

## THE SCIENCE OF MODELLING AND PREDICTING OF ENVIRONMENTAL PHENOMENA ON INVESTIGATING THE GEO-ENVIRONMENTAL CONDITIONS INFLUENCING THE OCCURRENCE OF GULLY EROSION IN UYO, AKWA IBOM STATE, NIGERIA

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D.O.I: 10.5281/zenodo.20289478

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### ARTICLE INFORMATION

Received: 28<sup>th</sup> June, 2024

Accepted: 1<sup>st</sup> July., 2024

Published: 30 Aug., 2024

**KEYWORDS:** Science, Modelling, Predicting, Environmental Phenomena, Investigating, Geo-Environmental, Conditions, Influencing, Occurrence, Gully Erosion, Nigeria.

**Publisher:** Empirical Studies and Communication - (A Research Center)

**Website:** [www.cescd.com.ng](http://www.cescd.com.ng)

### ABSTRACT

Gully erosion contributes to land degradation and destruction of physical infrastructures and properties as well as retarding the socio-economic growth and development of the inhabitants of a community. This research investigated the geo-environmental factors influencing the occurrence of gully erosion in Uyo, Akwa Ibom State, Nigeria. Ten gully sites in the study area were purposively selected with training datasets of 80% and validation dataset of 20% were used in the study. Nine gully-related geo-environmental factors namely slope, aspect, curvature, rainfall, distance from stream, topographic wetness index, lithology, distance from road and NDVI were identified from literature and examined. The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) 2022 with a spatial resolution of 30m and Advanced Spaceborne Thermal Emission and Reflection (ASTER) Digital Elevation Model (DEM) 2004-2022 with a spatial resolution of 30m were used to extract the topographic features. Data were analysed using ARCGIS 10.7 with Frequency Ratio (FR) as the main statistical tool. The results indicated that all the geo-environmental factors examined in the study were positively associated with gully erosion, with rainfall (FR= 3.26), distance from road (FR = 2.71), NDVI (FR= 2.59) and distance from stream (FR = 2.34) being the most significant geo-environmental factors influencing gully occurrence. It was concluded that a wide range of geo-environmental factors contributed to gully expansion at different susceptible rates. Proper land management practices is recommended. It is also recommended that government should regulate land use and urban development in its effort to control gully formation.

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### INTRODUCTION

Igbokwe et al (2008) explains that soil erosion begins with the delayed type of rainfall droplets dislodging particles of soils and depositing them at another location when the surface of the soil is not protected by plant covers. The author identified the factors contributing to gully erosion be natural (topography, geology, nature and texture of soil and vegetation) and anthropogenic (laterite excavations, bad farming practices, unplanned road construction and urbanization, wood harvesting for fuel and bush burning to clear lands for farming, among others), contribute to the speedy development and expansion of gullies in an area.

According to Rahmati 2022, gully erosion is a form of land degradation characterized by the formation of deep channels or gullies in the landscape. Gully erosion is a major problem for natural resource management, leading to land degradation and economic losses worldwide. This phenomenon causes different types of damage to roads, natural resources and agriculture (Nyssen *et al.*, 2002; Valentin *et al.*, 2005; Yalcin *et al.*, 2011). Gully erosion is considered as one of the principal agents of geo-environmental degradation (Noormohammadi *et al.* 2013, 2014). The development of gully is a complex process depending on a wide range of geo-environmental factors. These factors are primarily associated with topography, lithology, rainfall, soil, distance from river and land use (Poesen *et al.*, 2003; Marti´nez-Casasnovas *et al.*, 2004).

The yearly heavy rainfall has very adverse impacts altering existing landscape and forms. Such landforms create deep gullies that cut into the soil. The gullies spread and grow until the soil is removed from the sloping ground. Soil erosion when formed expand rapidly coupled with exceptional storm or torrential rain down the stream by head-ward erosion gulping up arable lands, economic trees, homes, lives, and sacking of families and valuable properties that are worth millions of naira (Umudu, 2008). Kirkby and Bracken (2009) pointed out that surface runoff is one of the principal factors contributing to the occurrence of gully erosion. The velocity and volume of concentrated surface flow are also controlled by land use and topographic attributes such as contributing drainage area, slope steepness, and slope curvature (Valentin *et al.*, 2005; Zucca *et al.*, 2006; Svoray and Markovitch, 2009; Conoscenti *et al.*, 2013).

Reliable estimate suggests that over 6,000 km<sup>2</sup> of land in Nigeria is affected by erosion while about 3,400 km<sup>2</sup> is highly exposed to soil degradation (Merem *et al.*, 2019). Gully erosion, with

an estimated annual damage of ₦35 billion, has devastated many lives and destroyed essential infrastructure for economic development and poverty alleviation. This undermines economic growth and poses serious threat to Nigeria's developmental effort (NEWMAP, 2017). Large sections of Southern Nigeria, especially the south-south face severe problems of soil erosion and slope failure, both of which are processes of gully erosion and mass wasting (Igwe, 2012).

Gully erosion is a significant environmental problem that can have various negative impacts. Ajearo and Mozie (2011) documented that gully erosion menace has over the years been responsible for increasing losses of houses and land of the people, thereby displacing affected inhabitants. Also, it has led to the loss of lives and livestock, as well as the destruction of farms on which the majority of the population depend for survival. Musa *et al.* (2016) observed that Gully erosion within settlements requires peculiar attention because of the threat it poses to buildings and other structures that endanger human lives.

Generally, the growing interest in studying gully erosion reflects the need to increase our knowledge on its impacts and conditioning factors that vary under a wide range of causes (Valentin *et al.*, 2005). The knowledge of the factors influencing the advancement of gully will provide a useful guide for mitigating the impact of gully erosion. Most international studies have focused on identifying the factors controlling the appearance of gullies (Conoscenti *et al.*, 2014; Arabameri *et al.*, 2020; Gayen *et al.*, 2019; Lei *et al.*, 2020). However, studies on the geo-environmental factors influencing the development of gullies in Nigeria and Uyo in particular are limited. This study therefore seeks to identify and investigate the geo-environmental conditions influencing the occurrence of gully erosion in Uyo, Akwa Ibom State.

### Review of Related Literature

Some studies have been undertaken to examine the factors affecting gully erosion. Arabameri *et al.* (2018) carried out a spatial modelling of gully erosion using GIS and R programming at Shahroud Watershed in Iran. The author compared three data mining algorithms and used twelve (12) gully-related geo-environmental variables (GEVs) and Normalised Difference Vegetation Index (NDVI) to model gully erosion. The study used Random Forest (RF) and Boosted Regression Tree (BRT) models and the results indicated that distance from road, elevation and lithology had the highest effect on gully erosion occurrence.

In another related literature by Rahmati *et al.* (2016), the most effective factors in the prediction of gully erosion susceptibility were discovered to be distance from river, drainage density and Land Use factors. Azedou *et al.* (2021) in their study used twelve (12) conditioning factors namely elevation, slope, aspect, curvature, slope length, stream power index (STI), land use, NDVI, composite topographic index (CTI), lithology and vegetation cover (C factor) underlying gully formation were considered and mapped. The results revealed that the factors that most contributed to the prevalence of gully erosion were topographic factors which were slope, slope length and Composite topographic index (CTI). In another study by Rasyid *et al.* (2016) the predisposing factors used as independent variables were lithology, distance from road, distance from river, land use, curvature, aspect and slope degree.

A study conducted by Igbokwe *et al.* (2008) established that the major causative factors of gully erosion were natural and anthropogenic. The author argued that urbanization involving road constructions and building developments contribute immensely to gully sites development. The author further identified excavations being carried out by individuals on existing road sides as a major contributing factor to gully site developments, as some of these mining pits have been abandoned over the years have developed into gully sites. Another study by Udosen *et al.* (2014) concluded that gully complex at Oron is caused by heavy rainfall exceeding the capacity of the drainage systems which included the outfall drains, culverts and the estimated catchment area, increased paved area giving rise to increased runoff; other anthropogenic activities in the vicinity of the gully and the weak and unconsolidated coarse-textured coastal plains sand.

