Determining Causes of Gully Erosion and Associated Rates of Change in South-East Nigeria, using a Remote Sensing and GIS Methodology

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Abstract

In this work a study of gully erosion in southeast Nigeria is presented. The study of gully development on a regional scale is currently undermined by the inherent costs associated with consistent field monitoring and the lack of historic measurements to perform time series analysis. As a result, there are very few studies which implement long term analyses of gullies in the region as a collective. Consequently, the building of knowledge of the role of environmental changes on the development of gullies is inhibited. Remote sensing methodologies, via the Landsat archive, are used as a low-cost data source to allow analyses of gullies over the time period 1986 to 2015. In conjunction with long term environmental variables, the Landsat data is used to establish landcover changes over the time period, via pixel and object-based classification, to identify its role in gully development. The use of classification for this purpose identifies this study as a first of its kind in Nigeria. Aiming to link environmental characteristics and land cover changes with gully development and erosion rates at multiple current locations. 14 gully sites, identified via field work validation of remote sensing imagery, are monitored in terms of extent and rates of change. Digital Elevation Models (DEM) and remote sensing imagery are used to detect topographical and landscape characteristics and to calculate gully dimensions. The influence of environmental variables on gully development is directly examined using soil, geology, and precipitation. Landscape analysis over the study period reveals a steady increase in Gully/Open Land both locally and regionally; the increasing area of gullies consistently correlating with vegetation clearance, ($r= -0.97$ ($p<0.05$)). Analysis of study area topography at 30m resolution reveals 85% of the surveyed gullies develop on concave slopes with high values of 6 plan curvatures and $>5^0$ inclines. Results also reveal high association with ferralsols soils. Statistical analysis to determine significance of variables on the proportional yearly gully change in metre squared per square metre were conducted via hierarchical cluster analysis, principle component analysis and multiple linear regression. For this, analysis was restricted to the time periods 2006/7, 2009/10, and 2014/15. None of the approaches reported the existence of one singular driver of erosion across the studied years and multiple sites confirming the complexity of gullies. Regression R^2 achieved a maximum of 0.325 in year 2014/15 when using the independent variables Gully Area, Vegetation Loss, Elevation, Gully Stream Order, Slope, and Soil. Cluster analysis showed contrasting results across the 3 studied time periods with yearly gully change in metre squared per square metre clustered most closely with vegetation loss, slope, gully stream order and soil in year 2014/15 and 2009/10 and vegetation loss and elevation for 2006/07 in the respective years. The PCA showed that the level of variance explained in the yearly gully change variable was most similar in

PC1 (representing the component with the highest eigenvalue) to Vegetation loss, Vegetation loss and slope in the respective years. Comparison of open source and proprietary approaches to the methodology reported close similarity in results with no statistically significant differences. The study offers a method of monitoring gully development from early stage to maturity and exemplifies the complexity and variability of erosion drivers in the SE Nigeria region. It presents a verified approach to local and regional monitoring of gullies, enacted through use of low budget/computing cost remote sensing and classification technologies, and serves to embolden civilian and governmental efforts to manage the societal and environmental menace of soil erosion.

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Declaration

I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author. The thesis has not been previously submitted to this or any other university for a degree, and does not incorporate any material already submitted for a degree.

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1 Introduction

Gully erosion has been recognized as one of the major causes of land degradation worldwide (Valentin et al. 2005). Gully erosion has attracted a growing interest as reflected by some international conferences at Leuven, Belgium (Poesen and Valentin 2003), at Chengdu, China (Li et al. 2004) and Purdue University in West Lafayette, Indiana, USA, May,2016. Some recent research works (Wu and Cheng 2005; Okoro et al. 2013; Castillo and Gomez 2016) have shown that the loess plateau of China, Orlu Nigeria and Cordoba, Spain land surfaces are being eroded, washed away and rendered sterile due to gully erosion. Gully erosion has been a growing concern to mainly the developing world which could be due to both intentional and unintentional activities of humans on the physical environment (Duke et al. 2012).

In southeast Nigeria, gully development has become one of the greatest environmental hazards in many villages and towns (Ezezika and Adetona 2011). Ofomata (2008) observed that about 2% of the area is fast becoming hazardous to human habitation because of gully formation and subsequent degradation in the area.

Figure 1:Gully Erosion in Onitsha southeast Nigeria

Unfortunately, according to Igbozurike (2010) about 5000 people are directly or indirectly affected by this, causing forced relocation from ancestral homes every year, as can be found in Nanka-Agulu and Onitsha southeast Nigeria observed in **Figure 1** above. About 12% of agricultural lands are becoming unsuitable for cultivation as gully erosion destroys farmlands and lowers agricultural productivity through removal of essential top soil (Egboka et al. 1990). The formation of gully erosion and sediments are a function of rainfall, soil properties, and topography, and can be induced by human interference including land management practices. The rainfall intensity is high in this area of Nigeria and often persists for long durations. Storms with over 25 mm/h intensity have been reported by Hudson (1981) to be particularly erosive. Igwe (2004) observed in the region that most gullies develop at slopes, cuestas, fractures and joints which are common features in the gully-erosion-prone areas of Southeast Nigeria and have been identified as significant factors in the formation of gullies and subsequent erosion. The study area has also seen increased erosion rates through the exacerbating effect of mineral extraction sites (Gobin et al. 1999; Okagbue and Uma 1987). The loss of soil degrades arable land and eventually renders it unproductive. As a result, there are significant per capita shortages of arable land. The effects of this erosive action are made more severe by recent and rapid population growth in the Southeast region of Nigeria. Loss of agricultural output is one of the greatest economic costs of gully erosion (Pimentel et al. 1995). Unquantified large portions of land have been degraded in recent years in towns such as Ekwulobia, Agulu-Nanka, Orlu, Iyioku, Njaba, Igboukwu, Okigwe, Abiriba, Mbaise, Uturu, Ideato, Amucha. In addition, infrastructure, and in particular roads, have been damaged, leading to numerous vehicle accidents and displacement of residential houses. A number of studies have been conducted on the causes of gully erosion in Southeast Nigeria and ways to control them. Most of the studies primarily revolve around causes based on the immediate scenario rather than the long term causes as can be found in (Igbokwe et al. 2008; Ezezika and Adetona 2011). They also deal more with combating gully erosion rather than its prevention and pay little attention to methods of managing this natural hazard.

1.1 Gully Erosion as a Global Issue

“The past is the key to the present and the future” and “Those who cannot remember the past are condemned to repeat it” (Lang and Bork 2006; Argentieri et al. 2015). Gullies and their morphology can provide evidences of past soil erosion periods showing changes on environmental impacts like landcover and rainfall pattern (Poesen 2011). Soil erosion and gullying is not solely a modern phenomenon relating to modern industrialised land management. There have been documented cases throughout history which provide evidence and warnings of the difficulties gullies can cause. Research carried out by Mieth and Bork 2005 on Easter Island for example, revealed, through stratigraphic analysis, that from the beginning of human settlement around AD 300/600 until AD 1280 the agriculture on the Poike peninsula (in the northwest of the island) was characterised by sustainable land use and traditional agro-forestry. Soil erosion was not significant until around AD 1280 when the woodland on Poike, dominated by the endemic palm Jubaea, was cleared following a slash and burn approach. Intensive farming on the upper slopes of the volcanic peninsula resulted in sheet erosion lasting until the 20th century.

