can be observed that from the entire gully sites covered in the study area, a total of seven (7) large gullies were recorded (e.g., Tse Baka, Tyotsar, Genger, Abado, Ityov, Koti, and Acha) are characterized by significant length, width, and depth. These indicate advanced degradation and greater environmental risk, including land loss and sediment yield. The largest gully is found in Tyotsar shoulder width of 25.3m, depth of 10.6m, bed width of 16.2m. Medium gullies (e.g., Gbinde, Manor, Ichol, and Ada) show moderate dimensions and possibly transitional states while Small magnitude gullies (e.g., Ikpa-Jov, Usambe, Kuhe, and Gbe) are more recent or occur in areas with protective vegetation or lower runoff intensity. As Chen *et al.* (2021) emphasize, large gully magnitudes are commonly linked to high-intensity rainfall events, bare soil exposure, and poor watershed management. Their presence signals a tipping point in soil erosion that must be addressed through mechanical and vegetative stabilization measures.

Table 5 presents data on the frequency and percentage distribution of gullies by magnitude and form, based on a total of 15 observed gullies. The result revealed that over half of the gullies with 53.3% representing 8 gullies are large while 26.70% representing 4 gullies are medium and 20.00% representing 3 gullies are small indicating dominance erosional features in the area. Smaller gullies are less frequent.

Table 5: Frequency and Percentage Distribution of Gullies by Magnitude and Form

Magnitude	Frequency	Percentage (%)	Gully Form	Frequency	Percentage (%)
Large	8	53.30%	V Shape	6	40.00%
Medium	4	26.70%	U Shape	7	46.70%
Small	3	20.00%	V& U Shape	2	13.30%
Total	15	100%	Total	15	100%

The results also reveal that out of fifteen gullies, 6 gullies representing 40% are V-shape form while 7 gullies representing 46.70% are U-shape and 2 gullies representing 13.30% are Combined V and U shapes show variability, appearing as both small and large, likely depending on the stage of development or local slope/soil conditions. The U-shaped gullies are slightly more common than V-shaped ones. The presence of gullies with combined characteristics (V & U) suggests variability in erosional processes or development stages likely influenced by environmental or land-use factors. U-shaped gullies tend to be larger, while V-shaped gullies tend to be smaller or medium in magnitude, which aligns with their typically narrower and incised form.

The slope angle (SA) is a crucial geomorphic parameter that influences both the initiation and evolution of gullies. In Table 3, the SA across 15 sites ranges from 1° to 8°, with a mean of 4.2° and a coefficient of variation (CV %) of 45.18%, indicating moderate variability among sites. Tyotsar, with a slope angle of 8°, corresponds to the highest values in gully depth (10.6 m), bed width (16.2m), and material removed (11,848.68 m³). This supports the observation by Wang *et al*. (2023) that steeper gully profiles tend to exhibit greater erosive power and sediment yield. Kuhe and Gbe, with the lowest slope angles (1°), exhibit relatively minimal material removal and cross-sectional areas, indicating subdued erosive activity, consistent with Bashir *et al.* (2021), who found that low-angle gullies tend to stabilize faster due to slower flow velocities and vegetation establishment. Sidorchuk (1999) proposed that slope influences whether gullies develop V-shaped or U-shaped cross-sections. Steep slopes often lead to V-shaped profiles due to dominant vertical erosion.

Recent studies have underscored the relationship between slope angle and gully morphology. Omar *et al.* (2024) emphasized that thresholds exist beyond which slope increases have diminishing or even destabilizing effects due to slope failure or sediment choking. According to studies by Poesen *et al.* (2022) and Valentin *et al.* (2019), steep slopes increase the velocity of surface runoff, promoting the detachment and transport of soil particles, thus accelerating gully formation. Also, Ayele *et al.* (2015) found that most gullies initiate on slopes greater than 15°, correlating with high runoff energy and weak soil cohesion While Frankl *et al.* (2021) observed in Northern Ethiopia that steeper slopes correlate with deeper and narrower gullies due to vertical incision dominance. In contrast, Castillo and Gómez (2016) in Spain showed that gentle slopes (5–10°) often lead to wider gullies with more lateral expansion.

Cross-sectional area and estimated volume of soil loss (L×D×BW) provide a quantitative basis for evaluating the severity of gully degradation. The highest cross-sectional area was captured in Tyotsar with (268.18 m²) followed by Abado (98.64 m²), Koti (67.50 m²) and Ityov (65.52 m²) respectively with a mean of 69.47m^2 SD of 57.28 and CV of 82.46% (Figure 4.2), Tyotsar, Abado, Ityov and Koti were among the most degraded. The total estimated soil loss from all gullies was 34,700.42m³ (Table 11), a catastrophic volume (>10,000m³), volume, implying extensive land degradation and potential threat to nearby infrastructure or farmland. These values serve as empirical evidence of geomorphic change, reinforcing calls for integrated watershed management, as emphasized by Okoroafor *et al.,* (2023) and (UNCCD) (2022). The cross-sectional area and volume of removed soil provide a quantitative basis for evaluating the severity of gully degradation. This pattern aligns with Oke and Adeoye (2021), who emphasized the critical role of gully morphology in predicting sediment yield and potential impacts on agricultural productivity. Chen *et al.,* (2023) also reported that cross-sectional area can act as a proxy for hydrological disturbance in semi-arid zones, where gully formation is a major contributor to land degradation. The mean material loss per site was 2,313.36 m³, underscoring the environmental and socio-economic threat posed by unchecked gully expansion. As highlighted by Egboka and Nwankwor (2022), such massive soil displacement contributes not only to land loss but also to increased downstream sedimentation and infrastructure vulnerability. Research by Okoroafor et al. (2023), UNCCD (2022), and Chen *et al.* (2023) emphasized the use of gully morphology as a predictor of environmental impact which strongly supports the need for integrated watershed management, gully control structures, and soil conservation practices.

C. Morphometric Parameters of Amire Ukiriki Watershed

According to the form and texture of the streams, the drainage pattern of the study area is dendritic pattern where the tributaries are joined to the main stream (River Amire Ukiriki) at an acute angle as shown in figure 5. This is the most common drainage pattern which resembles the twigs of the tree.

Subsurface geology, surface structure, slope, local topography, and terrain condition affects the formation and shape of drainage pattern in the watershed. Tassew *et al*, (2023), Wang *et al,* (2023), Hammouda and Mahmoud (2023). Figure 5 show the drainage pattern and stream order of River Amire Ukiriki Watershed.

The linear aspects of the River Amire Ukiriki Watershed were quantitatively evaluated using the formulas in the Arc GIS 10.7.1, the result of the linear features of the watershed analysed in this research is shown in table 6. The Stream Order (U) of River Amire Ukiriki watershed is identified using Strahler's (1952) ordering scheme and the result shows a classified seven-order watershed. From Table 14 above, a total number of 24061 streams joined the 7th order stream in which 19178 streams are 1st order, 4084 streams belong to the 2nd order, 603 streams fall under the 3rd order, 165 streams belong to the 4th order, 23 streams occupies the 5th order, 8 streams belong to the 6th order and the major trunk wish is River Amire Ukiriki a 7th order stream.

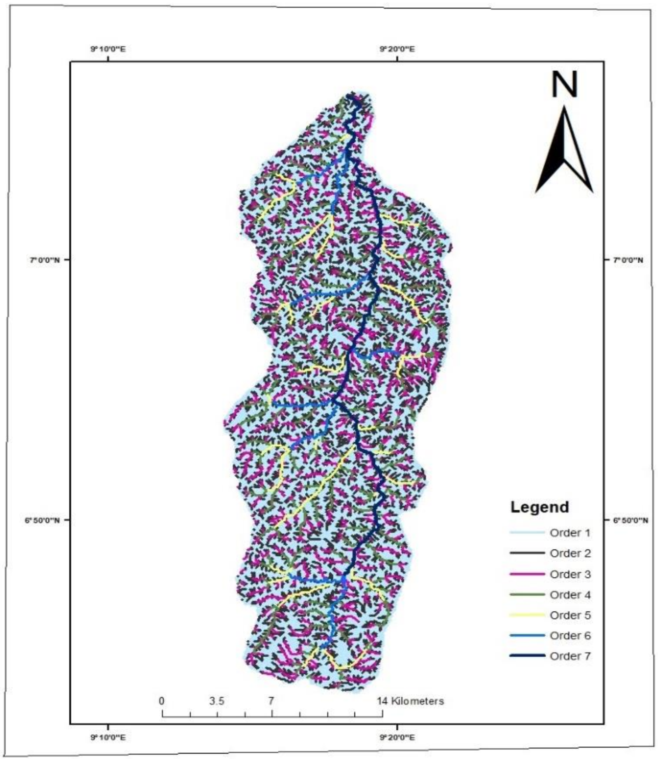

Figure 5: Stream Order of River Amire Ukiriki Watershed

The presence of a large amount of stream segments indicates that the basin is largely dominated by erosional processes (Tassew, 2023). The presence of higher amounts of lower-order streams in a river basin generates more water flow (Mahala, 2019) and by implication the large number of lower-order streams in the Amire Ukiriki watershed indicates its potential to be affected by flash floods during excessive rainfall. The lower-order streams are more dominated in the hilly areas in the watershed figure 5. The Total Stream Length (Lu) of the Amire Ukiriki watershed is 4264.31km. The length of the 1st order is 3754.39km, while 2nd streams occupied a total of 289.23km, 3rd order streams have 99.25km, 4th order stream have 34.81km, the 5th order stream have 28.33km while the 6th order stream have 18.46km and the 7th order have a total length of 39.83km as indicated in (Table 14).