Umo *et al.* (2018) assessed gully erosion in the humid tropics of Eniong Offot in Uyo, Akwa Ibom State using geospatial technologies. The author adopted three methods in data generation including the creation of signatures for supervised classification of the satellite image and generation of NDVI. The result of the study indicated that the analysis of vegetation using NDVI and three digital elevation models revealed that scarcity of vegetation cover, high to moderate relief and the bedding plains of the coastal sands deposits also exercised the strong influence on the gully migration in the area. The study concluded that gully erosion in the Etim Umana area of Uyo is caused by high incidence of rainfall and surface configuration but accelerated by anthropogenic activities (urbanisation, farming and construction related activities).

### Geo-environmental Factors Influencing the Occurrence of Gully Erosion

Geo-environmental factors are referred to as the physical, geological and environmental aspects of a particular location or region that influence the natural processes, ecosystems, and human activities of a soil. It encompasses a range of natural elements, including geological, climatic, hydrological, and topographical features, as well as anthropogenic influences such as land use and pollution, which collectively contribute to the characterization and

functioning of an environment (Atkinson and Massari, 2011). These factors play a crucial role in shaping the landscape, determining the distribution of flora and fauna, and affecting the overall environmental quality of an area (Scholz and Harris, 2008). The geo-environmental factors influencing gully erosion occurrence and development are primarily associated with;

**Rainfall** – Rainfall is a critical geo-environmental factor that significantly influences the occurrence of gully erosion. The intensity, duration, and distribution of rainfall events plays a key role in activating and accelerating gully erosion processes. High-intensity rainfall events can cause the detachment and transport of soil particles, leading to erosion. The impact of raindrops on the soil surface dislodges soil particles, making them susceptible to being transported by surface runoff. Research by Boardman and Poesen (2006) demonstrated that high-intensity rainfall events are more likely to generate gully initiation and accelerate gully development. Prolonged rainfall contributes to gully erosion by increasing the volume and duration of runoff. As water infiltrates the soil and the soil's capacity to store water is exceeded, excess water becomes surface runoff. Over time, this surface runoff accumulates and concentrates in certain areas, leading to the formation of gullies. Studies by Verstraeten and Poesen (2000) have shown that longer durations of rainfall events are associated with more severe gully erosion. The spatial and temporal distribution of rainfall influences gully erosion. Concentrated rainfall in a particular area increases the amount of surface runoff and enhances gully formation. Regions with uneven rainfall distribution, such as high-intensity storms in specific seasons, are more prone to gully erosion. An investigation by Nearing *et al.* (2005) found that the spatial patterns of rainfall strongly influence the occurrence of gully erosion.

**Lithology** – Lithology, which refers to the physical and chemical characteristics of rocks and sediments, is an important geo-environmental factor that can influence the occurrence and severity of gully erosion. The lithological properties of an area play a significant role in determining the susceptibility and extent of gully erosion. The lithological composition of the soil and underlying rocks influences soil erodibility, which is the susceptibility of the materials to erosion. Some lithologies, such as soft and easily weathered rocks or loose unconsolidated sediments, may be more erodible than others. For instance, fine-grained clays or silts are generally more prone to erosion than coarser sediments or rocks with higher resistance (Montgomery *et al.*, 1995). Lithological variations can influence the development of drainage patterns and the concentration of water flow in certain areas. Differences in rock permeability, fracture density, or lithological contacts can create preferential flow paths for water, increasing the likelihood of gully formation. In some cases, lithological boundaries may act as barriers to water flow, leading to the accumulation of runoff and potential gully initiation. (Carretier *et al.* 2011). Also, lithological properties such as rock hardness, cementation, and jointing influence the resistance of the materials to erosive forces. Rocks that are more resistant to weathering and erosion, such as hard sandstones or granites, are less likely to be eroded by concentrated water flow and therefore may not contribute significantly to gully formation. Conversely, weaker lithologies or those with pervasive jointing may be more susceptible to erosion. (Zhan *et al.* 2016). The lithological characteristics of eroded materials influence their transport and deposition downstream. Fine-grained sediments, such as silts and clays, can be easily transported by water and contribute to the formation of sediment-laden runoff. The deposition of eroded materials in downstream areas can exacerbate gully erosion and sedimentation processes (Mitasova, *et al.*, 1996).

**Aspect** – Aspect refers to the direction in which a slope faces, typically expressed in terms of cardinal directions (north, south, east, west) or degrees of azimuth. It is an important geo-environmental factor that can influence the occurrence and severity of gully erosion. The slope aspect can indirectly influence erosion processes because it controls duration of

sunlight exposition, evapotranspiration, moisture retention, vegetation cover type, and vegetation distribution on slopes (Wang *et al.* 2011). The aspect of a slope plays a significant role in gully erosion for several reasons. Aspect affects the amount and intensity of solar radiation received by a slope. South-facing slopes in the Northern Hemisphere (north-facing slopes in the Southern Hemisphere) receive more direct sunlight and are exposed to higher temperatures. This leads to increased evaporation rates and drier surface conditions, making the soil more susceptible to gully erosion. Aspect effects the availability and distribution of water on a slope. North-facing slopes in the Northern Hemisphere (south-facing slopes in the Southern Hemisphere) receive less direct sunlight and are generally cooler and moister. These conditions promote higher soil moisture content, which can contribute to increased infiltration and reduced runoff, limiting gully erosion. Aspect affects the distribution and growth of vegetation on a slope. Different aspects receive varying amounts of sunlight and moisture, creating microclimatic variations that influence plant communities. Vegetation plays a crucial role in stabilizing soil, reducing surface runoff, and protecting against erosion. Variations in vegetation cover resulting from aspect differences can impact gully erosion patterns. Aspect influences soil temperature and moisture conditions, which, in turn, affect soil properties. Variations in temperature and moisture regimes can lead to variations in soil composition, structure, and erodibility. Slopes with different aspects may have differing soil types, organic matter content, or compaction levels, which can influence their susceptibility to gully erosion.

**Curvature** – Curvature refers to the rate of change of slope along a land surface. It can be categorized into two types: convex curvature and concave curvature. Convex curvature indicates an outward bulging shape, while concave curvature represents an inwardly curved shape. The relationship between curvature and gully erosion occurrence has been studied in various geomorphic and geo-environmental research (Simon and Collison 2002) investigated the impact of curvature on gully erosion rates by utilizing radioisotopic dating techniques. The study provides empirical evidence of the influence of curvature on gully erosion and discusses the underlying processes. Another study by Chandler and Dunne (1988) focused on the effects of curvature on hillslope runoff, which is an important process contributing to gully erosion. It presents field evidence and discussed the relationship between curvature, surface runoff, and erosion. Borselli *et al.* (2008) explored the concept of sediment connectivity and its relationship with gully erosion. It discussed the role of curvature in influencing sediment transport and connectivity in the landscape, which can contribute to the initiation and development of gullies. Deffontaines *et al.*, (2003) utilized airborne Light Detection and Ranging (LIDAR) data to analyse gully morphometry, including curvature. It examined the relationship between curvature and gully erosion features and discusses the potential of LIDAR data for studying gully erosion.

**Distance from road** – The distance from the road can indeed be considered as a geo-environmental factor that influences the occurrence of gully erosion. Several studies have examined the relationship between the distance from the road and gully erosion, providing insights into how road networks can impact erosion patterns. Zhang *et al.* (2015) investigated the impact of roads on gully erosion in a less hilly area of China. The researchers found that gully density was significantly higher in areas closer to roads compared to areas farther away. They attributed this to increased surface runoff and sediment transport caused by road construction and associated disturbances. Wei *et al.* (2016) focused on the effects of road networks on erosion and deposition in a hilly region. The study found that gully density was positively associated with road density, indicating that gully erosion was more prevalent in areas with a higher concentration of roads. The researchers suggested that roads contributed to the concentration and acceleration of surface runoff, leading to increased erosion.

Sidorchuk *et al.* (2013) examined the influence of road proximity on gully erosion in the Mexican tropics. The findings revealed that the likelihood of gully formation increased with decreasing distance from the road. The authors attributed this relationship to the alteration of natural drainage patterns caused by roads, resulting in enhanced erosion processes.

**Distance from streams** – Gullies are linked to the drainage and stream networks facilitating the evacuation of materials eroded from upland areas (Conoscenti *et al.*, 2014). The distance from a stream is truly a significant geo-environmental factor that can influence the occurrence of gully erosion. This factor interacts with various other factors such as topography, soil characteristics, vegetation cover, and rainfall patterns (Eckelmann and Rojas, 2015; Yitbarek *et al.* 2016).