In Europe, Dotterweich (2008) reported that the most remarkable phases of soil erosion occurred in the first half of the 14th century. In central Europe, phases of agricultural expansion and regression occurred with land clearance and deforestation back to the onset of agriculture, around more than 500 years ago and towards the mid-18th to early 19th century which was reported first in Germany (Lederman et al. 2017).

Hugh Hammond Bennett, who was a soil surveyor for the USDA Bureau of Soils from 1903 through the 1920s, emerged as a national spokesman and advocate for soil conservation and soil erosion research (Cook 2015). Bennett brought the problem of erosion to the forefront of public and political attention. Combined with the devastating drought, wind erosion and dust storms of the "Dust Bowl" in the Great Plains, impetus was provided for Congress to provide initial funding of $160,000 in 1929 for research on soil erosion (Cook 2015).

Africa remains an understudied continent compared with other continents like Europe and America (Showers 2005). Few documents have been analysed from an earth perspective, oral histories of societies and their landscapes have not been fully collected, analised and in most locations, archaeological research has been very limited (Asrat et al. 1996). During the colonial era, governments tried to force peasants and farmers to adopt scientifically approved farming techniques. This led to the dropping of shifting cultivation method which has been providing long fallows to the soil, providing instability to soil leading to soil/gully erosion development (Showers 2005).

Gully erosion has been progressing in the continent of Africa rapidly for many generations, owing to the settled conditions attendant on European rule, it has become urgent importance and it is now recognized as a vital problem (Fleitmann et al. 2007). Until recently, the human inhabitants were not sufficiently numerous in Africa to bring about gully development as can be observed today which has now increased by natural processes (Mulwafu 2011).

The Democratic Republic of Congo is within the tropical Congo basin rainforest in Central Africa, the climate is generally hot and humid (Imwangana et al. 2014). Mokembe (1994) reported that Gully erosion was noticed during the time of colonial era thus incessant logging, introduction of mechanized agriculture and solid mineral extraction. In Kinshasa, the first signs of gullying were reported by

Ploey (1975) and by Caillie 1983 when the western plain along the Malebo Pool became completely Urbanised in early 1970s and the built-up areas started to extend into the hilly landscape to the south. Caillie (1983) correlated the vertical incision of drainage lines with slopes steeper than 0.12 to 0.25mm-1. According to Caillie observation most of the gullies develop due to high runoff from the bare slope where the vegetation cover has been removed and the convergence of runoff develop gully head. Democratic Republic of Congo has the same climate and soil with southeast Nigeria.

An overview of contemporary global soil degradation is shown in **Figure 2**. As of 2006, the proportion of degraded areas in the world varied from approximately 16% in Europe to 30% in North America, 35% in South-America and 45% in Africa with the highest proportion of degraded land located under rain-fed agriculture and rangeland (Food and Agricultural Organisation 2006). According to the Food and Agricultural Organisation (1993), the first global survey of soil erosion revealed a steady decline in crop land over the 30 years from 1961 to 1991, amounting to a decrease in useable soil area of between 20% and 30% globally. For example, global cropland area (hectares) per person in Africa reduced from 0.6 ha. /person to 0.2 ha/person, North and Central America from 1 to 0.8 ha. /person, Asia 0.4 to 0.2 ha./person, South America 0.4 to 0.3 ha./person and Europe 0.4 to 0.35 ha./person.

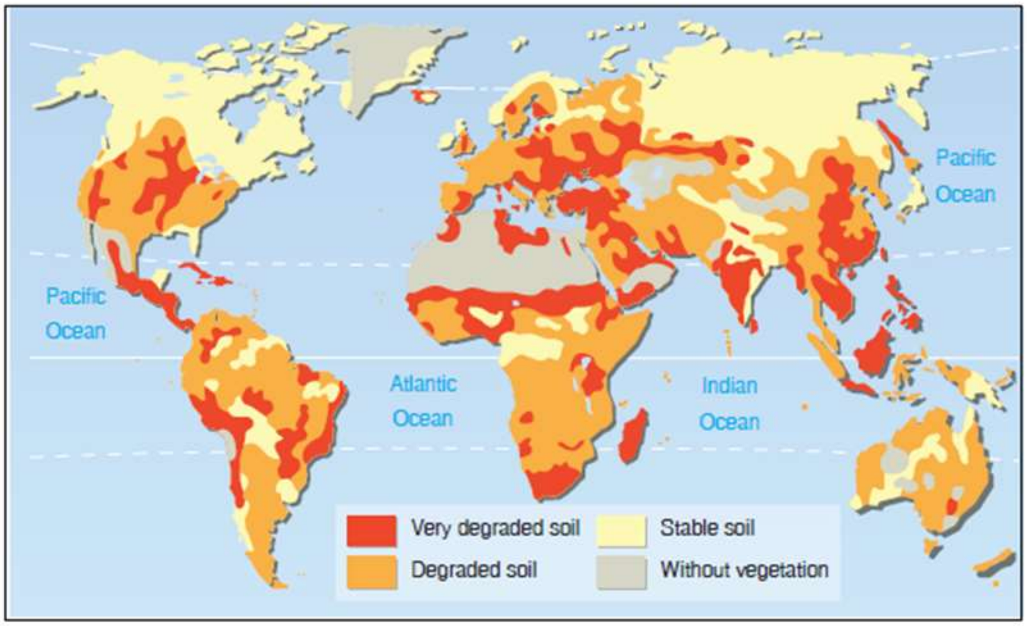


Figure 2: Areas of Concern for Soil Degradation (International Soil Reference and Information Centre 2008).

Sub-Saharan countries in Africa are plagued by serious environmental degradation resulting in desert encroachment, drought, and soil erosion due to either wind impact or very high intensive rainfall, resulting in heavy runoff and soil loss. The Food and Agriculture Organisation (2006) have identified the crop land of south-east Nigeria as an area that is in increasing danger from soil degradation and in particular gully erosion. According to Udo (2010) and Igwe (2012), gully erosion has caused massive soil loss, greatly reducing agricultural production in the area, has destroyed lives and properties, and forced community displacement as unsafe or unsustainable ancestral homes must be abandoned.

In southeast Nigeria, anthropogenic activities such as mineral and resource exploration, and extraction have a detrimental effect on the environment and landscape. As recently as 150 years ago south-east Nigeria was covered by thick rainforest which included the indigenous tree species of Iroko, Bamboo, and Mahogany (Integrated Regional Information Network, 2011). The loss of vegetation cover is often a major consequence of resource extraction. Illegal activities conducted without regard to conservational laws are common place in the region, and the consequences are manifested in the landscape by soil erosion enacted by the processes of weathering and erosion.

1.2 Methods of Monitoring Gully Erosion

Gully processes have for sometimes been neglected because gully processes are difficult to study, difficult to monitor and to control (Ehiorobo and Izinyon 2012). When gully erosion is not properly studied and monitored, the control of such gully will be difficult. Monitoring techniques as listed by some studies like visual indicators of gully erosion, remote sensing and ground monitoring and close-range photogrammetry (Ypsilantis 2011). All these have been used in monitoring gullies but Du and Noguchi (2017) recommended remote sensing and field work monitoring as being more efficient and effective. Poesen (2011) opined that classical aerial photos rarely provide sufficient detail for gully monitoring, hence low-altitude aerial photos like the additional use of kites, poles and balloons to gather aerial data are needed. and this approach has been recently explored by various researchers in Germany, Spain and the USA. For instance, Marzolff and Poesen (2009) explored the potential of 3D gully monitoring with GIS using high-resolution (low-altitude) photography and a digital photogrammetric system to document gully head evolution over a 6-year period which shows a possibility of distinguishing different zones of activity both at the gully rim and within the gully interior, identifying patterns of erosion and deposition. Wang et al. 2016 utilised multi-source remote sensing data, including satellite and UAV (unmanned aerial vehicle) imagery simultaneously, for effective assessment and monitoring of gully erosion at the Sancha River catchment in Northeast China, where gullies extend over a vast area. This method was also used by Klaus et al. 2015.