Table 6: Linear Parameters of River Amire Ukiriki Watershed

Basin	Stream Order	Stream Number (Nu)	Stream Length (Lu) (km)	Mean Stream Length (Lsm) (km)	Stream Length ratio (RI)	Bifurcation ratio (Rb)	Mean Bifurcation ratio
	1st	19178	3754.39	0.20	-	4.70	5.53
River Amire	2nd	4084	289.23	0.07	0.08	6.77	
Ukiriki	3rd	603	99.25	0.16	0.34	3.65	
Watershed	4th	165	34.81	0.21	0.35	7.17	
	5th	23	28.33	1.23	0.81	2.88	
	6th	8	18.46	2.31	0.65	8.00	
	7th	1	39.83	39.83	2.16	-	
Total	7 Orders	24062	4264.31				

This is in conformity with the Horton's (1945) law of stream number which states that the numbers of streams of different orders in a given drainage basin tend closely to approximate an inverse geometric series. The steep slope in the high elevated areas in the Amire Ukiriki watershed produces numerous streams of lower order with short length. Stream length decreases with increasing stream order (Fig.5) and the lower order streams typically have high stream length. Longer streams in higher orders (particularly the 7th order) indicate increased channel efficiency and maturity, which aligns with Chaitanya *et al.* (2023) who argue that stream length is not only a function of order but also of lithological resistance and slope. The number is inversely correlated with stream order in a drainage basin (Horton, 1945). It is an indication that with the increment stream order, stream frequency tends to decrease. Figure 6 illustrates the correlation between stream order, stream number and stream length in the Amire Ukiriki watershed.

The Mean Stream Length (Lsm) of the watershed ranges from 0.20 km to 39.83km (Table 6). Mean stream length has a significant correlation with size and other inherent characteristics of stream networks. The surface of the watershed also has an influence on mean stream length (Strahler, 1964).

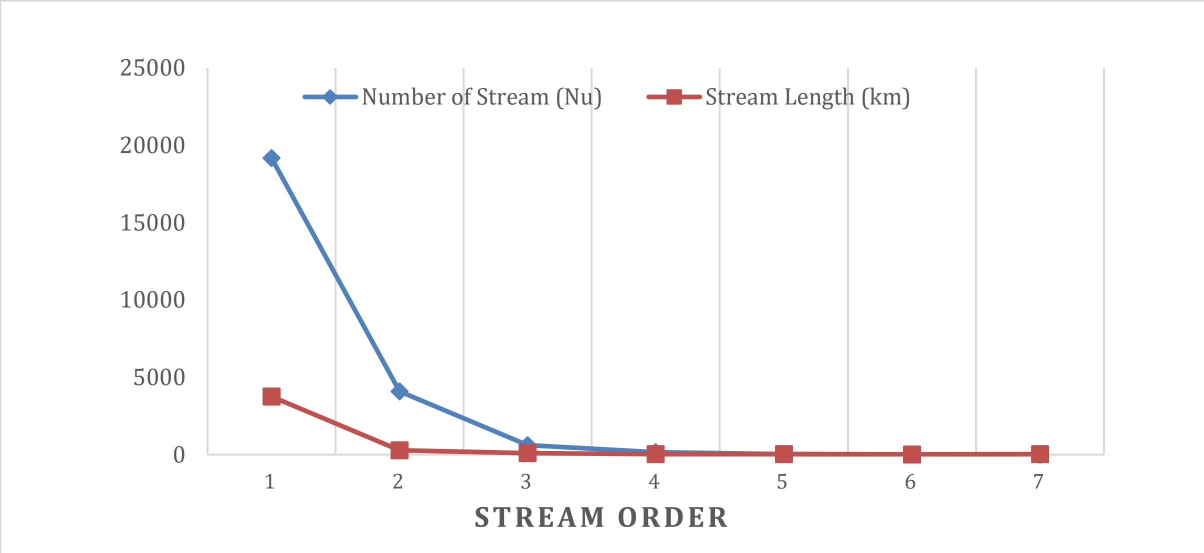

Figure 6: Interrelationship between stream order, stream number and stream length.

The low Lsm indicates higher runoff and high erosion in the basin area (Kumar, 2023). Furthermore, the Stream Length Ratio (Ri) of River Amire Ukiriki is found to be between 0.08 and 2.16, indicating a youthful stage of landscape development which is in agreement with the finding of Moges and Bhole (2015) that high variation in stream length ratio indicates the late youthful stage of the landscape development. These irregularities are often attributed to heterogeneous lithology, geological controls, and anthropogenic modifications such as land use change (Kumar *et al.,* 2020).

The Bifurcation Ratio (Rb) for the studied watershed ranges from 2.88 to 8.00 with a mean bifurcation ratio (Rbm) of 5.53 indicates an elongated basin where geological structures significantly control the basin's shape, resulting in a high degree of branching complexity and its coarse nature of the watershed. The Bifurcation ratio of individual orders varies between 3 and 5 as in table 1. However, Rb values tend to be higher in the 2nd order, 4th order and 6th order streams indicating accelerated erosion in the corresponding areas (Verstappen, 1983). Such high Rb values can also be linked to slope variation and basin asymmetry, indicating potential zones of structural complexity or steep terrain where stream branching is forced rather than freely developed.

Table 7 shows the aerial parameters of River Amire Ukiriki Watershed that were computed and generated from the ArcGIS 10.7.1 environment. It also shows that river Amire Ukiriki watershed occupies an area of 1116.87km^2 and its length is 43.25km with a very high stream frequency of 21.54 stream/km^2 indicating a high level of hydrological activities (See Table 2).

Table 7: Areal Parameters of River Amire Ukiriki Watershed

S/No	Areal Parameters	Values
1	Basin area	1116.87km^2
2	Basin Length	43.25km
3	Stream Frequency (Fs)	21.54 Stream/km^2
4	Drainage Density (Dd)	3.83km/km^2
5	Drainage Intensity (Di)	5.64 km/km^2
6	Constant of Channel Maintenance (C)	0.26
7	Form factor (Rf)	0.6
8	Circularity ratio (Rc)	0.68
9	Elongation ratio (Re)	0.44
10	Length of overland flow (Lof)	0.13
11	Shape Index (Sb)	1.67
12	Infiltration Number (In)	82.5
13	Shape factor (Sf)	1.68

A higher stream frequency value corresponds to more surface runoff, resistive subsurface material, and sparse vegetation (Obi *et al.,* 2002). Furthermore, drainage density of the study watershed is found to be 3.83km/km^2 indicating a fine texture while the streams are still relatively closely spaced, Fine-textured watersheds may occur in regions with moderately steep slopes and a moderately developed drainage network with weak and impermeable underlying

materials and scarce flora (Nautiyal, 1994). Imperatively, Climatic characteristics, vegetation coverage, rock and soil types, rainfall intensity, infiltration capacity, relief, run-off intensity, permeability terrain, slope has played vital role in controlling the drainage frequency and density (Figure 7).

Also, the drainage intensity of the River Amire Ukiriki watershed is 5.64 km/km^2 indicating highly efficient and well-developed drainage network with high surface runoff, highly vulnerable to flash floods and soil erosion, but slightly vulnerable to riverine floods (Das, *et al.,* 2021). High denudation process is active in the study area and the terrain affects the streams and erosional process (Das, *et al*, 2021, Ganie, 2022).