**Slope degree** – Slope degree, also known as slope steepness or gradient, is an important geo-environmental factor that plays a critical role in the occurrence and development of gully erosion. This factor influences the velocity and volume of water runoff, erosion rates, and the stability of the soil. Several studies (Poesen *et al.* 2003; Le Bissonnais and Cerdan, 2005) have investigated the relationship between slope degree and gully erosion, highlighting its importance in the erosion process.

**Normalized Difference Vegetation Index (NDVI)** – NDVI is one of the geo-environmental factors that plays a key role in determining the occurrence of gully erosion. NDVI is a commonly used index in remote sensing to measure vegetation health and density based on satellite imagery. It provides information about the amount and strength of vegetation in a given area. Gully erosion occurs when there is excessive water flow and limited vegetation cover, leading to the removal of soil and sediment. The presence or absence of vegetation can significantly influence the occurrence and severity of gully erosion. Several studies (Verstraeten and Poesen, 2000; Bui and Moran, 2001; Yuan and Bauer, 2007; Dabral *et al.*, 2012) have investigated the relationship between NDVI and gully erosion.

**Stream Power Index (SPI)** – Stream power index (SPI) is one of the significant geo-environmental factors used to determine the occurrence and intensity of gully erosion. SPI combines the hydraulic and topographic characteristics of a landscape to quantify the erosive power of flowing water in a channel. The concept of stream power index was initially developed by Hack in 1957 and has been widely adopted and modified by successive researchers. The SPI is calculated based on the stream's slope and drainage area, which are key factors affecting the erosive potential of flowing water. The formula for calculating SPI is as follows:

$$SPI = (Q / A) * S^{0.5}$$

**Where:** SPI = Stream Power Index

Q = Discharge (streamflow) in cubic meters per second

A = Drainage area in square meters

S = Channel slope in meters per meter

The SPI represents the potential energy available to erode and transport sediment in a stream. Higher values of SPI indicate greater erosive power and, consequently, a higher likelihood of gully erosion. The relationship between SPI and gully erosion occurrence is based on the principle that when the erosive forces of flowing water exceed the resistance of the soil and vegetation cover, gully erosion can occur.

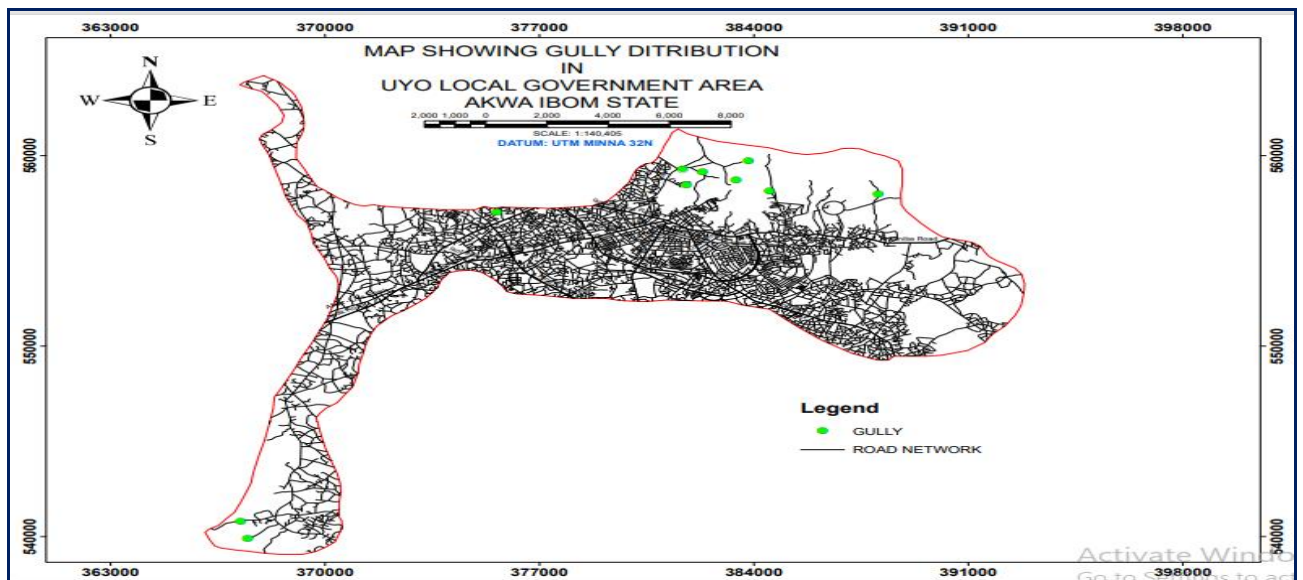
**Topographic Wetness Index (TWI)** – The topographic wetness index (TWI) is a water-related and secondary topographic factor within the runoff model which is commonly applied to quantify topographic control in hydrological processes (Rahmati *et al.*, 2016). The

topographic wetness index (TWI) is a widely used parameter in geomorphology and hydrology that provides information about the relative wetness or moisture availability of a landscape. It is used to determine the potential occurrence of various land surface processes, including gully erosion. TWI is based on the concept that areas with higher TWI values are more prone to saturation and water accumulation, making them susceptible to erosion processes such as gully formation. The TWI is calculated using digital elevation models (DEMs) and it considers the relationship between slope and the contributing areas, which influences the potential for water accumulation.

**Topography** – Topography, which is the physical features of land surface, plays a critical role in determining the occurrence and severity of gully erosion. Steep slopes are more prone to gully erosion than gentle slopes. High slope gradients accelerate the flow of water, increasing its erosive power and the likelihood of gully formation. The steeper the slope, the greater the potential for gully erosion to occur (Boardman, 2013). Longer slopes provide more distance for water to gain momentum and erode the soil, increasing the chances of gully development. Longer slopes can also contribute to increased sediment transport and deposition downstream, further exacerbating gully erosion (Cerdan *et al.*, 2010). The density of channels within a landscape affects the occurrence of gully erosion. A high-density channel concentrates water flow, increasing the erosive power and the likelihood of gully formation (Favis-Mortlock *et al.*, 2002). The distribution and connectivity of channels influence the potential pathways for water to concentrate and form gullies. The spatial arrangement of natural drainage patterns, such as dendritic or parallel patterns, can impact gully erosion. Dendritic patterns, characterized by a network of interconnected tributaries, may distribute water more evenly across the landscape, reducing the likelihood of concentrated flow and gully formation. In contrast, parallel patterns may promote concentrated flow, increasing the potential for gully erosion (Dearing *et al.*, 2003). Specific landform features, such as concave slopes, depressions, or knickpoints, can influence the occurrence and development of gullies. Concave slopes tend to concentrate water flow, increasing erosive power, while depressions may trap sediment and promote gully initiation. Knickpoints, sudden changes in slope gradient, often act as focal points for gully formation due to increased energy and hydraulic pressure (Phillips and Atkinson, 2000). The size and shape of a drainage area as well as the length and gradient of its slopes have an effect on the run-off rate and amount of surface water. Therefore, all topographic characteristics should be studied in detail before gully control work begins.

## 2.0 Study Area

The study was conducted in Uyo which is the capital city of Akwa Ibom in Nigeria. It is one of the important cities in the Niger-Delta region which is the predominant oil and gas producing area in the country. Uyo is situated between latitude 5° 01' North of Equator and longitude 7° 56' East of the Meridian. Large parts of the city are affected by gully erosion



**Figure 1: Distribution of gullies in Uyo metropolis**

Figure 1 shows the distribution of gullies on the map of Uyo, with majority of the gullies found in the north-eastern region. The central and southernmost parts of the study area also have few existing gullies while North-west and South-East do not currently have any existing gullies.

Gully erosions have serious social, economic and environmental impact on the affected communities. Table 1 shows the location of gullies in Uyo including some notable properties that are endangered as a result of the gully menace.