Mathias and John (2009) used documented ground measurement in monitoring Agulu-Nanka gully erosion in southeast Nigeria and discovered that the gully is retreating since 2009 due to government intervention. Igbokwe et al. (2012) used satellite images in Mapping and Monitoring of the impact of gully erosion in southeastern Nigeria with satellite remote sensing and geographic information system. Di Stefano and Ferro (2011) measured and monitored rill and gully erosion in Sicily it was observed that the length is a key parameter for the estimation of the eroded volume, also Magnus and Audu (2010) used manual ground measurement in Monitoring of Ndombolo gully site in southern Cameroun and observed that the gully has been developing in size from 1998 to 2002. Short-term gully head retreat monitoring only reveals short-term retreat rates and these can be significantly different from long-term trends. Hence there is a need for longer term monitoring, not only of gully heads but also of entire gully channels to better understand gully dynamics (Poesen 2011).

1.3 Aim and Objectives of the Study

The aim of the research described in this thesis is to develop a low cost GIS and Remote Sensing methodology for monitoring and quantifying gully erosion and development over time, identifying the impact and incorporating analysis of environmental factors and land use change. The specific objectives of this study are to:

1. Use remote sensing data (Landsat and ALOS PALSAR) to determine change in land-cover through Pixel based and Object Based Image Analysis (OBIA) classification over a maximum 30-year period (1986 – 2015) in SE Nigeria. The classification methods for this purpose will be compared and contrasted.

2. Vectorise and quantify gully extent and rates of change of gully sites over identified life spans. Gullies chosen using remote sensing data according to associated severity and level of management.

3. Generate Digital Elevation Models (DEM) to detect changes and calculate gully dimensions of focused gully sites (to observe how slope, nature of slope, aspect and gully stream order influence gully development).

4. Map dynamics of deforestation and forest degradation in southeast forests using radar satellite data and identify, if any, links between gully erosion rate and vegetation removal.

5. Employing the use of soil and geology maps of the study area to determine the prevalent types of soil and sediment, and identify relationships with those sites yielding more rapid gully erosion and associated meteorological data.

6. Identify the feasibility of establishing an open source methodology, comparing with commercial one to incorporate those living in low GDP countries like Nigeria.

1.4 Study Area

Gully Erosion occurs in numerous areas within the South-East states of Nigeria. Erosion problems arise mainly from natural causes but their extent and severity are increasingly attributed to anthropogenic ignorance and unintentional action (Enabor and Sagua 1988). In spite of technological advancement including land-use planning (United Nations Development programm 2015), run-off catch pits (Igbozurike 1989), and drainage channels (Nekatet 2006), gully erosion still remains a major problem in the region. The academic community has observed that gully erosion, is largely a result of natural factors including rainfall run-off (Njoku et al. 2014), and the geological (Nachtergaele 2002) and geomorphological (Bennard 2012) context of the area. There is further agreement that these naturally occurring conditions are prime for gully erosion but are exacerbated by anthropogenic factors such as land-use change and degradation (Vander Veen, 2010). Each of these occurrences act as push factors in causing gully erosion (Egboka et al. 1990).

The study area is located in south-east Nigeria between 7^0 8'N 6^0 34' E and 4^0 49' N 8^0 15' E covering a land area of approximately 57,758.034Km^2, as shown in **Figures 3, 4 and 5**. It is characterised by coexisting types of land use and land cover, which are mainly affected by gully erosion.

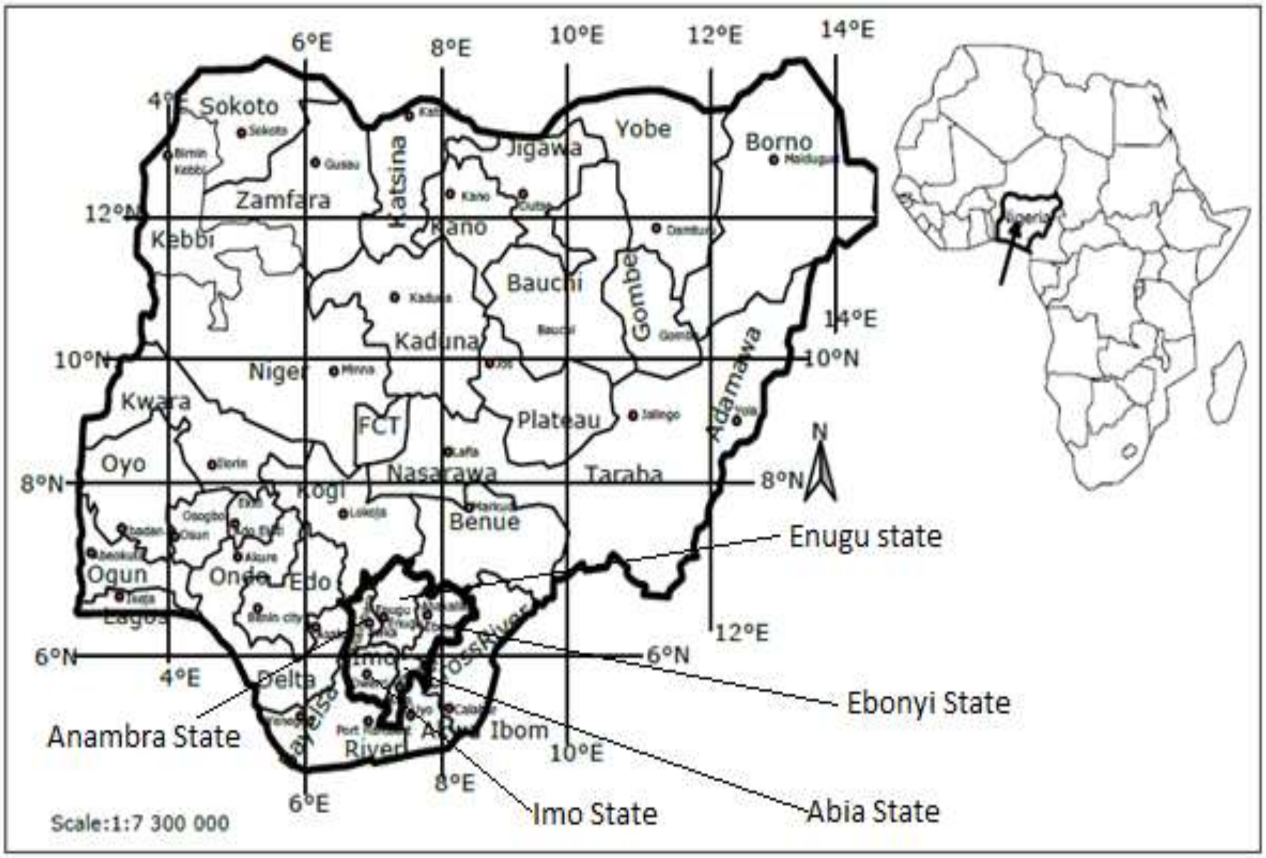


Figure 3:Nigeria highlighted within the continent of Africa. Study area outlined for context (Iloeje 2010)