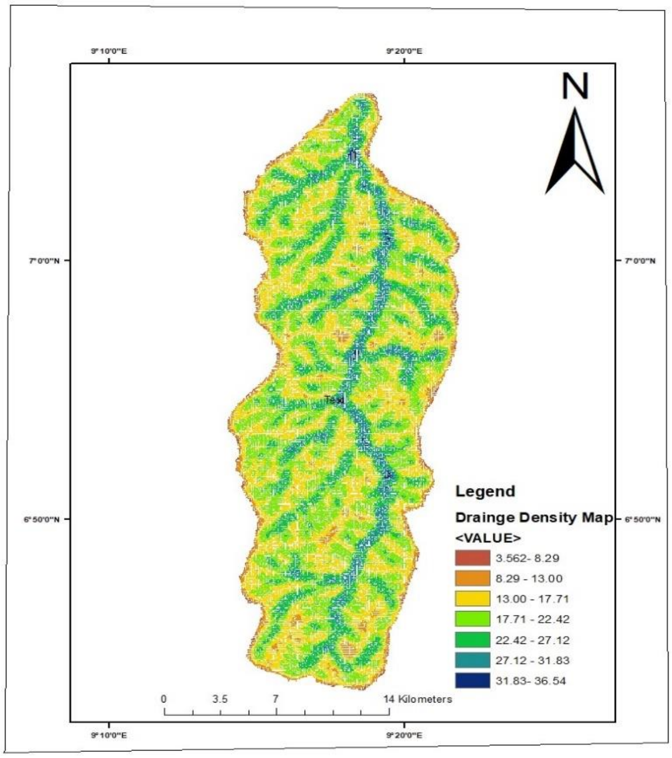

Figure 7: Drainage Density of River Amire Ukiriki Watershed

Drainage intensity varies spatially over the study area occurring either following the drainage line or along the areas with high elevation and steep slope. Moreso, the form factor for River Amire Ukiriki watershed is 0.6 which is in line with Gopinath *et al.* (2016) who opined that, a perfectly elongated basin has a form factor value of less than 0.75 indicating the basin is elongated in shape and have lower peak flows for longer duration.

Flood flows of such elongated basin are easier to manage than those of the circular basin (Altaf; Meraj; and Romsho, 2013). The circularity ratio of the basin under examination is found to be 0.68, According to Miller (1953), this value indicates there is a control of geologic material on stream development, and the watershed is elongated. In addition, the high, medium and low value of the Circularity ratio represents the youth, middle and old stages of stream development, respectively. The elongation ratio of the river is 0.44 which indicates that the watershed is elongated. Notably, a circular basin is more efficient in the discharge of runoff than an elongated basin (Singh and Singh, 1997).

Constant channel maintenance(C) is 0.26 indicating a higher potential for erosion and sediment movement, more erodible channels are the most vulnerable to erosion. Length of overland flow is 0.13 indicating lower distance runoff in the study area. The length of overland flow is affected by underlying geological, structural control, rock hardness, relief, water permeability and infiltration, erosional capacity, climatic condition, and vegetation pattern (Horton, 1945 Schumm, (1956). The high Lg value indicates that the rainwater had to travel a relatively longer distance before getting concentrated into stream channels (Chitra *et al.,* 2011).

Infiltration Number of 82.5 is significantly high, suggesting low infiltration capacity, high runoff, and potential flood hazards consistent with findings of Das and Sarkar (2024) in basaltic terrains. Finally, the study further revealed a shape factor of 1.68 indicating that the elongated shape of the basin tends to have a higher susceptibility to runoff and erosion. The relief parameters of River Amire Ukiriki Watershed were computed in ArcGIS 10.7.1 software and the findings are presented in Table 8.

Table 8: Relief Parameters of River Amire Ukiriki Watershed

S/No	Relief Parameters	Values
1	Basin relief	545m
2	Max Elevation	655m
3	Min Elevation	110m
4	Relief ratio (Rr)	0.015
5	Dissection index	0.83
6	Ruggedness number (Rn)	2.08

It also indicates that the highest relief in the study area is calculated to be 655m while the lowest relief is 110m above mean sea level. Thus, mean basin relief is discovered to be 545m above sea level. According to Thomas *et al,* (2010), rivers within the plateau-plain front generally have lower relief whereas; mountain-plain front rivers have high basin relief as also observed in the study area. The result also revealed that the relief ratio of the study basin is found to be 0.015. The low value of relief ratio in the study area indicates a high relief and high slope.

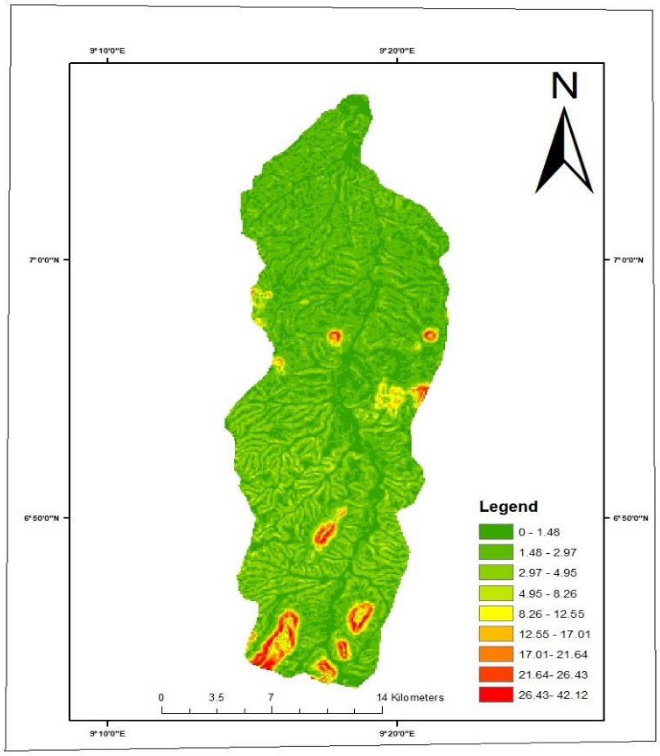

Figure 8: Slope Pattern of River Amire Ukiriki Watershed

This result is in line with the findings of Pareta and Pareta (2010) that areas with low to moderate relief and slope are characterised by moderate values of relief ratios which are mainly due to resistant basement complex rocks of the basin and low degree of slope. The result in figure 8 also shows that the index value of the study river is found to be 0.83 which indicates that the river is dissected and encourage vertical erosion. The Ruggedness Number of the basin is observed to be 2.08 which indicate that the watershed is steep and well-drained indicating vulnerable to significant runoff and erosion, and may require special management practices to control soil loss, sedimentation or flooding.

D. Relationship Between Gully Morphometric/Geometrical Parameters and Watershed Parameters

The results of correlation matrix in table 9, revealed reveal intricate relationships between gully parameters and the morphometric characteristics of the drainage basin. The results show that there is strong positive relationship between gully length and Bifurcation Ratio (Rb) ($r = 0.884$). This suggests that areas with a higher degree of branching in the stream network are associated with longer gullies. Bifurcation ratio reflects the complexity of the drainage network, and its influence on gully length likely relates to enhanced runoff concentration. Gully length shows a negative correlation with stream number (Nu) (-0.557) and stream length (SL) (-0.592) indicating that areas with more streams or longer streams tend to have shorter gullies, possibly because water is more evenly distributed and less likely to concentrate and erode a single channel. Also, a moderate correlation with drainage density (Dd) (0.435) and drainage intensity (Di) (0.548) suggesting that denser and more active drainage systems can affect gully length to some extent, though the relationship is not as strong as with Rb.

The result also shows that, gully depth and bed width ($r = 0.895$), gully depth and cross-sectional area ($r = 0.943$), gully depth and volume of soil material removed ($r = 0.965$), bed width and shoulder width (r =0 .946), bed width and cross-sectional area ($r = 0.953$), bed width and volume of soil material removed ($r = 0.953$), shoulder width and cross-sectional area ($r = 0.953$), shoulder width and volume of soil material removed ($r = 0.900$), cross-sectional area and material removed ($r = 0.980$) shows a very strong positive correlations and statistically significant ($p < 0.01$).

These very high correlations suggest that as gully depth, bed width, and shoulder width increase, the cross-sectional area and material removed also increase significantly. The gully geometry (depth and width) is tightly linked with the volume of material eroded. Depth is tightly linked with all other dimensions and erosion volume. As gullies deepen, they also widen and remove more soil.

Table 9: Pearson Correlation Coefficients between Various Gully Morphometric/Geometrical Parameters and Watershed Parameters

	GL	GD	BW	SW	SA	CSA	VMR	Nu	SL	Rb	Fs	Dd	Di	Slope	Elev	Lof	CCM	In	Sf
GL	1																		
GD	.476	1																	
BW	.248	.895**	1																
SW	.111	.838**	.946**	1															
SA	.282	.571*	.695**	.701**	1														
CSA	.284	.943**	.953**	.953**	.648**	1													
VMR	.435	.965**	.953**	.900**	.641*	.980**	1												
Nu	-.557	-.211	-.332	-.137	-.011	-.195	-.324	1											
SL	-.592	-.184	-.281	-.097	.017	-.164	-.289	.990**	1										
Rb	.884*	.697	.476	.439	.642	.523	.603	-.149	-.187	1									
Fs	-.517	-.338	-.442	-.243	-.062	-.273	-.400	.896**	.835*	-.147	1								
Dd	.548	.272	.286	.094	-.093	.122	.254	-.722	-.654	.212	-.932**	1							
Di	-.508	-.210	-.316	-.115	.067	-.148	-.277	.935**	.890**	-.077	.985**	-.908**	1						

Slope	.051	-.015	.109	.080	-.243	-.046	-.007	-.596	-.528	.250	-.849*	.983**	-.821*	1					
Elev	-.524	-.251	-.223	-.047	.166	-.076	-.197	.622	.555	-.226	.865*	-.986**	.839*	.997**	1				
Lof	.405	.232	.201	.240	.358	.266	.276	-.287	-.392	.575	.045	-.253	-.014	-.344	.340	1			
CCM	-.429	-.264	-.282	-.152	.187	-.184	-.256	.770*	.751	-.040	.837*	-.820*	.862*	-.774*	.816*	.000	1		
In	-.487	-.586	-.534	-.562	-.761*	-.547	-.577	.113	.143	-.902*	.064	.034	.010	.081	-.114	-.707	-.137	1	
Sf	-.306	.277	.486	.458	.499	.370	.365	.023	.149	-.180	-.259	.213	-.134	.177	-.156	-.439	.135	-.135	1

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Key: GL = Gully Length, GD = Gully Depth, BW = Bed Width, SW = Shoulder Width, SA = Slope Angle, CSA=Cross Section Area, VMR = Volume of Soil Material Removed, Nu = Stream Number, SL = Stream Length, Rb = Bifurcation ratio, Fs = Stream Frequency, Dd = Drainage Density, Di = Drainage Intensity, Slope, Elev = Elevation, Lof = Length of overland flow, CCM = Constant of Channel Maintenance, In = Infiltration Number, Sf = Shape factor.