**Table 1: Distribution of Gullies Uyo and Some of the Endangered Properties**

S/N	Location	Projects/ properties endangered
1.	Uniuyo Permanent Site	A part of University of Uyo main campus, Private properties, farm lands, private properties within the environment
2.	Asutan Street	A part of University of Uyo town campus, Private properties, farm lands, churches, private properties within the environment.
3.	Effiong Udo Akpan	Private properties, churches, farmlands
4.	Calabar-Itu-Highway	AKBC Broadcasting Station, Calabar-Itu Expressway, private properties, churches, farm lands etc.
5.	Uyo Village Road	Science Park, Primary Health Center, Uyo Local Government Council Headquarters, Government House, Governor’s Office annex.
6.	Science Park and Environs	Uyo City Polyethnic, farm lands, private properties and churches.
7.	Dominic Utuks Avenue	Akwa Ibom State Government House, NITEL, Christ the King Nursery and Primary Schools,

		St. Brains Secondary Schools, farm lands and private properties.
8.	Udo Inwang	Residential properties, churches and farm lands
9.	Etim Umanah	Residential properties, churches and farm lands
10.	St Luke's Anua	General Hospital, school of Nursing and Mid-wifery, farm lands, churches, residential houses etc.
11.	Cornelia Cornelly Collage (CCC) Afaha Oku	Structures in the school compound which include class rooms, dormitories, refectory, administrative office, staff office/ apartments.

### 3.0 Materials and Method

The population of the study comprised gully sites within Uyo metropolis. Ten gully sites were purposively selected. The selection was based on the fact that these gullies were active and were very close to developed areas. The gully inventory maps of Uyo which shows Landsat images of various gully locations within the study area are shown in Figure 2.



Gully site at Cornelia Cornelly Collage (CCC) Afaha Oku



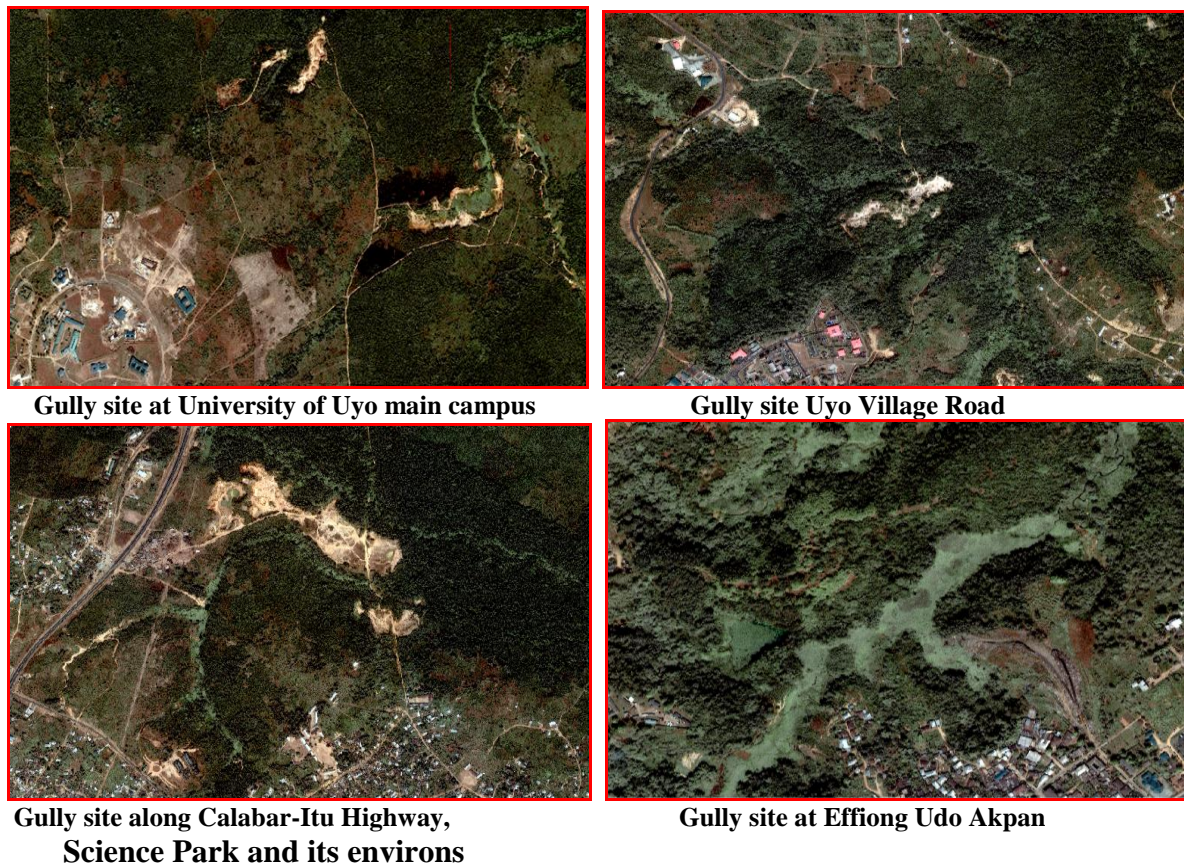
Gully site at Asutan Str., Effiong Udo Akpan



Gully site at Dominic Utuks Avenue, Etim Umanah, Udo Inwang



Gully site at St. Luke's Hospital Anua



**Figure 2: Gully Inventory Map of Uyo, Akwa Ibom State.**

Data for the study were obtained through extensive fieldwork and they were classified into primary and secondary data. The primary data sources included field observation using Unmanned Aerial Vehicle (UAV) and field measurements using RTK Dual Frequency Global Positioning System (DGPS), while the secondary data sources included unpublished documents, archives, statistical abstracts and reports from different offices. The elevation data and contour map of the study area was derived from Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) 2022 of 30m resolution.

A reconnaissance survey of the selected gully sites was carried out. Reconnaissance survey has to do with taking a general view of the study area. It also indicates the need to obtain an overall picture of what is required before any survey work is undertaken. During the field recce, the method of survey was considered and the most suitable positions for the establishment of Ground Control Points (GCPs) were decided on. The purpose of the survey and the accuracy required was known as these affected the choice of GCP stations and instrument.

Ground Control Points (GCPs) were established in the vicinity of the gully sites. A Ground Control Point (GCP) is a feature with known real-world coordinates that can be clearly identified in an image. GCPs are used in the orthorectification process to augment the geometric parameters embedded in the raw image and improve the accuracy of the resulting ortho-rectification. During the ground survey, the GCPs established was surveyed to obtain the precise coordinates with the aid of an RTK DGPS. The location of the GCP can be any point on the ground that can be precisely identified at the resolution of the raw image. During the ground survey, important precautions were considered when selecting the locations for GCPs. These precautions had to do with avoiding non-permanent features, shadows and

repetitive features such as periodic lines along a road, as it may be difficult to uniquely identify the matching point in the raw image.

First, the points were located on the ground with clear surroundings to make sure they are visible on the raw image. Selecting locations on flat ground also increases the expected accuracy of the digital elevation model (DEM) at the GCP location, having in mind that the DEM accuracy is another key factor affecting quality of the orthorectification. Second, it was important to choose a point that had high contrast with its surroundings to ensure that the point can precisely be identified in the imagery. Optimally selected GCPs can have a substantial positive effect on the resulting accuracy of orthorectification. Together with the image's geometric parameters and a high accuracy DEM, GCPs are a very vital component in ensuring the best orthorectification possible.

An Unmanned Aerial Vehicle (UAV) named Phantom 4 Pro was flown across each of the selected gully sites with a flight height of 100m above the ground and 80% overlap/ side lap and an average Ground Sampling Distance (GSD) of 3.08cm. Prior to flying the UAV, a flight plan was mapped out. A flight plan in drone mapping is the pre-defined route or path that a drone follows to capture aerial imagery or data for mapping purposes. These flight plans are essential for achieving accurate and efficient data collection, especially when conducting large-scale surveys or mapping projects.