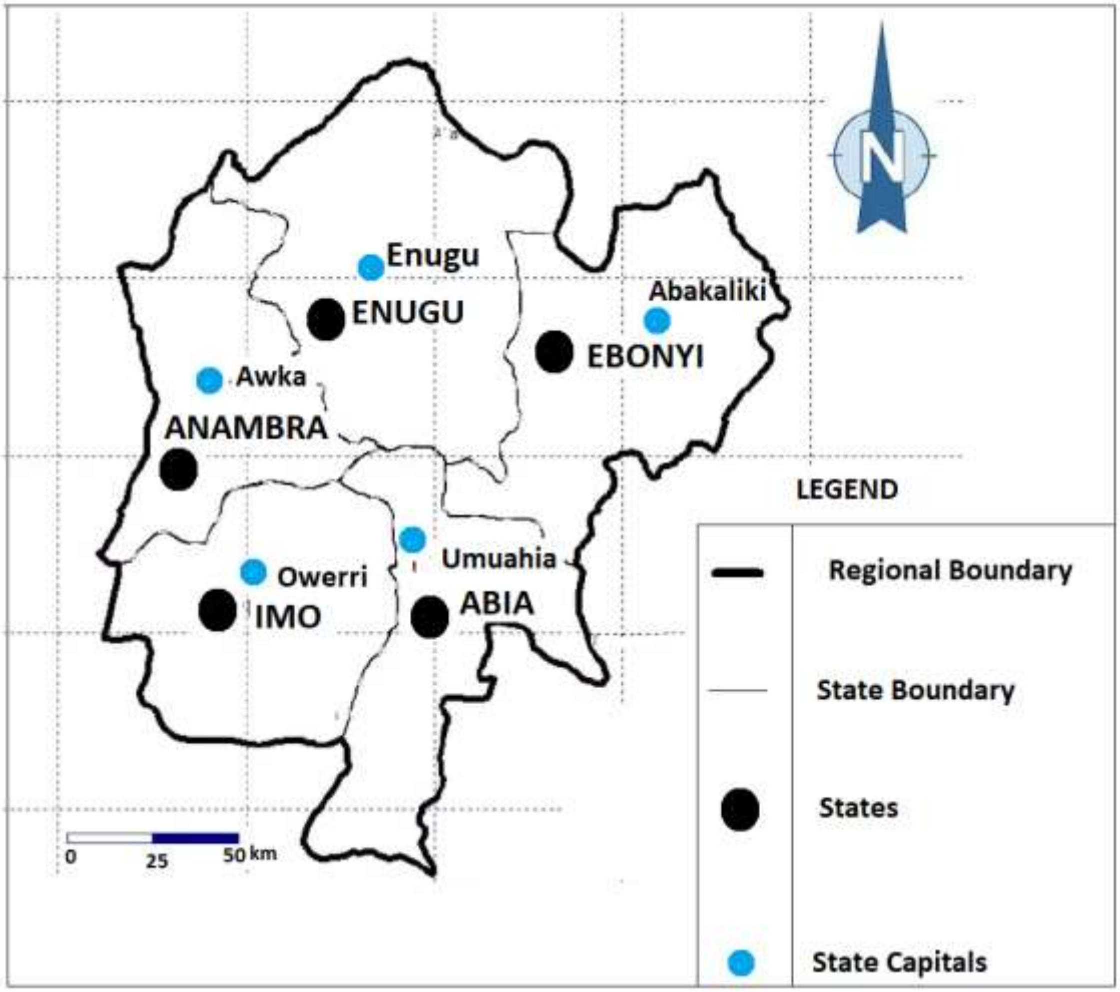


Figure 4: Map of south-east Nigeria showing the states and their capitals (Iloeje 2010)

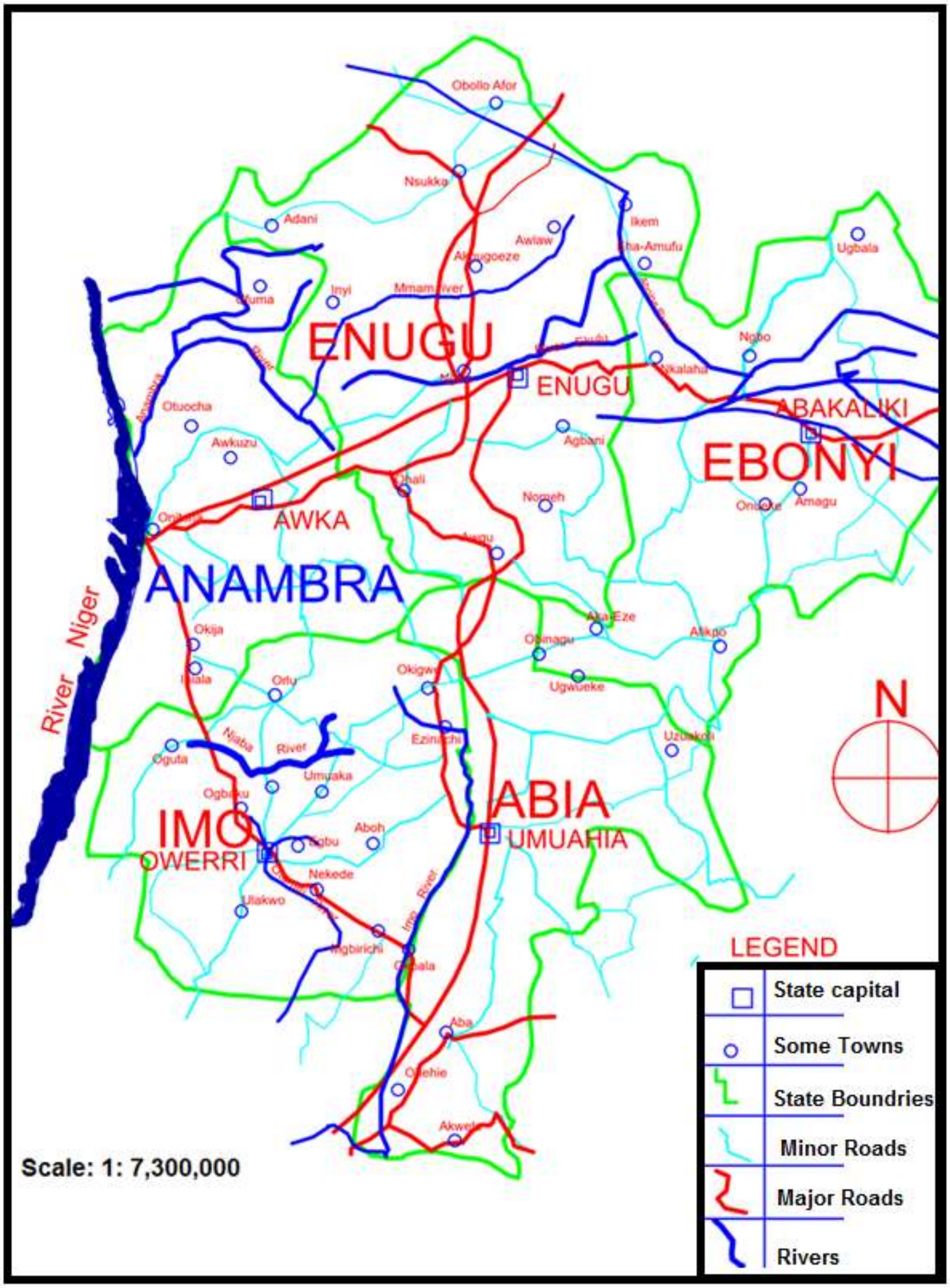


Figure 5: Map of south-east Nigeria showing rivers and major urbanisations (Iloeje 2010)