By implication, the internal geometry of gullies is highly interdependent and largely shaped by slope conditions and erosion intensity. The volume of soil material removed (VMR) shows a moderate positive correlation with bifurcation ratio (Rb) (0.603) and drainage intensity (Di) (0.254) indicating that a denser drainage network and more intense drainage systems may lead to more runoff, which can erode and remove more material. However, the relationship is not strongly significant, suggesting that VMR is also influenced by soil type, land cover, and rainfall. VMR also shows a negative correlation with stream number (-0.324) and stream length (-0.289) implying that more distributed runoff (many streams) may reduce the concentration of flow and thus reduce the volume of material removed by gullies.

Stream Number (Nu) shows a strong positive correlation with stream length (SL) (0.990), stream frequency (Fs) (0.896) and drainage density (Dd) (0.935). This suggests that as the number of streams increases, the total stream length also tends to increase and higher frequency and denser networks have more streams leading to higher drainage density. Drainage Density (Dd) also shows a strong positive correlation with stream frequency (Fs) (0.985) suggesting that areas with high drainage density tend to have a higher number of streams, slope (0.983), indicating that as slope increases, drainage density tends to increase strongly suggesting Steeper slopes facilitate gravity-driven processes, such as runoff and erosion, which contribute to the development of drainage networks implying drainage density is a strong control on hydrological and erosional response while strongly negative with drainage intensity (Di) (-0.908) suggesting that areas with high drainage densities have more efficient drainage network leading to lower drainage intensity.

Elevation shows a very strong positive correlations with slope (0.997), drainage intensity (0.839), stream frequency (0.865), constant of channel maintenance (0.816) suggesting that as elevation increases, slope, drainage intensity, stream frequency and the constant of channel maintenance tends to increase due to increased runoff and erosion at higher elevations, formation of more streams and rivers at higher elevations ad might indicate that higher elevations require more maintenance to sustain channels. Elevation plays a significant role in shaping drainage-related variables, such as drainage intensity, stream frequency. While elevation show an extremely strong negative correlation with drainage density (-0.986) indicating that as elevation increases, drainage density tends to decrease strongly implying that as higher elevations significantly influence drainage density in the study area especially in matured terrains. Slope is a central factor influencing both gully dimensions and drainage properties, acting as a control for erosion potential and flow velocity.

Summary and Recommendations

This section succinctly gives a summary of the entire study and makes recommendations accordingly, and issues suggestions based upon the outcomes of the research findings for better decision making as the case maybe.

A. Summary

Gully erosion is a very serious environmental issue in the region leading to land degradation, loss of farmland, and infrastructure damage. Gullies are caused by a variety of factors, including heavy rainfall, flooding, landslides, agricultural activities, deforestation, overgrazing construction among others. At a watershed/catchment scale, slope gradient and slope aspect as well as altitude/elevation are the key factors for the formation of these gullies. The rapid development of remote sensing and spatial information processing techniques enables a quantitative evaluation for the contribution of these factors to gully erosion.

The study analyzed gully morphometry in the Amire Ukiriki watershed of Benue State, North Central Nigeria, focusing on the geometry of gully channels, morphometric parameters of the watershed, and the relationship between gully geometry and Amire Ukiriki watershed characteristics. The research employed field measurements, GIS, and remote sensing techniques to assess gully dimensions (length, depth, width, slope angle, cross-sectional area and volume of soil material removed) and watershed morphometry (stream order, drainage density, bifurcation ratio, among others).

The data needed for the study were information on dimensions of gully parameters and quantitative information on morphometric parameters of Amire Ukiriki watershed including linear, arial and relief were sourced from analyzing satellite imageries of the study area using GIS techniques. The results of dimensions of gully parameters and information on morphometric parameters of Amire Ukiriki watershed were subject to simple descriptive statistics of tables, mean, standard deviation and coefficient of variation to ascertain variation in the data set and inferential statistics of Pearson's Product Moment Correlation Coefficient analysis to examine the strength of the linear relationship between dimensions of gully parameters and Amire Ukiriki morphometric parameters.

The study revealed significant variability in gully dimensions, with U-shaped gullies dominating, indicating mature erosion. The watershed exhibited a dendritic drainage pattern, high stream frequency, and elongated shape, contributing to erosion susceptibility.

B. Major Findings

Gullies varied in length (46–82 m), depth (3.6–10.6 m), and cross-sectional area (30.24–268.18 m²). U-shaped gullies were predominant, suggesting advanced erosion stages. High volumes of material loss (up to 11,848.68 m³ per gully) were recorded, with Tyotsar being the most degraded. The total estimated volume of materials removed from all gullies was 34,700.42m³, a significant volume, implying extensive land degradation and potential threat to nearby infrastructure or farmland. These values serve as empirical evidence of geomorphic change, reinforcing calls for integrated watershed management. The mean material loss per site was 2,313.36 m^3, underscoring the environmental and socio-economic threat posed by unchecked gully expansion.

The drainage pattern is dendritic composed of 24062 streams where most of the streams are lower orders. The River Amire Ukiriki watershed is categorized as 7th-order system. The length of the lower-order streams is higher than higher-order streams. High drainage density (3.83 km/km²) and stream frequency (21.54 streams/km²) indicated intense hydrological activity and erosion risk. The elongated shape (elongation ratio = 0.44) and low circularity ratio (0.68) suggested structural control over drainage and prolonged runoff. The mean bifurcation ratio of (5.53) indicates an elongated basin where geological structures significantly control the basin's shape, resulting in a high degree of branching complexity and its coarse nature of the watershed.

Also, the drainage intensity of the watershed (5.64 km/km^2) indicating highly efficient and well-developed drainage network with high surface runoff, highly vulnerable to flash floods and soil erosion, but slightly vulnerable to riverine floods. And the Infiltration Number of 82.5 is significantly high, suggesting low infiltration capacity, high runoff, and potential flood hazards and gully erosion. Finally, The Ruggedness Number of the watershed (2.08) reviewing a steep and well-drained indicating vulnerable to significant runoff and erosion, and may require special management practices to control soil loss, sedimentation or flooding.

The relationship between gully and watershed parameters reveals that, gully length shows a strong positive correlation with bifurcation ratio (Rb) (r = 0.884), higher branching in drainage networks leads to longer gullies due to increased runoff concentration but negative correlation with stream number (nu) (-0.557) and stream length (SL) (-0.592) implying more streams distribute water, reducing concentrated erosion and shortening gullies and moderate positive correlation with drainage density (Dd) (0.435) and drainage intensity (Di) (0.548) suggesting denser drainage systems moderately influence gully length.

Gully Geometry shows a very strong positive correlations ($r > 0.895$, $p < 0.01$) between gully depth, bed width, shoulder width, cross-sectional area, and volume of soil material removed implying that gully expansion (deepening/widening) directly increases erosion volume while slope and erosion intensity shape gully morphology. Gully depth, width, and volume are controlled more by local terrain features, especially slope and slope angle. Gully length is influenced more by the overall structure of the drainage basin, especially stream bifurcation.

Stream number (Nu) strongly correlates with stream length (SL) (0.990), stream frequency (Fs) (0.896), and drainage density (Dd) (0.935 implying that more streams increase total length and drainage density. Drainage density (Dd) strongly correlates with stream frequency (Fs) (0.985) and Slope (0.983) suggesting steeper slopes intensify drainage density. Elevation Strong positive correlations with slope (0.997), drainage intensity (0.839), stream frequency (0.865), and constant of channel maintenance (0.816) suggesting higher elevations increase runoff, stream formation, and channel maintenance needs. Elevation inversely affects drainage density but enhances stream formation and erosion intensity at higher altitudes. Morphometric parameters such as stream frequency, drainage density, and bifurcation ratio are closely interrelated and impact how water is distributed across the landscape, thereby influencing erosion potential.