There are several types of flight plans commonly used in drone mapping. The Grid Flight Plan was adopted during the field observation for this study. In this plan, the drone flew back and forth in a grid pattern over the area of interest. This pattern ensured complete coverage of the area and helped in creating a detailed map. The grid flight plan is commonly used for topographic mapping, agriculture surveys, and construction site mapping. The same processes were carried out at on all the gully sites for this study. The data for the study were analysed with the aid of these software, ArcGIS 10.7, Pix4D mapper version 4.4.9 and Microsoft Office 2016. Pix4D mapper which is a graphic software was used to analyse images captured using Unmanned Aerial Vehicle (UAV) also known as a drone. It is an aircraft that operates without a human pilot on board. These vehicles can be remotely controlled by a human operator or operated autonomously using onboard computers or pre-programmed flight plans

The frequency ratio (FR) method was used to analyse the data for this study using ArcGIS 10.7 software. The FR method chosen in this work have been widely used in gully mapping studies. As a commonly used method, the frequency ratio model employs bivariate statistical analysis to quantify gully susceptibility through individual factors related to gully and offers better accuracy than other methods. It takes into account the relationship of each predisposing factor and the occurrence of gully erosion, whereas it does not consider the relationship of all controlling factors on their own. In calculating the frequency ratio for each factor, the ratio of gully-affected cells to the total number of cells within specific classes of the factor's values were calculated. This calculation was done by dividing the frequency of gully affected cells by the frequency of non-affected cells within each class. Weights were assigned to frequency ratios of different factors based on their importance and influence on gully formation. These weights were determined subjectively or through statistical analysis. A summation was done for the weighted frequency ratios for each factor to obtain the final gully susceptibility index for each cell in the study area. The susceptibility index values were classified into different categories to represent varying level of gully susceptibility. Susceptibility is defined as the probability of the spatial occurrence of a phenomenon based on the relationship between the distribution of the studied phenomenon and a

set of geo-environmental factors controlling it (Luca et al., 2011)

#### 4.0 Results and Discussions

The geo-environmental conditions that determined the occurrence of gully were analysed using Frequency Ratio (FR). After the analysis, maps of the study area showing the gully conditioning factors are presented as Figures 2 to 9.

An aspect map is a geographical representation that shows the direction that a slope faces. From Figure 2, it is evident that the Northeastern part of the study area has high aspect.

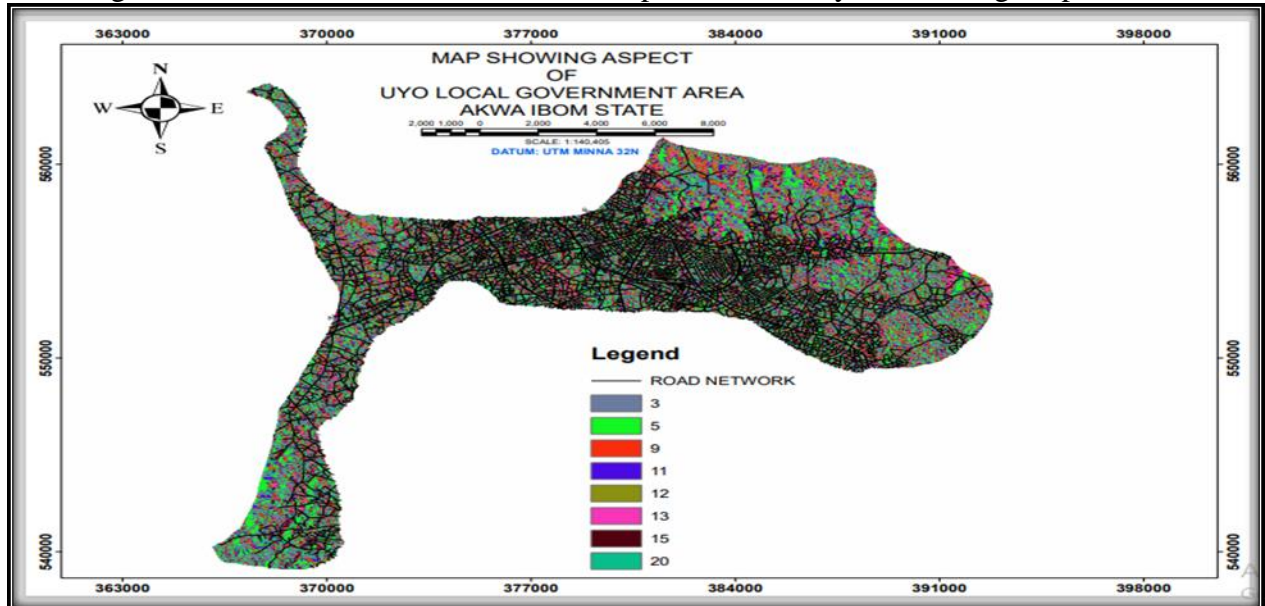


Figure 2: Map of Uyo indicating Aspect

Figure 3 shows the stream power (SPI) map of Uyo. From the map, high SPI values are revealed in the northeastern part of Uyo which indicates the erodibility nature of the terrain confirming the likelihood of sediment transport and gully formation while the low SPI values indicate areas with relatively low erodibility and less sediment transport.

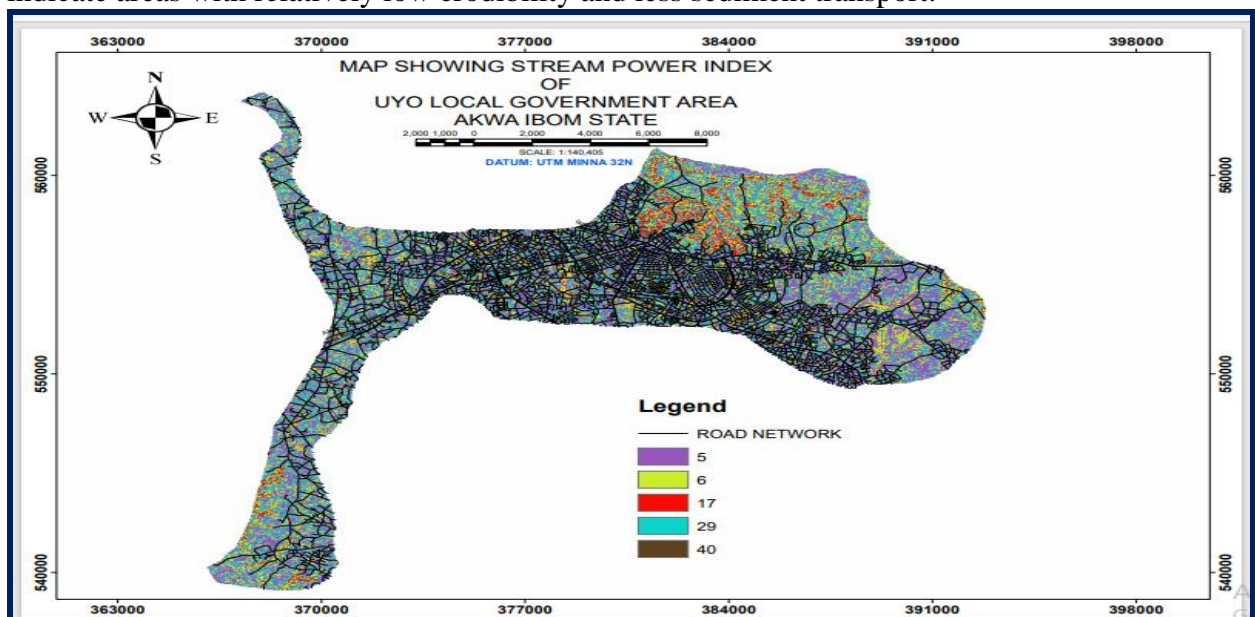


Figure 3: Map of Uyo indicating Stream Power Index

In the study, NDVI was used to assess vegetation distribution and vegetation health. As indicated in Figure 4, built-up and partly built-up areas are seen in the south-south and northwestern part of Uyo indicating urbanization while bare land and secondary vegetation is predominant in the northeastern part of Uyo indicating low vegetation coverage as a result of anthropogenic factors and natural events. The areas showing primary vegetation as indicated in the southeastern region have healthy vegetation which is important for soil compaction and stabilization which prevents surface runoff that results in gully erosion.