The study area lies within the humid tropical rainforest belt with an annual rainfall of approximately 1800-3000mm (Abayomi et al. 2001). Vegetation in the area is controlled by topography (which varies mainly from flat to swamp like regions), relief and lithology, with anthropogenic factors such as abandoned industrial sites also playing a defining role (Igwe, 2005). The vegetation ranges from rainforest to Guinea Savannah (Iloeje 2010). Dense vegetation with high trees is prominent around streams and shaley lowlands while guinea vegetation and isolated trees are prominent on sandy soils in highland areas (Obiadi et al. 2011). The tropical soil of the area supports extensive plantation forests, such as Oil palm, Rubber, Cocoa and Bananas (Aregheore 2009). Human activities such as bush burning, agriculture and construction works have greatly modified the natural vegetation in the area, potentially contributing to the creation and extent of gullies (Ujoh, et al.2011). Moreover, soil, geology, slope and rainfall maps of the study area are included in the literature review of this research work.

Figure 6: Nkpor gully site (Onitsha – Owerri Road) southeast Nigeria.

The Anambra and Enugu basins are the areas most affected by gully erosion (Umudu 2008), an example of this can be seen in **Figure 6.** Most of the gullies develop on areas with valley topography rather than areas with flat land (Ofomata, 2002). The region is highly dynamic with regards to exploitation and extraction of mineral resources, agriculture, urban growth and wood logging which create high pressure on arable land (Iloeje 2010). The tropical climatic conditions in combination with the deep porous and clayey soils effectively combine to foster the development of gully erosion (Onwumerobi 2002). Gully erosion may therefore be considered a direct threat to the non-rural population, as well as to farmers.

Research work and other gully studies such as (Ezezika and Adetona 2011) in the area have revealed that the causative factors of gully erosion in the area can be traced to both physical/natural and anthropogenic factors. With the highest rainfall average of 3000 mm from March to November, erosion results from impacts of rain drops on the topographic surface (Igbokwe et al. 2008). Similar cases of exacerbation of gully erosion caused by human activities, rather than natural occurrences, abound in parts of the area. Good examples are those of the Ajali water scheme at Owa, the Enugu-Onitsha highway, the Umuchiana gullies at Ekwulobia, the gullies along the Umuchu – Umunze Road, Iyioku gully, Njaba and Agulu – Nanka gullies. Urbanization involving road construction, building developments, and other similar activities, contribute immensely to gully development in the zone (Obiadi et al. 2011). Resource extraction processes such as sand excavations, and illegal solid mineral mining are also being carried out in this area with a detrimental effect on the landscape. In areas around Emekuku, Njaba of Imo State, and Owerrenta in Abia state, people have illegally acquired the permission to excavate sands. Their activities are greatly contributing to gully development.

1.5 Organisation of the Thesis

The thesis is structured in the following way. Chapter 2 will review the literature of the work; Chapter 3 will look at the methods of data acquisition, sources and their descriptions; Chapter 4 will look at the methodology and data analysis. Chapter 5 will present the associated results of the analysed data. In Chapter 6, the presented results are discussed while Chapter 7 summarizes and makes recommendations arising from the study.

This study will allow insight into and determination of real and current causes of gully development, examining the landcover classification transitions occurring between vegetation, openland (gullies), urban land, agriculture, and water. In addition, it will analyse deforestation and degradation in relation to gully development. Such analysis will allow application of appropriate mitigation measures in future to slow and reverse gully sizes, effects, and prevent future occurrence as guided by increased knowledge of landuse related triggers. This study will also be beneficial to policy makers and town planners in the development of urban centres, in particular guiding the appropriate location of adequate run-off channels, sustainable farming, and infrastructure such as roads, electric lines and poles. The proposed method is intended for global application, essentially in areas experiencing similar problems and especially those of low GDP where more expensive methods are not feasible. Moreover, this research will provide recommendations on the best land management practices to prevent future gully development and to deliver the aim set out in this chapter.

2 Literature Review

Gully erosion generally is caused by several factors that work simultaneously or individually, to detach, transport and deposit sediments in a different place from where they were formed (Igwe 2012). The resultant effects of this phenomenon are deep cuttings and ravines which dissect the land surface (Okagbue and Ezechi 1988). These are very common occurrences across the geographical region of southeast Nigeria (Igwe 2012). A number of environmental factors as well as pedological parameters influence the extent of gully erosion development wherever it occurs globally. These factors may also be influenced by human activities which have contributed to preserve, reshape, and deteriorate the quality of the Earth's surface, they have also been influential in disrupting the equilibrium in the natural ecology which has led to the rapid spread of environmental problems such as gully erosion (Bajracharya et al. 1992).

2.1 The Causes of Gully Erosion

Gully erosion is constantly changing our landscape especially in areas where there are enabling gully factors which are triggered by intense and heavy rainfall that produces high runoff. The development of gullies is influenced by many factors.

2.2 Overland Flow

Most gullies develop as a result of erosion caused by shallow overland flow, mostly during periods of heavy rainfall. An extraordinary event of some type causes an initial erosion point to form somewhere along the drainage path (Chalapathi 2016). A scour hole sometimes forms at the head of the gully, which is usually deeper than the immediate downstream gully bed (Anthony 2011). The incision and widening of gully overland flow is dependent on the soil texture, soil structure and bedrock. The threshold for gully initiation and gully development can be extrinsic (e.g. climatic, anthropogenic) or intrinsic and inherent to the channel (as a consequence of geomorphological and sedimentological natural processes within the gully) (Chalapathi 2016).

Overland flow in Lavaka gullies, found in Madagascar, is influenced by rainfall levels of between 1000mm and 2000mm per annum at an elevation of between 1000m and 2000m. The soils in the region are ferallistic and underlain by thick saprollite. These gullies develop from bare patches which erode deeply into the saprollite (decomposed and porous rock, often rich in clay, formed by the in-place chemical weathering of rocks) meeting fresh rock, which prevents further incision but at the same time encourages widening of the gully area (Raveloson et al. 2013). The Lavaka gullies share many features associated with the Rampa gullies of eastern Brazil (de Oliveira 1990). In Manfe area southern Cameroon, Mbella (2011) highlighted that the gullies in the area are widening because the runoff cannot incise further down into the soil structure of the bedrock. Idah et al. (2008) observed this in Owerri-West south east Nigeria, with Igboka (2011) noting that a gully site in nearby Amucha started to expand in size when the runoff met more consolidated sediments on the bed. Such behaviour is visualised in **figure 7**.