C. Contribution to Knowledge

1. The study provides detailed field-based and GIS-supported measurements of gully dimensions in the Amire Ukiriki watershed, making the work an important reference point for understanding erosion dynamics.
2. The research delineates the Amire Ukiriki watershed as a 7th-order dendritic system with high drainage density, stream frequency and an elongated shape, highlighting its susceptibility to prolonged runoff and erosion influenced by geological structures. This adds to the understanding of how linear, areal, and relief aspects interact to control fluvial processes in elongated basins.
3. It demonstrates how watershed parameters influence erosion potential and water distribution, filling gaps in literature on the interplay between gully geometry and basin-scale morphometrics.
4. By integrating field measurements with GIS and remote sensing (e.g., DEM-derived parameters), the study exemplifies a robust, replicable approach for assessing erosion in data-poor areas, enhancing tools for hydrological and geomorphological analysis.
5. It recommends an integrated watershed management strategy that contributes to sustainable land-use planning, erosion mitigation, and environmental policy in erosion-prone regions.

D. Recommendations

1. There should be implementation of vegetative stabilization (agro forestry, grass planting) and structural interventions (channelization, check dams, terraces) in high-risk areas.
2. Promotion of sustainable land-use practices, such as contour farming and reduced tillage, to minimize runoff.
3. Development of a comprehensive watershed management plan focusing on reducing peak runoff and enhancing infiltration.
4. Prioritization areas with high drainage density and stream frequency for targeted conservation efforts.
5. Strengthening policies on land-use planning and enforcement of soil conservation practices.
6. Raising awareness among local communities about gully erosion risks and mitigation strategies.

E. Suggestions for Further Research

Based on the limitations identified in the studies such as challenges with field measurements due to rough terrain, financial limitations knowledge gaps in literature specific to the Amire Ukiriki watershed and the need for more detailed investigations, the following suggestions for future research are proposed. To conduct long-term monitoring of gully evolution and sediment yield, investigate the role of climate change in altering rainfall patterns and erosion dynamics, detailed Investigation into the geological structures, soil properties and their interactions with morphometric parameters in greater depth, examine the role of human activities, such as land use changes, agricultural practices, deforestation and urbanization, in exacerbating gully erosion.

Conclusion

The study highlights the severe impact of gully erosion in the Amire Ukiriki watershed, driven by geomorphic, climatic, and anthropogenic factors. The dendritic drainage network and elongated basin shape exacerbate erosion, while U-shaped gullies indicate long-term degradation. The values of Amire Ukiriki watershed parameters revealed that the basin is at youthful stage of landscape development and hence, erosion and sediment yield processes are expected to be high. Gully erosion depends on drainage network structure (bifurcation ratio, stream number, and drainage density), slope, and elevation. Concentrated flow (high bifurcation ratio, low stream number) increases gully length and erosion, while dispersed flow (high stream number, stream length) reduces it. Steeper slopes and higher elevations intensify drainage activity. Soil loss is highest where gullies deepen and widen, emphasizing the need for erosion control in such areas. The findings underscore the need for integrated watershed management to mitigate erosion and protect livelihoods.

REFERENCES

- Abdeta, G.C., Tesemma, A.B., Tura, A.L., & Atlabachew, G.H., (2020). Morphometric analysis for prioritizing sub-watersheds and management planning and practices in Gidabo Basin, Southern Rift Valley of Ethiopia. *Appl Water Sci*. 10, 158. https://doi.org/ 10.1007/s13201-020-01239-7.
- Adebola, A. O., (2022). Geospatial assessment of morphometric parameters and gully erosion susceptibility in Ogun River Basin, Southwestern Nigeria. *Environmental Challenges*, 8, 100543.
- Adelalu, T. G, Yusuf, M.B, Ibrahim A, & Idakwo V. I, (2019). Morphometric Analysis of River Donga Watershed in Taraba State Using Remote Sensing and GIS Techniques. *International Journal of Geography, Environment and Earth Science 20(3):1-13,2019; Article no. JGEESI.48219 ISSN: 2454-7352*
- Abdulfatai, I. A., (2023). Impact of gully erosion on agricultural productivity and rural livelihoods. *Journal of Soil and Water Conservation*, 78(2), 150-162.
- Ahile, O.J. (2019). Assessment of soil physical characteristic for crop production around Ushongo hills in Benue State, Nigeria. *Journal of Geography and Development* 8(1):881-891.
- Ahmed, S., Musa, T. A., & Yakubu, Y. (2022). Gully erosion dynamics and control strategies in semi-arid environments. *Journal of Environmental Management*, 306, 114546.
- Amare, T., Demissie, S. A., & Hurni, H. (2022). Gully morphology and dynamics under changing land use systems in the Ethiopian highlands. *Catena,* 211, 105939.
- Anderson RL, Rowntree KM, &Le Roux JJ (2021). An interrogation of research on the influence of rainfall on gully erosion. *CATENA. Volume 206, 105482*, ISSN 0341–8162. https://doi.
- Asemakaha S, Johnson O M, Achagh V, & Solomon G. (2024). Effect of External Geomorphic Process on Ushongo Hills and its Environs, Ushongo Local Government Area of Benue State. *International Journal of Research Publication and Reviews,* Vol 5, no 3, pp 6240-6246 www.ijrpr.com ISSN 2582-7421
- Ayodele O.O. (2020). Geological assessment of landslide occurrences in the Okemesi area, southwestern Nigeria. *Journal of African Earth Sciences, 166, 103744.*
- Bartley R, Poesen J, Wilkinson S, & Vanmaercke M (2020). A review of the magnitude and response times for sediment yield reductions following the rehabilitation of gullied landscapes. *Earth Surf Process Landf 45(13):3250–3279. https:// doi. org/ 10. 1002/ esp. 4963*
- Bayik, C., Becek, K., Mekik, C., & Ozendi, M., (2018). On the vertical accuracy of the ALOS world 3D–30m digital elevation model Remote Sens. Lett. 9 (6), 607–615. Bharath,
- Bello, N. J., & Aina, Y. O. (2022). Morphotectonic indices and their implications for drainage evolution in the Chad Basin, NE Nigeria. *Nigerian Journal of Environmental Sciences and Technology*, 6(1), 12–25.
- Billi, P., & Dramis, F. (2021). Gully erosion processes and modeling in Mediterranean environments. *Geomorphology*, 385, 107696.
- Bogale, A., (2021). Morphometric analysis of a drainage basin using geographical information system in Gilgel Abay watershed, Lake Tana Basin, upper Blue Nile Basin, *Ethiopia. Appl. Water Sci. 11, Issue 7.*
- Borrelli, P., & Gupta S. (2023). Global soil erosion models: State of the art and new perspectives. *Earth-Science Reviews, 228, 103997.*
- Borrelli, P. (2020). "Land use and climate change impacts on global soil erosion by water (2015-2070)". *Proceedings of the National Academy of Sciences. 117 (36): 21994–22001. ISSN 0027-8424.*
- Bunmi MR, Yusuf OM, &Oladapo AI (2017). Morphometric Analysis of Asa and Oyun River Basins, North Central Nigeria Using Geographical Information System. *5*(6), 379–393. *https://doi.org/https ://doi.org/10.11648 /j. ajce.20170* 506.20
- Çadraku, H., (2023). Morphometric analysis of Llap River watershed (Kosovo). *Roman. J. Geography 67 (1), 33–49.*
- Castillo, C., Pérez, R., James, M. R., Quinton, J. N., Taguas, E. V., & Gómez, J. A. (2022). High-resolution topographic modelling of gully evolution: Integrating UAV photogrammetry and hydrological thresholds. *Geomorphology, 413, 108348.* `DOI: 10.1016/j.geomorph.2022.108348`
- Castillo, C., Pérez, R., James, M. R., Quinton, J. N., Taguas, E. V., & Gómez, J. A. (2020). Comparing the accuracy of several field methods for measuring gully erosion. *Soil Science Society of America Journal,* 84(4), 1120-1135.
- Chen, H., Wang, Y., & Zhang, J. (2023). Quantitative morphometric analysis of gully evolution under changing climate. *Land Degradation & Development*, 34(2), 276–289
- Choudhari, P.P., Nigam, G.K., Singh, S.K., & Sapana (2018). Thakur Morphometric based prioritization of watershed for groundwater potential of Mula river basin Maharashtra, *India. Geol., Ecol. Landscapes 2* (4), 256–267.