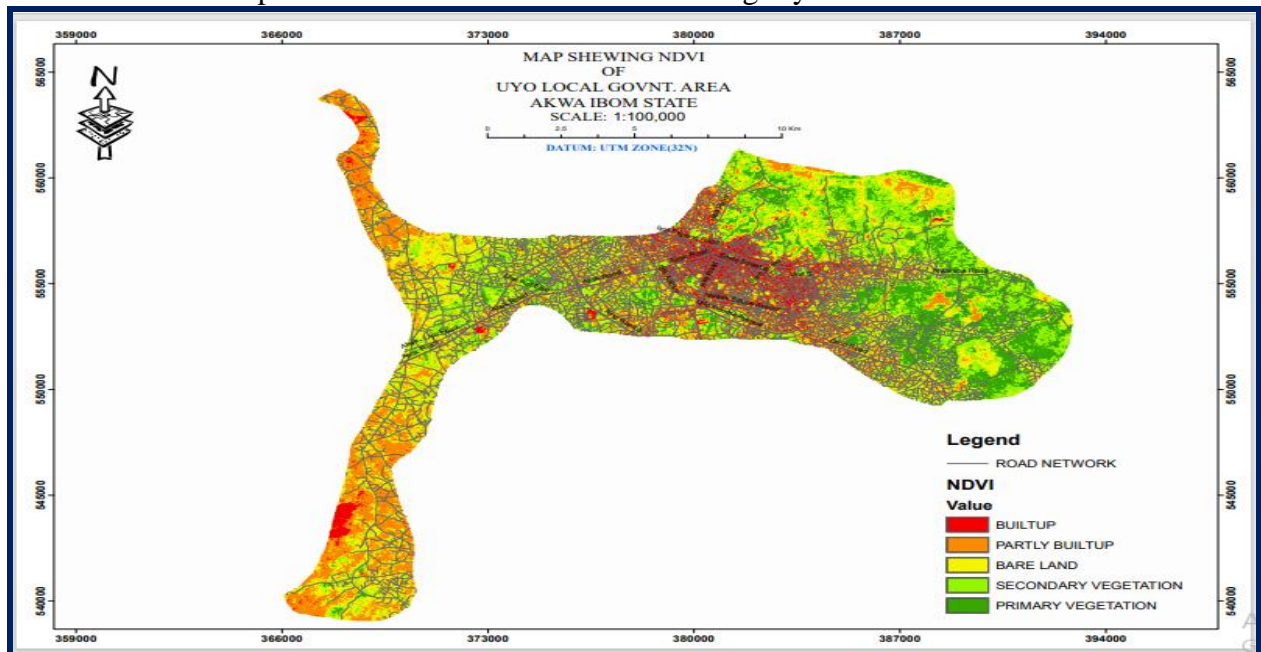


Figure 4: Map of Uyo indicating Normalised Difference Vegetation Index (NDVI)

From Figure 5, distance from road is closer to the gully points in the north-eastern and southwestern parts of Uyo. This is mostly due to concentrated and improper channelization of surface runoff along the pavement surface.

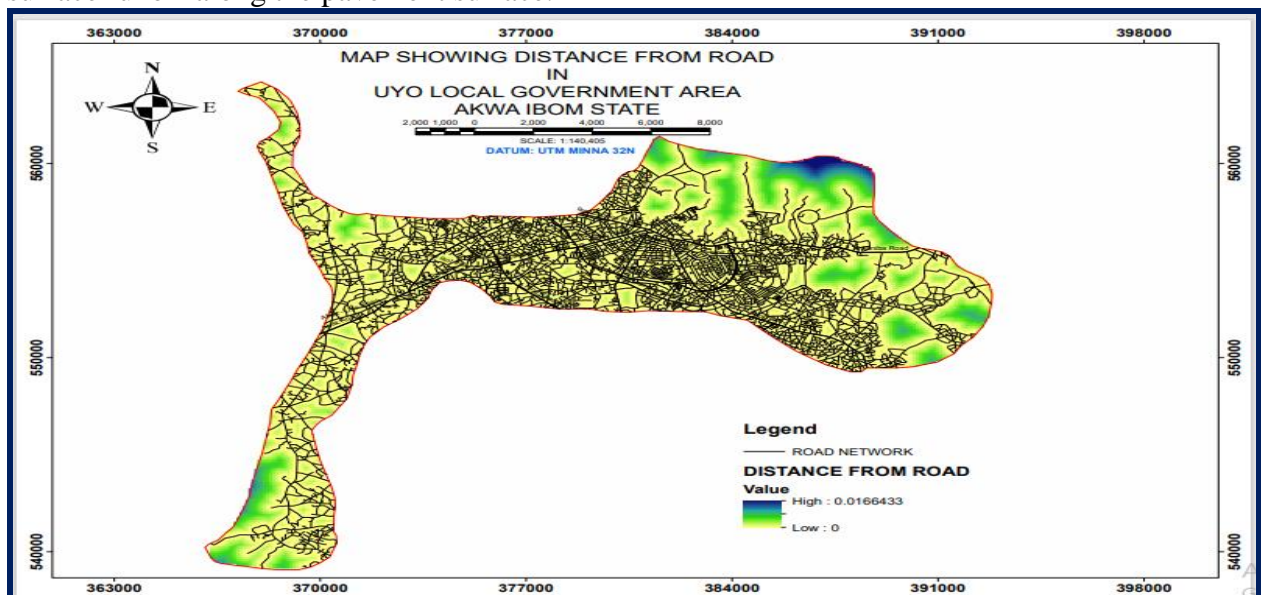
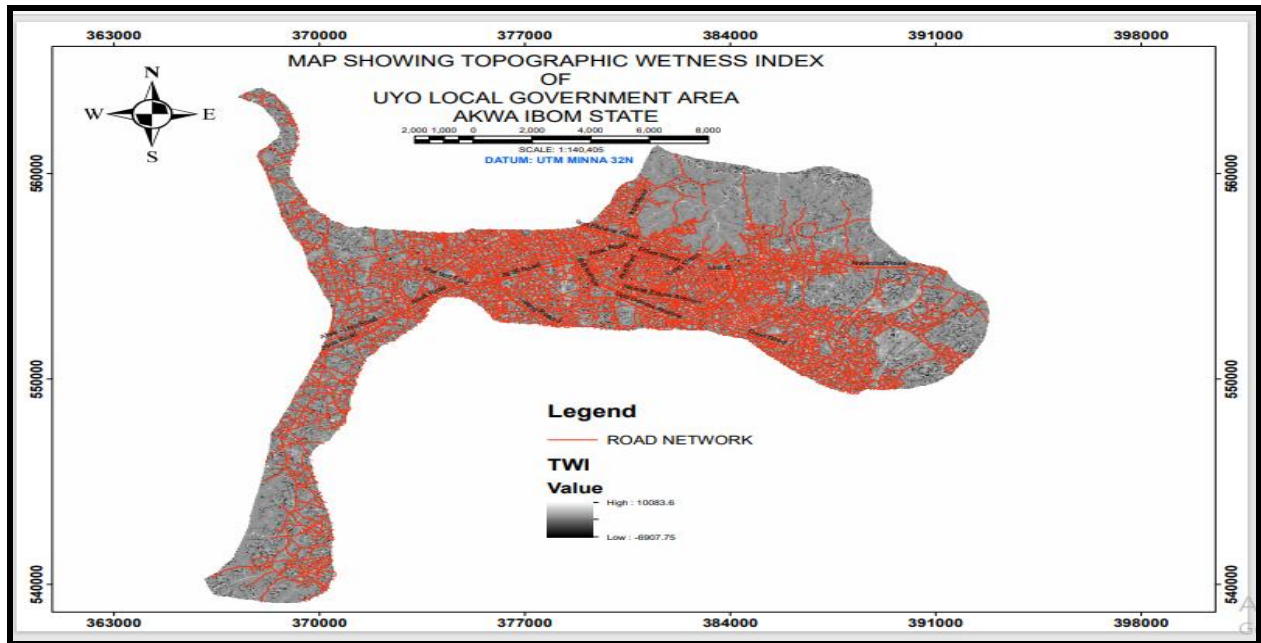
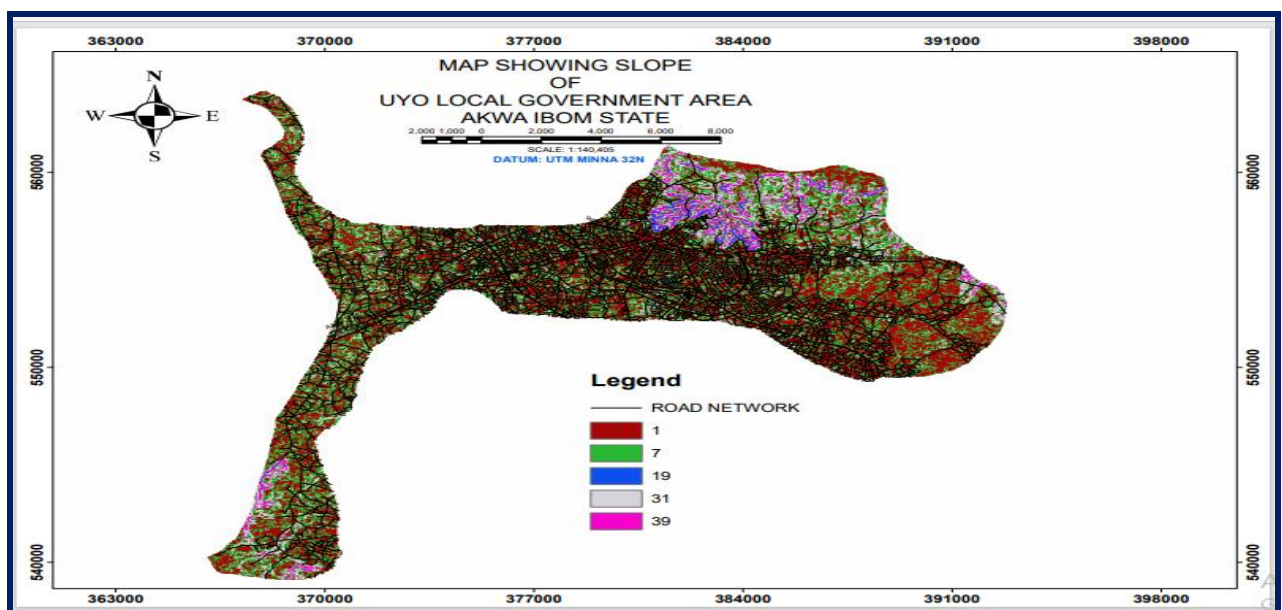