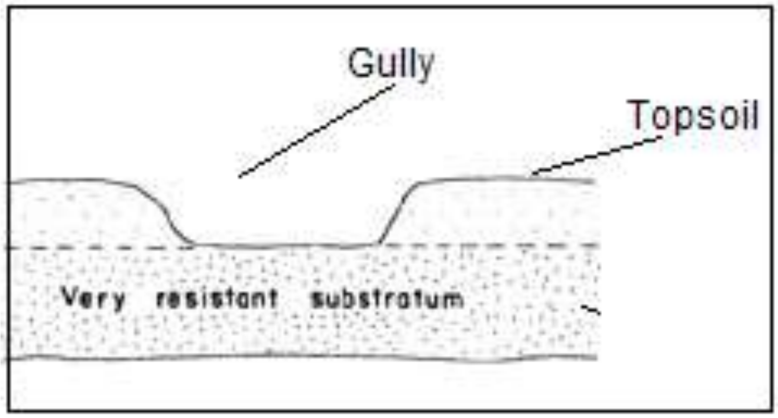


Figure 7: Schematic cross section of subsoil resistant to gully incision (Desta and Adugna 2012)

In a study of slope geometry and gully erosion development in Bananal, Sao Paulo, Brazil, Oliveira (1990), classified hillslopes as convex or concave in both elevation and plan. The upper slopes are thus convex in both dimensions and the hollows, in contrast, can be described as concave (Thomas 1994). Oliveira highlighted three types of gully evolution concentrated on slopes. The first type is of gullies connected to the drainage network, located on footslopes, where the dominant process is seepage erosion. Seepage erosion takes place when the water head can be dissipated at a scarp or at any other discontinuity (Pack et al. 1998). Observation reveals that most gullies of this type widen downstream and join the stream network. This was observed by Fox et al. (2007) in northern Mississippi, and at Ngwo hills in southeast Nigeria (Okeke 2010; Ezurike et al. 2012; Nwankwo et al. 1998). The second type of gully described is of gullies not connected to the drainage network, located on the higher slopes, where the dominant process is concentrated overland flow. Narrow gullies form on the upper and lower slope systems developed in homogenous saprolite and then narrow downstream, remaining unconnected to the stream network. This was noticed in the Kintampo area of Ghana (Kumi et al.2009). Columbus (2011) observed that the gully development at Udi hills, southeast Nigeria, was related to overland flow on a homogenous lateritic soil. The third type of gully is a combination of these two types, connecting upper and lower slopes. A few examples of gullies developing connections between upper and lower slope systems have been recorded. In such instances the lower slope develops through seepage erosion which could include pipe flow (see section **2.2.1**), while the upper slope gullies arise from concentrated overland flow. This has been observed in Queensland Australia by Brooks et al. (2009) who identified extensive areas of alluvial lands that have been impacted by a pervasive form of gully erosion. In the European Limestone Alps, Strunk (2003) noted that degraded soils and the rainfall of an average thunderstorm may cause overland flow and erosional features on the slopes as well as on the valley bottoms. Similar theories were presented by Horst (2003), in Regensburg, Germany where on the degraded soils and the rainfall of an average thunderstorm may cause Horton overland flow and erosional features on the slopes as well as on the valley bottoms., Nkuruziza (2006) in Kwazulu-Natal, South Africa where Wetland degradation in the form of channel incisioning can significantly alter the hydrological functioning of a wetland. Rautela and Lakhera (2000) in Giri and Ton Rivers in Himalayan India where ovrtland flow has caused Landslide risk between Giri and Tons Rivers, and Declan (2005) in Southern Cameroon where overland flow has exposed the Limbe are to gully erosion . In southeast Nigeria, Ofomata (1985), Igwe (2012), and Obi and Salako (1995) all determined that the gully erosion process in the area can be attributed to overland flow. Using a GIS and remote sensing methodology Adediji et al. (2009) observed that the work carried out on gullies in Abakaliki Local Government Area of Ebonyi-State, southeast Nigeria, revealed that the slope shapes determined from Digital Elevation Models (DEMs) are dominantly convex, implying that overland flow will be generated from all sides of the slope. Uma and Onuoha (1988) and Onu 2005) incorporated the same methodologies to arrive at the same result as Adediji et al. (2009).

2.2.1 Piping and Subsurface Erosion

In addition to overland flow, surface water movement may trigger gully formation. Soil pipes are discrete preferential subsurface flow paths that run parallel to the slope (Weller and McDonnell 2007; Wilson 2015). Soil piping according to Verachtert (2011) can be described as the formation of linear openings or voids through concentrated flowing runoff in soils and unconsolidated sediments, such that soil pipes are effectively pores with a “water- sculpted form” (Jones 2012). Piping is a geomorphological process, but it is difficult to quantify using conventional field survey or through remote sensing (Oltmanns et al. 2014). In Thomas (1994), the association of gully development with piping is clearly stated, and is reported as one of the initialising processes for gully incision, typically in semi-arid areas. Although topographical variables (sufficient hydraulic gradient, contributing area, curvature) influence pipe development, the subsurface pipe network may owe more to in-profile variations than to surface topography (Verachtert 2011). Pipe development is usually associated with discontinuities in the physical composition of soil (Faulkner 2006). The importance of piping processes is evident when considering how widespread and common it is around the world. **Figure 8** depicts the climatic distribution of piping of the world as reported in the Jones (1994). According to Jones (1994) piping has been reported across all major climatic regions, but its effect depends on the geomorphic function of the soil (Jones 2007).

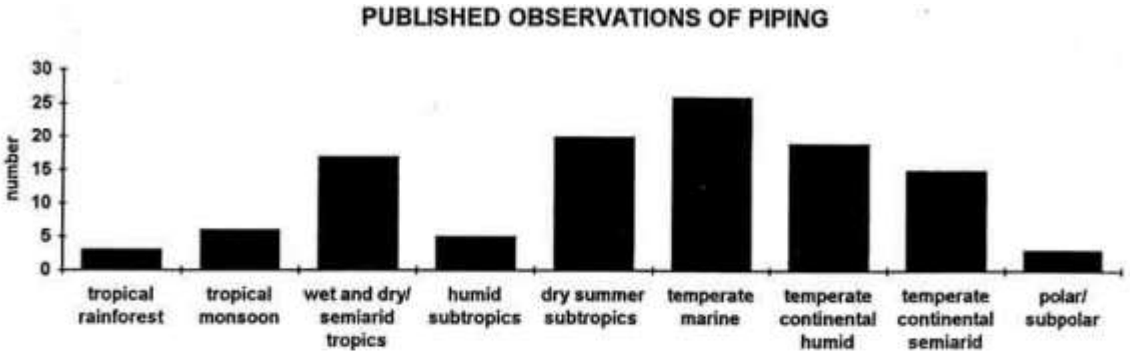


Figure 8: A global distribution of published reports of piping, according to major climatic regions (Jones 1994)

In light of the eminence of the piping process of gully erosion across all major biomes, gullies are typically divided according to whether the dominant process is overland flow, creating a waterfall headcut, or subsurface flow and seepage involving pipe flow (Thomas 1994).

Subsurface processes of gully erosion involve the removal of materials by water below the soil surface which can develop gullies (Onwumerobi 2009). Subsurface or tunnel scouring takes place when subsurface water flows sufficiently fast to entrain soil particles. Tunnel gullies, also known as under-runners, occur in soils derived from fine sediments such as Loess (Thomas 1994). Gullies formed in this way commonly occur on sites where deep Loess has accumulated on rolling to moderately steep slopes. These features form when runoff water enters the subsoil through soil cracks, old tree root holes, or down animal burrows. Water can also be channeled by the hard, Fragipan layer which some Loess soils exhibit (Thomas 2004). Runoff carries the dispersed material away, scouring out ever-enlarging underground tunnels. Sections of the tunnel roof periodically fall in, creating the characteristic holes. Examples of this were found in Southeast Spain by Faulker et al. (2007). In Aroyo-Cuts, in Arizona USA, Mansannat (1980) reported that piping and piping collapse were responsible for gully formation in the area. Some of the eroded material is redeposited down-slope where collapsed tunnel gully material then restricts the passage of water. There are natural cycles of erosion, deposition and back filling occurring in severely tunnel gullied areas, depending on rainfall and control measures.