- Choudhari, P.P., Nigam, G.K., Singh, S.K., & Thakur, S., (2018). Morphometric based prioritization of watershed for groundwater potential of Mula river basin, Maharashtra, *India. Geol., Ecol. Landscapes* 2 (4), 256–267. https://doi.org/ 10.1080/24749508. 2018.1452482. Clarke, J.I., 1966. *Morphometry from maps. Essays in geomorphology.*
- Chowdhuri, I.; Pal, S.C.; Saha, A.; Chakrabortty, R.; &Roy, P. (2021) Evaluation of different DEMs for gully erosion susceptibility mapping using in-situ field measurement and validation. *Ecol. Inform*. 2021, 65, 101425.
- Collins, A. L., Zhang, Y., &Duethmann, D. (2021). The role of soil erosion in water quality deterioration. *Hydrological Processes*, 35(10), e14248. doi:10.1002/hyp.14248
- Dagar J.C. (2018) Ravines: formation, extent, classfication, evolution and measures of prevention and control. In Dagar, J. C., Singh, A. K. (Eds.), Ravine lands: *greening for livelihood and environmental security. https:// doi. org/ 10. 1007/ 978- 981- 10- 8043-2_2*
- Das B., Singh S., Jain S.K., &Thakur P.K. (2021). Prioritization of sub-basins of Gomti river for soil and water conservation through morphometric and LULC analysis using remote sensing and GIS. *Journal of the Indian Society of Remote Sensing.* 49:2503–2522. doi: 10.1007/s12524-021-01410-w.
- Del-´Aguila, & S., Mejía, A., (2021). Morphometric characterization of two high Andean basins of Peru using Geographic Information Systems. Tecnologia y Ciencias Del Agua 12 (2), 1–20. Deng, Y., 2007. *New trends in digital terrain analysis: landform definition, representation and classification. Prog Phys Geography* 31 (4), 405–419.
- Egboka, B. C. E., & Nwankwor, G. I. (2022). Land degradation and gully erosion in Southeast Nigeria: Causes, impacts and controls. *Environmental Earth Sciences, 8*1(7), 1–14.
- Eze, P. N., & Okeke, O. C. (2021). Land use and soil erosion in South Eastern Nigeria: A GIS-based approach. *Catena,* 201, 105218.
- Frankl A, Nyssen J, Vanmaercke M, & Poesen J (2021). Gully prevention and control: techniques, failures and effectiveness. *Earth Surf Process Landf 46:220–238. https:// doi. org/ 10. 1002/ esp. 5033*
- García-Ruiz, J. M., Beguería, S., & Nadal-Romero, E. (2022). Contour farming and terracing in the Mediterranean: Reducing soil erosion on steep slopes. *Land Degradation & Development, 33(3), 547-560. doi:10.1002/ldr.4210*
- Hammouda S.A.I., & Mahmoud S.A.E.A. (2023). Analysis of morphometric parameters and Radioactive characteristics using remote sensing data and GIS techniques in the Wadi Wizr Basin Area, central eastern Desert, Egypt. *J.Geosci. Environ. Protect.*11(6):197–219. doi: 10.4236/gep.2023.116014.
- Hassan, M. & Kabir, A. (2019). Morphometric and Vulnerability Analysis of Gada River Basin to Erosion and Sediment Yield. Department of Geography, Umaru Musa Yar'adua University, P.M.B 2218 Katsina, Nigeria. *FUDMA Journal of Sciences (FJS) Vol. 3 No. 2 pp 58 – 66.*
- Harris, Peter T. (2020). "Seafloor geomorphology coast, shelf, and abyss". *Seafloor Geomorphology as Benthic Habitat:*115–160. doi:10.1016/B978-0-12-814960-7.00006-3. ISBN 9780128149607.
- Horton, R.E. (1932). Drainage Basin Characteristics. *Trans. Am. Geophys. Union.* 13, 350–361.
- Horton R.E. (1945). Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. *Geol. Soc. Am. Bull.* p56:275-370. doi: 10.1130/0016-7606(1945)56[275: EDOSAT]2.0.CO;2.
- Hou, X., Zhang, H., & Liu, Y. (2023). Gully erosion hotspots and sediment dynamics in hilly watersheds. *Remote Sensing of Environment*, 298, 113826.
- Intergovernmental Panel on Climate Change (IPCC) (2022). "Second Assessment Synthesis of Scientific-Technical Information relevant to interpreting Article 2 of the UN Framework Convention on Climate Change" *(PDF). p. 5. Archived from the original (PDF) on 2022-03-09. Retrieved 2023-10-05.*
- Ismail, M., Singh, H., Farooq, I., &Yousuf, N., (2022). Quantitative morphometric analysis of Veshav and Rembi Ara watersheds, India, *using quantum GIS. Appl. Geomat*. 14 (2), 119–134.
- Jacques, P.D., Salvador, E.D., Machado, R., Grohmann, C.H., & Nummer, A.R., (2014). Application of morphometry in neotectonic studies at the eastern edge of the Parana Basin Santa Catarina State Brazil. *Geomorphology* 213, 13–23.
- Kandekar, V.U., Gavit, B.K., Atre, A.A., & Bansod, R.D., (2021). Nimbalkar CA (2021) Morphometric analysis of Agadgaon watershed using remote sensing and geographic information system. *J. Pharmacog. Phytochem*. 10 (2), 450–460.
- Kant, C., Kumar, G., &Meena, R.S., (2023). Modeling morphometric and geomorphological parameters of mountainous river basin for water resource management using remote sensing and GIS approach. Model. *Earth Syst. Environ. 9 (*2), 2151–2163.
- Lal, R., & Moldenhauer, W. C. (2022). Advanced modeling of gully morphological parameters using UAV and SfM techniques. *Remote Sensing Applications in Geosciences. DOI: 10.3390/rs14040818*
- Lal, R. (2020). Soil erosion and the global food security crisis. *International Soil and Water Conservation Research*, 8(4), 337-348. doi: 10.1016/j.iswcr.2020.08.004
- Lal, R. (2022). Sustainable soil management: Concepts, strategies, and applications. *Springer*.
- Li, J., Wang, X., Dong, Z. (2022). Wind erosion and dust storms in northern China: *Trends and mitigation. Aeolian Research,* 53, 100774. doi: 10.1016/j.aeolia.2022.100774
- Li, Z., (2020). Assessing gully erosion risk using GIS-based models: A case study in Southwest China. *Journal of Environmental Management*, 259, 110050.
- Liniger, H., & Critchley, W. (2020). Sustainable Land Management in Practice: Guidelines and Best Practices for Sub-Saharan Africa. *World Overview of Conservation Approaches and Technologies (WOCAT).* ISBN: 978-92-5-132482-0
- L´opez-Ramos, A., Medrano-Barboza, J.P., Martínez-Acosta, L., Acu˜na, G.J., Remolina- L´opez, J.F., & L´opez-Lambra˜no, A.A., (2022). Assessment of Morphometric Parameters as the Basis for Hydrological Inferences in Water Resource Management: A Case Study from the Sinú River Basin in Colombia. *ISPRS Int. J. Geo Inf. Volume 11, Issue* 9.