Figure 5: Map of Uyo indicating Distance from road



**Figure 6: Map of Uyo indicating Topographic Wetness Index**

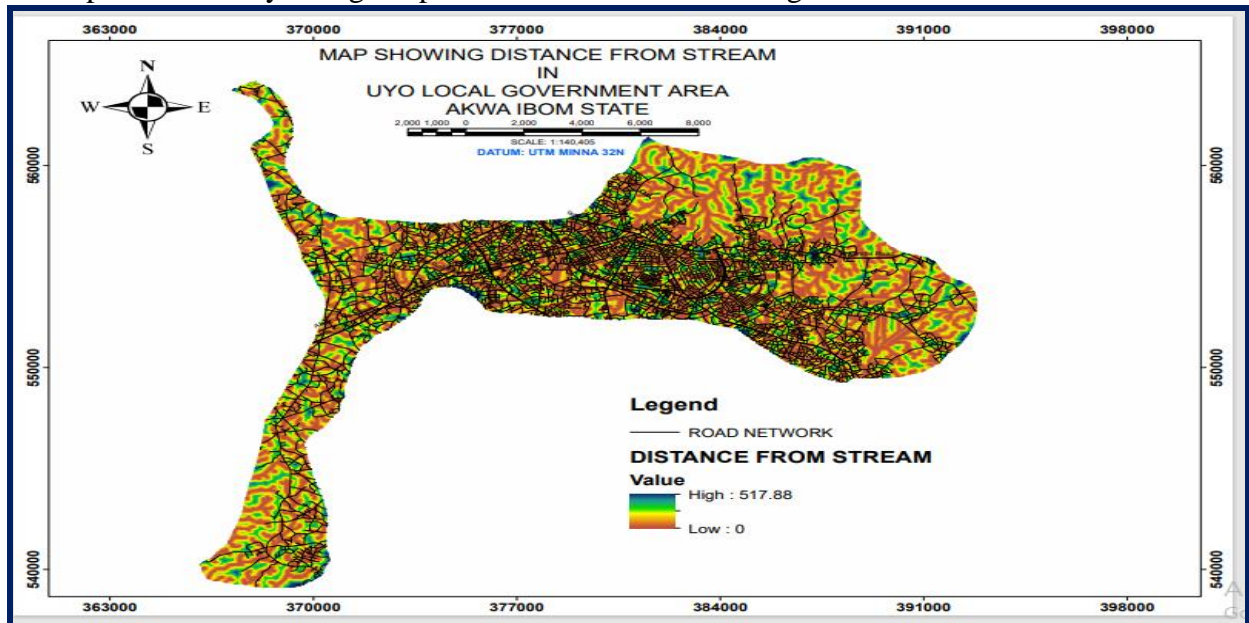
Topographic wetness index is used to locate possible gully head cuts. From figure 6, the TWI values in the northeast region suggest increased soil moisture and saturation content which indicates wetter conditions that is susceptible to gully erosion, and low TWI values are likely to be well-drained and less saturated, indicating drier conditions. Also, Figure 7 shows the slope map of Uyo. As shown in the map, the north-eastern and southwestern part of the Uyo indicates steeper slopes which tend to promote the velocity surface runoff. The high values of slope indicate the likelihood of gully erosion occurrence. The low values indicate a gentle slope, representing relatively flat terrain while the moderate slope percentage suggests moderate terrain, which can support a variety of land uses with proper management.



**Figure 7: Map of Uyo indicating Slope**

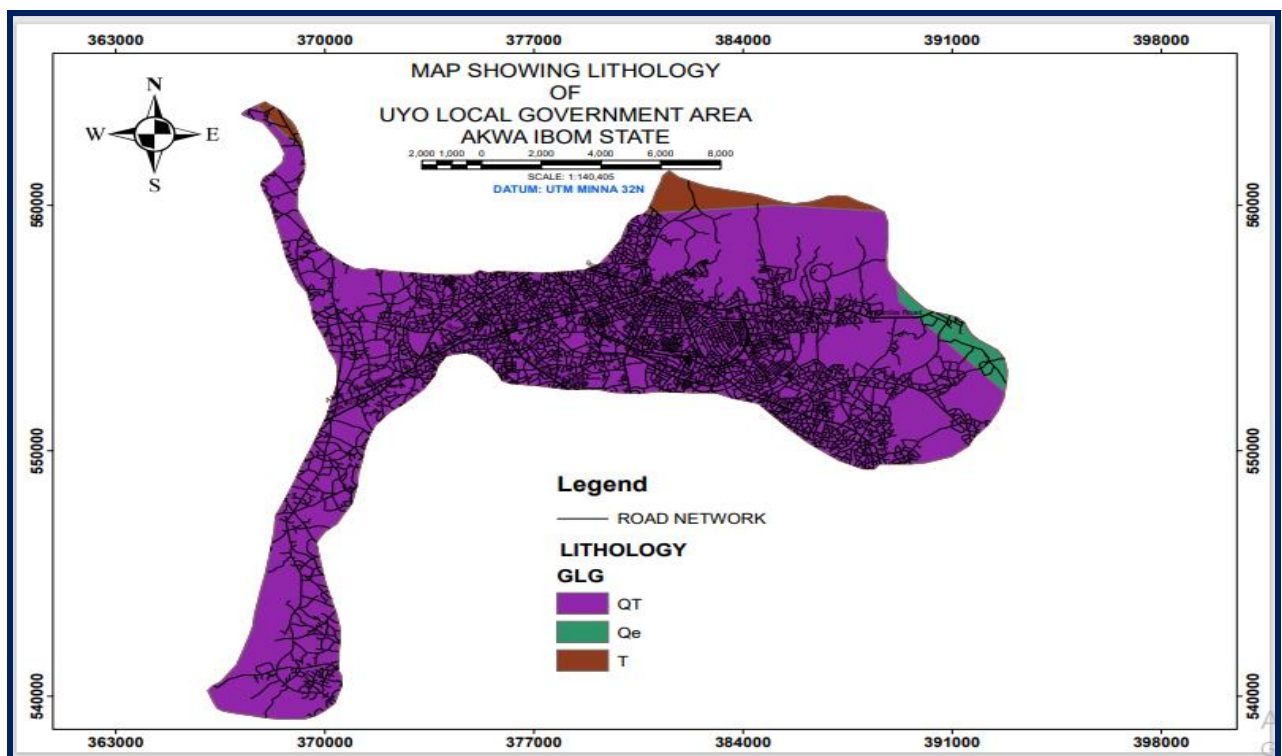
Distance from stream indicates the connectivity or the nearness between a gully and water body. From figure 8, water bodies in blue dots are closely scattered, which indicates that

gullies closer to the stream will experience higher moisture content and are at risk to flooding because of the stream related hydrological processes while gullies farther from streams will not experience the hydrological processes and risk of flooding.