Observations by Tebedu et al. (2010) reveal some effects of subsurface flow process in Ethiopian Highlands. Abdulahi (2006), recorded that the development of gullies in Tudu-Wada and Gwoza areas of Northern Nigeria resulted from piping attributed to lithosol soil structure and texture (imperfectly weathered rock fragments) in the area. This equally can be seen in the work of Ajayi et al. (2007) when considering contributions to gully development in Okufua Kwara state Nigeria.

In both tropical and sub-tropical soils, not all gully forms depend on pipe flow. Tropical soils like ultisols with A and B horizons markedly have contrasts which lead to strong subsurface flows associated with stone-line gravels (compact illuvial clay horizons formed at the base of the soil layer; (Reading et al. 1995). The channeling of subsurface flow, and formation of pipes depend on the presence of spatial anisotropy (preferential flow direction in soils and other geologic materials).

Subsurface flow can also be channeled around corestones lodged in colluvial or landslide debris and along sheeting planes that are frequently quasi parallel with valley sides. These are typically associated with steep mountain slopes on which gullies can be initiated. This behaviour is recorded by Heede (1974) in gullies in the Western USA, in which it is argued that diversion of surface drainage into open fissures initiates piping. In near similar opinion, Boling (1986) observed in South-Central Arizona, U.S.A, that the diversion of surface-water flow and stream flow into fissures results in gully development and enlargement. As surface water continues to flow, it starts to remove the cementing materials of the soil through the fissures, which develop into gullies depending on the nature and gradient of the slope (Igwe 2012).

A strong connection has been made between the formation of rills and the development of pipe flow on one hand and the formation of badland topography on the other. It is common for badlands to occur where rilling leads to a dense network of small surface channels, feeding into more permanent gullies (Zhang et al. 2007). According to Morgan (1980) the breaching of vegetation cover is a common cause of gully development (Food and Agricultural Organisation 2015). Breaks in the vegetation cover lead to sealing of the soil surface, as the soil aggregates are broken down by intense rainfall. Shallow depressions form, which concentrate runoff and because of this concentration, small headwalls upslope develop. This may create a small waterfall and the soil may submerge. The gully headcut now develops by scouring a channel downslope. This development is visualised in **Figure 9**. As the headwall retreats, it becomes higher, and the gradient will encourage pipe flow. This process was observed by Jones (2007) in upper Maesnant stream in mid-Wales, and also recorded in lkyogen Hills, Benue state Nigeria by Ogbodo et al. (2008). These vastly different climates show that these processes may occur globally.

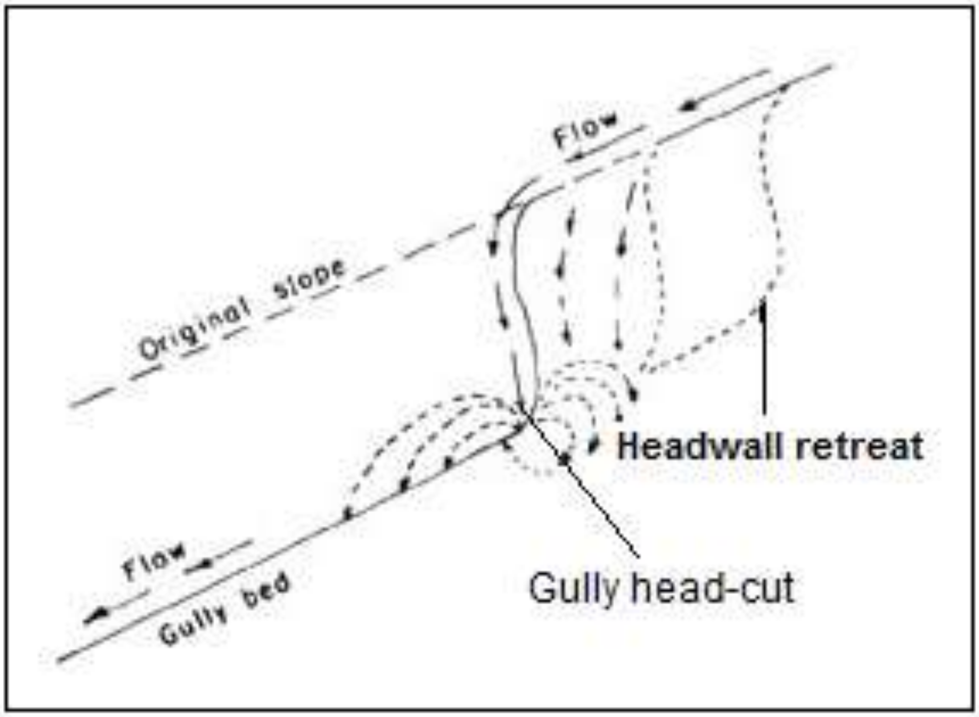


Figure 9:Gully head development and scouring down slope, showing gully headwall retreat from the gully head (Desta and Adugna 2012)

2.2.2 Factors Controlling Gully Development

A number of physical controlling factors determine the formation and development of gullies; these include intensity and duration of rainfall, topography, soil characteristics, geology of the area and vegetation cover.

2.2.3 Rainfall Dependence

In linking rainfall intensity and duration to the causes of gullies, Velantin et al. (2005) state that the reconstructions of historical causes of gully erosion, using high-resolution stratigraphy, archaeological dating of pottery, and dating of wood and charcoal, show that the main gully erosion periods identified in Europe correspond to a combination of events. These not only relate to deforestation and overuse of the land but also to periods with high frequency of extreme rainfall events.

Writing about rainfall intensity and duration as the main contributing factor, John (2011) states that there is a relationship between rainfall intensity, rate of run-off, and size of catchment area. This relationship is expressed in equation 1 (Rational Equation):

$$Q = c \times i \times A \qquad (1)$$

Where Q = Peak discharge, (cubic feet per second), c = Rational method runoff coefficient, i = Rainfall intensity, (inch per hour), A = Drainage area, (acre). The Rational Formula, as it is known, is used in engineering design for gully and torrent control. It states the dependence of peak discharge on the key parameters of rainfall intensity and drainage area. It has been used in work such as John (2011); Chin (2013) and Corbitt (1999). Moreover, Egboka and Adetona (2011) states that if the amount of rainfall is more than the holding capacity of the soil (high i), there will be increased surface run-off, followed by surface erosion and gullying. Horst (2003), studying gully erosion, degradation and overland flow in Regensburg, Germany, observed that rainfall was the main reason for gully degradation. The rainfall of an average thunderstorm was considered to have potential to cause overland flow and erosional features on slopes as well as valley bottoms.

In some tropical and subtropical countries, after the soil is completely saturated, almost all of the rainfall turns into run-off during the wettest months, which include the monsoon season, and during tropical cyclones. The increased run-off causes landslides, huge gullies and devastating floods. This was pointed out by Uwadi (2012) and Okonkwo (2014), that the increased run off in south east Nigeria was the main reason for gully erosion development in the area.