- Lulu Bai, Peng Shi, Zhanbin Li, Peng Li, Zhun Zhao, Jingbin Dong, Tanbao Li, Jingmei Sun & Dejun Wang (2024) Correlation Between Water Erosion and Hydraulics of Slope–Gully Systems According to Check Dam Siltation Depth. *Journal of Water Resources Management Volume 38, pages* 3489–3503.
- Maddamsetty A., R., & Pawar, U., (2023). Evaluation of the geomorphological scenario of Shimsha River Basin, Karnataka, India. *Water Sci. Technol.* 87 (8), 1907–1924.
- Mahala A. (2019). The significance of morphometric analysis to understand the hydrological and morphological characteristics in two different morpho-climatic settings. *Appl. Water Sci.* 2019;10 doi: 10.1007/s13201-019-1118-2.
- Mani, A., Kumari, M., &Badola, R., (2022). Morphometric Analysis of Suswa River Basin Using Geospatial Techniques. *Eng. Proceed.* 27, Issue 1.
- Mathew A. & Shekar PR (2023). Flood prioritization of basins based on geomorphometric properties using morphometric analysis and principal component analysis: A case study of the Maner River basin. *In River Dynamics and Flood Hazards* (pp. 273–288). *Springer, Singapore. Doi: 10.1007/978-981-19-7100-6_18.*
- Martínez-Casasnovas, J. A. (2019). Soil erosion processes in Mediterranean vineyards: A review of geomorphological and hydrological interactions. *Geomorphology*, 327, 23-39.
- Mensah, F. K., & Appiah, D. O. (2020). Analysis of morphometric characteristics of gullies and their environmental implications. *Environmental Earth Sciences*, 79(16), 1–14.
- Mohammed, M. I. (2023). Climate variability and its impact on drainage morphometry in the Hadejia River Basin, Northern Nigeria. *Geology, Ecology, and Landscapes*, 7(1), 1-14.
- Montgomery, D. R. (2022). Soil erosion and agricultural sustainability. *Proceedings of the National Academy of Sciences,* 119(26), e2117380119. doi:10.1073/pnas.2117380119
- Miniandi, N.D., Sulaiman, M.S., Zakariya, R., Razali, S.M., & Jamil, N.R., (2021). Morphometric analysis of the main river systems at Ulu Muda Forest Reserve, Kedah, Peninsular *Malaysia. Malay. Nat. J. 73* (3), 297–309.
- Najafi, S.; Dragovich, D.; Heckmann, T.; & Sadeghi, S.H. (2021). Sediment connectivity concepts and approaches. *Catena 2021*, 196, 104880.
- Nasiri, M., Ghorbani, A., & Afshar, A. (2021). Topographic and anthropogenic drivers of gully morphology. *Journal of Mountain Science, 1*8(3), 789–805.
- Nasr, A., et al. (2020). Gully erosion control measures in arid and semi-arid regions: *A review. Land Degradation & Development,* 31(2), 139-155.
- Nazari, S., Pourghasemi, H. R., & Shabani, F. (2023). Gully erosion susceptibility mapping using hydro-geomorphometric parameters. *Environmental Monitoring and Assessment.* DOI: 10.1007/s10661-023-11197-7
- Nearing, M. A., Pruski, F. F., & O'Neal, M. R. (2021). Expected climate change impacts on soil erosion rates: A review. *Journal of Soil and Water Conservation,* 66(4), 206-217. doi:10.2489/jswc.66.4.206
- Nigussie, T. A. (2023). Migration and livelihood impact of gully erosion: A case study in East Africa. *Environmental Management*, 72(2), 134-147.
- Niyazi, B., Zaidi, S., & Masoud, M., (2019). Comparative Study of Different Types of Digital Elevation Models on the Basis of Drainage Morphometric Parameters (Case Study of Wadi Fatimah Basin, KSA*). Earth Syst. Environ*. 3, 539–550.
- Nugroho, B., Suharyadi, D., & Dewi, I. K. (2023). Geospatial assessment of gully development and its drivers in tropical highlands*. Remote Sensing Applications: Society and Environment,* 32, 100914.
- Nyssen, J., Frankl, A., Zenebe, A., & Poesen, J. (2020). Gully erosion and environmental change: importance, research needs and challenges. *Earth-Science Reviews*, 201, 102949.
- Nyssen, J., Poesen, J., & Deckers, J. (2020). Soil erosion and gully formation in semi-arid landscapes. *Earth Surface Processes and Landforms*, 45(1), 50–64.
- Ocheli, B.A. (2021). Geology and geotechnical investigations of Anambra Basin, Southern Nigeria. *Journal of African Earth Sciences, 176, 104061.*
- Ogbonna, A. I., Eze, P. N., & Okeke, O. C. (2021). Morphometric classification of gullies in southeastern Nigeria using drone photogrammetry. *Journal of Environmental Management, 2*92, 112752.
- Oke, D. O., & Adeoye, B. A. (2021). Sediment yield and morphometric analysis of gully systems in southwestern Nigeria. *Geoderma,* 403, 115234.
- Okoro, E. I. (2020). Morphometric Analysis of the Upper Orashi River Basin, Niger Delta, Nigeria for Flood Risk Assessment. *Journal of Geography, Environment and Earth Science International,* 24(5), 1-15.
- Okoroafor, E. O., Chukwu, E. U., & Agbo, J. O. (2023). Integrated management strategies for gully erosion in Nigeria: A case study of Anambra Basin. *Journal of Environmental Planning and Management*, 66(5), 874–892.
- Pande C. B, Moharir KN, & Khadri SFR (2021). Watershed planning and development based on morphometric analysis and remote sensing and GIS techniques: A case study of semi-arid watershed in Maharashtra, India. *Groundwater Resources Development and Planning in the Semi-Arid Region, Pages* 199 – 220.
- Patel R.K., Rai V.K., Sharma D.K., & Prakash S. (2023). *Advances in Water Resource Planning and Sustainability.* Evaluation of morphometric analysis of Kharag River basin, odisha using geospatial techniques; pp. 305–322.
- Patil, S.K., &Bhagwat, T.N., (2023). Morphometric analysis and hydrological inferences for water resource management in Warana River basin of Maharashtra, India, using remote sensing and GIS. *Songklanakarin J. Sci. Technol*. 45 (1), 113–120.
- Panagos, P., Borrelli, P., & Poesen, J. (2021). Soil erosion in Europe: The impact of land use change and climate change. *Environmental Research Letters 16(11), 114027. doi:10.1088/1748-9326/ac2f84*

- Pimentel, D., Burgess, M., & Tomich, T. P. (2021). Soil erosion: A food and environmental threat. Environment, Development and Sustainability, 23, 1333-1349. doi:10.1007/s10668-020-00617-8
- Poesen, J. (2021). Gully erosion: A major threat to global soil resources. *Earth Surface Processes and Landforms,* 46(5), 889-905.
- Poesen, J., (2022). Gully erosion as a driver of sediment transport and land degradation. *Earth Surface Processes and Landforms,* 47(10), 2123-2141.
- Prakasam, C., Aravinth, R., Kanwar, V.S., & Nagarajan, B., (2021). Sustainable water resource management using watershed morphometry- a case study of Giri River Catchment, Himachal Pradesh, India. *Geographic Information Science for Land Resource Management, pp.* 229–250.
- Randhir, Timothy O. (2017). Watershed Management: Issues and Approaches. *IWA Publishing. p. 56. ISBN 978-1-84339-109-8.*
- Rajasekhar, M., Raju, G.S., & Raju, R.S., (2020). Morphometric analysis of the Jilledubanderu River Basin, Anantapur District, Andhra Pradesh, India, using geospatial technologies. *Groundw. Sustain. Dev*. 11 https://doi.org/10.1016/j. gsd.2020.100434.
- Real LSC, Crestana S, & Ferreira RRM (2020). Evaluation of gully development over several years using GIS and fractal analysis: a case study of the Palmital watershed, Minas Gerais (Brazil*). Environ Monit Assess 192:434. https:// doi. org/ 10. 1007/ s10661- 020- 08362*
- Reed, M. S., Moxey, A., & Prager, K. (2021). Integrated approaches to soil erosion management: A review and a new framework. *Environmental Science & Policy, 114, 239-246. doi: 10.1016/j.envsci.2020.10.009*
- Renard, K. G., Foster, G. R., Weesies, G. A., McCool, D. K., & Yoder, D. C. (2021). Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). *Agriculture Handbook No. 703. USDA, Washington, DC.*
- Romero-Díaz A, Díaz-Pereira E, & De Vente J (2019). Ecosystem services provision by gully control. *the review. Geogr Res Lett 45(1):333–366. https:// doi. org/ 10. 18172/ cig. 3552*
- Rotta CMS, & Zuquette LV (2014) Erosion feature reclamation in urban areas: typical unsuccessful examples from Brazil. *Environ Earth Sci 72:535–555. https:// doi. org/ 10. 1007/ s12665- 013- 2974-y*
- Sandeep, A. (2020). Morphometric Analysis of a Drainage Basin: A Study of Ghatganga River, Bajhang District, Nepal. Central Department of Geography, Tribhuvan University, Kirtipur, Nepal. *The Geographic Base Vol.* 7: pp 127-144, Doi: 10.3126/tgb. v7i0.34280
- Sanjay, P. Pendke, M.S. Shinde, R.V. Gopal, S. & Bhuibhar, B.W. (2024). Morphometric analysis using remote Sensing and GIS techniques of Pingalgarh watershed VNMKV, Parbhani, India. *International Journal of Research in Agronomy* SP-7(10): 118-124.
- Scalenghe, R.; Edwards, A.C. & Barberis, E. (2020). "Phosphorus loss in overfertilized soils: The selective partitioning and redistribution between particle size separates*". European Journal of Agronomy. 27 (11): pp 72–80. doi:10.1016/j.eja.2007.02.002.*
- Schumacher, J. A., Awale, R., & Kumar, S. (2021). Cover cropping and its impact on soil erosion and health in the Midwest USA. *Agriculture, Ecosystems & Environment*, 310, 107276. doi: 10.1016*/j.agee.*2021.107276
- Schumn, S.A., (1956). Evaluation of drainage systems and slopes in badlands at Perth Amboy, New Jersy. *Geol. Soc. Am. Bull.* 67, 597–646.
- Sener, M., & Arslano˘glu, M.C., (2023). Morphometric analysis in Google Earth Engine: An online interactive web-based application for global-scale analysis*. Environ. Model. Softw.* 162.
- Shamkhi, M.S., Azeez, J.M.R., & Abdul-Sahib, A.A., (2020). Morphologic and Engineering Characteristics of Watersheds (A Case Study: East Wasit Watersheds that Feed the Al- Shewicha Trough - Iraq). *IOP Conf. Ser.: Mater. Sci. Eng.* 870 012115 https://doi. *org/10.1088/1757-899X/870/1/012115.*
- Shamkhi MS, Mohson AJ, & Abdullah TJ (2020). Morphometric Analysis of Galal Bedrah River Basin Using STRM (DEM) Data and GIS Techniques. In: Mohamed Nazri, F. (eds) Proceedings of AICCE'19. AICCE 2019. *Lecture Notes in Civil Engineering, vol* 53. *Springer, Cham. Doi*: *10.1007/978-3-030-32816-0_16.*
- Shekar, P. R., & Mathew, A. (2024). Morphometric analysis of watersheds: A comprehensive review of data sources, quality, and geospatial techniques. Civil Engineering Department, National Institute of Technology, Tiruchirappalli 620015, Tamil Nadu, India. *Journal of Watershed Ecology and the Environment* www.keaipublishing.com/en/journals/watershed-ecology.
- Shekar, P.R., & Mathew, A., (2022). Evaluation of Morphometric and Hypsometric analysis of the Bagh River basin using Remote Sensing and Geographic Information System techniques. *Energy Nexus 7, 100104*. https://doi.org/10.1016/j. nexus.2022.100104.
- Shekar, P.R., & Mathew, A., (2023). Detection of land use/land cover changes in a watershed: A case study of the Murredu watershed in Telangana state, India. *Watershed Ecol. Environ.* 5, 46–55. https://doi.org/10.1016/j.wsee.2022.12.003.
- Shekar P.R, & Mathew A (2023). Delineation of groundwater potential zones and identification of artificial recharge sites in the Kinnerasani Watershed, India, using remote sensing-GIS, AHP, and Fuzzy-AHP techniques. AQUA - *Water Infrastructure, Ecosyst. Soc. 2023; jws2023052. Doi: 10.2166/aqua.2023.052.*
- Shekar PR, Mathew A, Arun PS, & Gopi VP (2023). Sub-watershed prioritization using morphometric analysis, principal component analysis, hypsometric analysis, land use/land cover analysis, and machine learning approaches in the Peddavagu River Basin, India. *Journal of Water and Climate Change 2023; jwc2023221. doi: 10.2166/ wcc.2023.221.*
- Shekar, P.R., & Mathew, A., (2023). In: Erosion Susceptibility Mapping Based on Hypsometric Analysis Using Remote Sensing and Geographical Information System Techniques. *Springer, Singapore, pp. 365–382. https://doi.org/10.1007/978-981- 19-7100-6_26Singh.*
- Singh S, Singh AK, Jaiswal MK, & Kanhaiya S (2021). The application of morphometric parameters in river watershed management: A case study of Rihand River, India. Geo-Information Technology in Earth Resources Monitoring and Management, Pages 357 – 368. *Smith, K., 1950. Standard for grinding texture of erosional topography. Am. J. Sci. 248, 655–668. https://doi.org/10.2475/ajs.248.9.655.*
- Smetanová, A. (2020). Topographic controls of gully erosion in agricultural landscapes: *A field study. Catena, 188, 104417.*
- Sonker, I., Tripathi, J.N., & Swarnim, S., Ak, (2023). Morphomertic and neotectonic study of Upper Teesta River basin, Sikkim Himalaya using geospatial techniques. *J. Appl. Geophys. 212, 104978.*