**Figure 8: Map of Uyo indicating Distance from stream**

Lithology is the physical and chemical characteristics of rocks. From figure 9, the predominant lithological composition of the soil in the study area is one consisting of gravel, sand, silt and clay.



**Figure 9: Map of Uyo indicating Lithology**

Curvature is a measure of how landform slope changes along a given direction. From figure 10 the higher curvature values with darker brown colours within the north-eastern region of

Uyo is more prone to gully formation while areas with low curvature values are not prone to gully erosion.

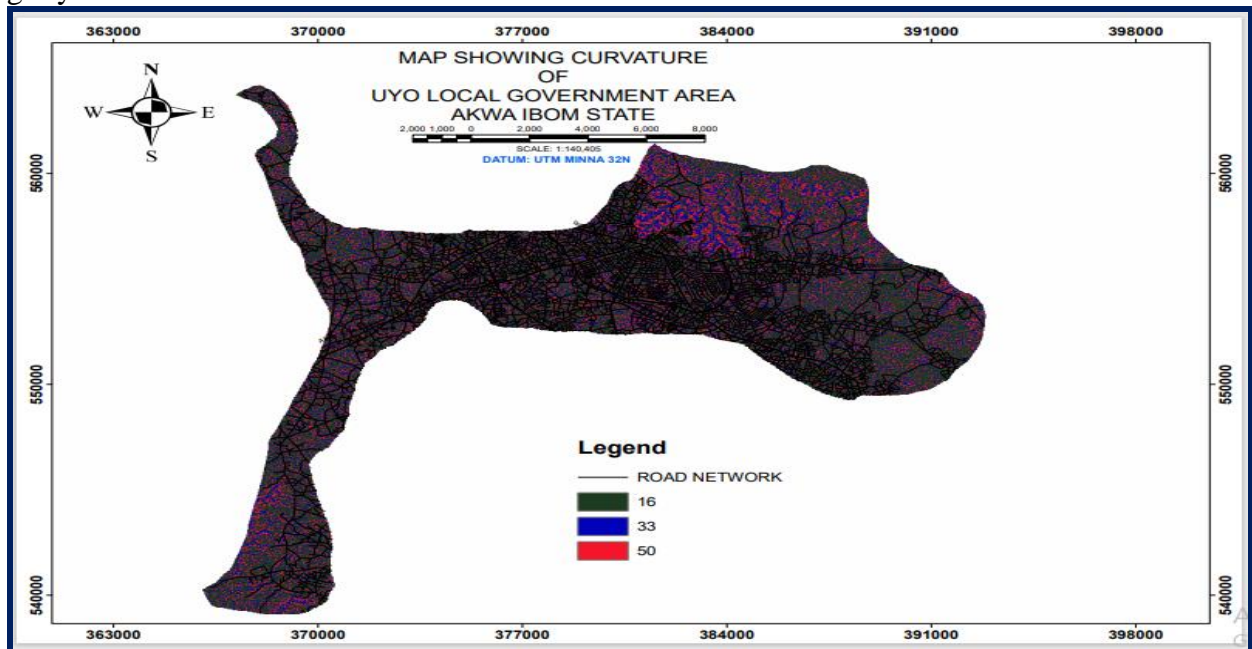


Figure 10: Map of Uyo indicating Curvature

Frequency ratio entails the use of bivariate statistical analysis. The spatial relationship between the gully origin and each predisposing factor was derived by the ratio of the area where gullies were concentrated with respect to the total area studied. Where the frequency ratio represented by the proper ratio (PR) is greater than 1, it indicates that the predictor is positively associated with gully erosion, and if the frequency ratio (FR) is less than one, it indicates that the predictor is negatively associated with gully erosion. The result of the frequency ratio analysis is reflected in Table 2 which shows that all the geo-environmental factors included in this study are positively associated with gully erosion since they all have a frequency ratio that is not less than 1.000. The result also shows that rainfall with a FR ratio of 3.267 is the most important predisposing factor contributing to gully erosion in the study area. Other important conditioning factors include distance from road, NDVI and distance from stream. The geo-environmental factor with the least influence on gully erosion in the study area is aspect which has a frequency ratio of 1.000.

Table 2: Frequency Ratio of Geo-environmental Factors Influencing Gully Erosion

Geo-environmental factors	Frequency Ratio	Rank	Remarks
Rainfall	3.267	1	Positively associated
Distance from road	2.710	2	Positively associated
NDVI	2.599	3	Positively associated
Distance from stream	2.345	4	Positively associated
Slope	2.295	5	Positively associated
Stream power index	2.058	6	Positively associated
Curvature	2.032	7	Positively associated
Aspect	1.000	8	Positively associated
Topographic wetness index	1.000	9	Positively associated

In summary, the analysis from the FR model shows that the geo-environmental factors that predisposes an area to be classified as highly susceptible to gully include rainfall, distance from road, normalised difference vegetation index (NDVI) and distance from stream.

The results as shown in Table 2 indicates that all the geo-environmental factors included in this study are positively associated with gully erosion. These factors include rainfall, slope, aspect, curvature, topographic wetness index, stream power index, NDVI, distance from stream and distance from road. In a study by Arabameri *et al.* (2008) distance from road was found to have a significant effect on gully erosion occurrence. Several authors (Poesen *et al.*, 2003; Martı́nez-Casasnovas *et al.*, 2004, Valentin *et al.*, 2005; Zucca *et al.*, 2006; Svoray and Markovitch 2009; Conoscenti *et al.*, 2013) have also noted that rainfall, distance from river, slope steepness, and slope curvature are critical conditioning factors for gully erosion occurrence and development.

The outcome of this study revealed that rainfall was the most significant geo-environmental factor for gully erosion in the study area. The yearly heavy rainfall has very adverse impacts altering existing landscape and forms. Such landforms create deep gullies that cut into the soil. The gullies spread and grow until the soil was removed from the sloping ground. Soil erosion when formed expand rapidly coupled with exceptional storm or torrential rain down the stream by head-ward erosion gulping up arable lands, economic trees, homes, lives, and sacking of families and valuable properties that are worth millions of naira (Umudu, 2008). The result of a study by Udosen *et al.* (2014) had concluded that gully complex is caused by heavy rainfall exceeding the capacity of the drainage systems which include the outfall drains, the culverts and the estimated catchment area, increased paved area giving rise to increased run-off; other anthropogenic activities in the vicinity of the gully and the weak and unconsolidated coarse-textured coastal plains sand. This result is also consistent with another study by Umo *et al.* (2018) which revealed that gully erosion in the Etim Umana area of Uyo is caused by high incidence of rainfall and surface configuration but accelerated by anthropogenic activities such as urbanisation, farming and construction-related activities.

The result of the present study also indicated that other important conditioning factors of gully erosion included distance from road, NDVI and distance from stream. This is in agreement with the research by Umo *et al.* (2018) which revealed that scarcity of vegetation cover exercised a strong influence on the gully migration.

## 5.0 Conclusion

From the result of the study, it is concluded that a wide range of geo-environmental factors are responsible for the occurrence of gully erosion, although rainfall, distance from road, NDVI and distance from stream are the most significant geo-environmental factors responsible for gully development. In addition, aspect, which measures the direction that a slope faces, is not a significant geo-environmental factor in gully development.

Based on the findings and of this study, it is recommended that proper land-management practices should be employed to prevent forest fires and illegal wood logging and to avoid open lands development which can evidently lead to gully development. It is believed that if the vegetal covers are allowed, it may lead to soil stabilisation. Since urban development is tied to the removal of vegetation and the physical environment which helps to create open lands, it can be reduced and controlled, and this in turn will reduce the level of gully formation and development. Also, farming along the slopes should be totally discouraged as this activity has the potential to expose the slopes to gully development.

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