- Sonneveld, B. G. J. S., & Keyzer, M. A. (2020). Land under pressure: The impact of soil erosion on food production in Ethiopia. *Agricultural Economics, 51(5), 773-784. doi:10.1111/agec.12589*
- Strahler, A.N., (1957). Quantitative analysis of watershed geomorphology. Trans. *Am. Geophys. Union 38, 913–920.*
- Strahler, A.N., (1964). Quantitative Geomorphology of Drainage Basins and Channel Networks. In: Chow, V. (Ed.), Handbook of Applied Hydrology. *McGraw Hill, NewYork, pp. 439*–476.
- Strahler A.N (1958) Dimensional Analysis Applied to Fluvially Eroded Landforms. *Geol. Soc. Am. Bullet. 1958;69(3):279.*
- Stringer, L. C., Fraser, E. D. G., & Harris, D. (2021). Policy interventions to promote soil conservation in Europe and North America. *Land Use Policy, 104, 105353. doi: 10.1016/j.landusepol.2021.105353*
- Sutradhar, S., & Mondal, P., (2022). Prioritization of watersheds based on morphometric assessment in relation to flood management: a case study of Ajay river basin, Eastern India. *Watershed Ecol. Environ., ISSN 2589–4714. https://doi.org/10.1016/j. wsee.2022.11.011.*
- Tassew B.G., Belete M.A., & Miegel K. (2023). Assessment and analysis of morphometric characteristics of lake Tana sub-basin, Upper Blue nile basin, Ethiopia. *Int. J. River Basin Manag.* 2023;21(2):195–209. doi: 10.1080/15715124.2021.1938091
- Telore N.V. (2020) Quantitative morphometric analysis of the yerla river basin, deccan trap region, India. *Geoecology of landscape dynamics.*115–132. doi: 10.1007/978-981-15-2097-6_9.
- Torrefranca I, & Otadoy R. E. (2022). GIS-based watershed characterization and morphometric analysis in Bohol Watersheds, Philippines. *Geol., Ecol. Landscapes, Doi: 10.1080/24749508.2022.2158554.*
- Tiwari, P. (2021). Conservation agriculture: Strategies for mitigating gully erosion in the Himalayas. *Environmental Research, 194, 110654.*
- United Nations Convention to Combat Desertification (UNCCD), (2022). Global Land Outlook: *Land Restoration for Recovery and Resilience.*
- Valentin, C. (2019). Gully erosion and its control in southeastern China: *A case study. Catena, 176, 155-165.*
- Valentin C, Poesen J, & Li Y (2018). Gully erosion: impacts, factors and control. *Catena 63:132–153.https:// doi. org/ 10. 1016/j. catena. 2005. 06. 001*
- Vanmaercke, M.,. (2019). Role of vegetation in gully erosion control: *A global review. Earth-Science Reviews, 191, 12-27.*
- Vanmaercke, Matthias; Panagos, Panos; Vanwalleghem, Tom; Hayas, Antonio; Foerster, Saskia; Borrelli, Pasquale; Rossi, Mauro; Torri, Dino; Casali, Javier; Borselli, Lorenzo; & Vigiak, Olga (2021). "Measuring, modelling and managing gully erosion at large scales: A state of the art". *Earth-Science 218: 103637. Bibcode:2021ESRv.21803637V.*
- Van Oost, K., Govers, G., & Cerdà, A. (2022). Remote sensing and GIS applications in soil erosion monitoring. *Earth-Science Reviews, 227, 103939. doi: 10.1016/j.earscirev.2022.103939*
- Wang W., Yan H., Lu X., He Y., Liu T., & Li W. (2023). Drainage pattern recognition method considering local basin shape based on graph neural network. *International Journal of Digital Earth.* 2023; 16:593–619. doi: 10.1080/17538947.2023.2172224.
- Wang, B. (2021). Climate change impacts on gully erosion in the Loess Plateau of China. *Environmental Research Letters, 16(4), 045009.*
- Wang, T. (2023). Climate change and the feedback mechanisms of soil erosion. *Nature Climate Change, 13(3), 320-328.*
- Wen, D. (2019): Soil Erosion and Conservation in China. In Soil Erosion and Conservation; Pimentel, D., Ed.; *Cambridge University Press: New York, NY, USA*, pp. 63–86.
- Wu, H.; Xu, X.; Zheng, F.; Qin, C.; & He, X. (2018). Gully morphological characteristics in the loess hilly-gully region based on 3D laser scanning technique. *Earth Surf. Process*. *Landf.,* 43, 1701–1710.
- Wuepper, David; Borrelli, Pasquale; Finger, & Robert (2020). "Countries and the global rate of soil erosion". *Nature Sustainability. **3** (1): 51–55. ISSN 2398-9629. S2CID 208539010.*
- Xie, J., Xu, W., & Zhang, Z. (2023). Hydrodynamic analysis of slope-gully erosion systems. *Water Resources Management*. DOI: 10.1007/s11269-024-03827-7
- Yildirim, U., (2021). Morphometric analysis to infer hydrological behaviour of Coruh river basin (Northern Turkey) using GIS technique. *Fresen. Environ. Bull. 30 (5)*
- Yitbarek, T. W. (2020). Impact of gully erosion on soil properties and crop productivity in Ethiopia. *Soil & Tillage Research, 202, 104636.*
- Zhang, K., Tang, S., & Li, Z. (2021). Slope distribution and stability of erosion gullies: A principal component and regression analysis approach. *Environmental Earth Sciences, 80(2). DOI: 10.1007/s12665-021-09605-7*
- Zhao, Y., Liang, H., & Zhang, T. (2023). Field and drone-based analysis of gully evolution in China's Loess Plateau. *Earth Surface Processes and Landforms*, 48(1), 122–138.
- Zhou, Q., Liu, D., & Peng, J. (2022). Gully erosion susceptibility mapping using random forest and high-resolution DEMs. *Geocarto International*, 37(4), 975–994.
- Zhou, W., Xu, X., & Tang, X. (2020). Deforestation in the Amazon: Impact on soil erosion and sedimentation. *Science of the Total Environment, 744, 140972. doi: 10.1016/j.scitotenv.2020.140972*