In designing engineering measures such as check dams or diversions in gully and torrent control, the rate of run-off is more important than the amount of run-off. In some areas, prolonged rains of moderate intensity (duration of several days), or short intensive rain storms lasting from 15 to 90 minutes (maximum rainfall intensity about 3mm/minute), cause landslides, gully formation and floods because of the increased run-off in the watersheds (Gulak, 2008). Equally, torrential floods, which generally occur after the short, intensive rain storms, destroy agricultural lands, residential areas, roads, irrigation ditches and canals at the base of the valley below a deteriorated watershed. Such behavior has been observed in Kizivu, Kenya (Makaya, 2010) and in Otamiri Southeast Nigeria (Okorie, 2013). Rapid snowmelts can also turn into high rates of run-off. The behaviour is similar to prolonged rains of moderate intensity and short intensive rain storms (Akinlo 2012). Igbokwe et al. (2011) agree with other studies that prolonged and high intensity rain is largely responsible for the gullies found in southern Nigeria. Similarly, the high rainfall of 2008 and 2012 caused much environmental devastation through gullying, flooding and mud falls in southeast Nigeria (Davis 2013 and Njoku et al. 2014). The devastating effect of rain fed run-off was captured by Mansour et al. (2011). Igbokwe (2008) and David (2012) observed that most gully degradation in the world today is caused by rainwater associated run-off triggered by crumbly textured soil, slopes and geological structure of the area.

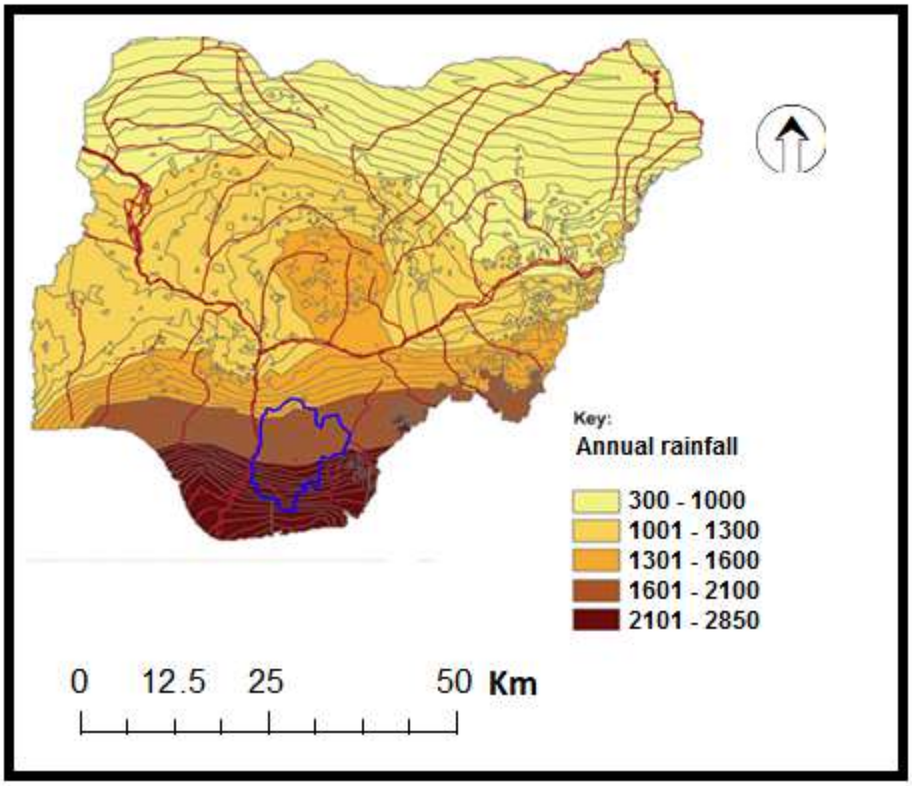


Figure 10:Rainfall distribution pattern of Nigeria with the study area outlined in blue for context (Iloeje, 2010)

Gully erosion in Southeast Nigeria in relation to the location of these gullies in the landscape is similar to numerous other gully sites in Nigeria. Igwe (2005), identified the influence of climate as one of the contributing factors, because of the nature of rainfall in Southern Nigeria being generally heavy and intensive. Rainfall ranges from over 2500 mm in the southernmost region towards the Atlantic Ocean to about 1500 mm annually around River Benue in the northern borders, **Figure 10**. Rainfall intensities are high and often above 50mm/h with short interval intensities in excess of 100 mm/h. Rainfall is seasonal and often comes between the months of March lasting until October or November (Igwe 2005; Strahler 2005). Rainfall erosivity differences were more pronounced between the Guinea Savanna and Forest or Guinea Savanna and Coastal belts than shown between the Forest and Coastal belts. The reason was that the forest belt contains ferralic-Arenosols soils which support gully erosion activities (Igwe 2012)

The magnitude of rainfall erosivity provides a useful insight into the causes of the catastrophic erosion problems in south-east Nigeria (Obi 1995). Greenland (1998); Eze (2000) and Udoh (2002) also identified rainfall as the major environmental cause of gully erosion, in southeast Nigeria. In disagreement to that, Igbozurike 1989; Njoku 2012 maintained that the runoff is almost the same during rainy season every year in southeast Nigeria and that the rate of gully development and change is not necessarily from the runoff but rather from other gully factors on ground such as slope, vegetation removal, and soil. In fact, Igbozurike maintained that these variables (slope, vegetation removal and soil) control runoff from rainfall and therefore, much influence should not be attached to rainfall as the main reason for gully development in areas such as southeast Nigeria.

This rainfall dependence as of the factors responsible for gully development in this study will be identified using Remote Sensing/GIS methodology. This has already been recognized using other methods such as interview, ground measurement, direct observation of gully sites identified above by Uwadi (2012); Okonkwo (2014); Gulak, (2008); Greenland (1998); Eze (2000); Udoh (2002) and Igbozurike 1989 as having much influence on gully developemt in southeast Nigeria. This Remote Sensing/GIS methodology will as well be used in other way to authenticate the genuiness of the above methods.

2.2.4 Soil Dependence

Some researchers have attributed soil as the main influence on gully development, (Lash et al. 1996; Wisner et al. 2004). Parnwell (2011) concludes that the main factors are dependent on the soil, geomorphology and rainfall pattern of the area. Ofomata (1985); and Arash et al. (2011), attribute gully erosion to physical factors, but suggest that its severity is greatly influenced by the structure and texture of the prevalent soil. The soil factor represents the soil erodibility which is also a product of geology and soil characteristics. It can be observed that the infiltration rate increases from clay to sand (for loamy sand 2.5-5 cm/hour), but resistance against erosion decreases (Abegunde et al. 2006). The reason being that sandy soils have larger pores and are coarse, they are easily removed by high runoff.

Giardina (2000), states that the erodibility of soil is defined by the vulnerability or susceptibility to erosion. Generally, soils with faster infiltration rates, with higher levels of organic matter and improved soil structure have a greater resistance to erosion, (Udo 2011; Akanwa et al. 2017). Sharhrivar and Christopher (2012) espoused the effects of soil physical characteristics on gully erosion development in Kohgiloyeh and Boyer Ahmad Province, Iran. While observing gully frequency, they showed that gullies developed on soil with silt loam and silt clay loam surface textures resulting in the highest gully frequency, particularly when in deeper layers (Morgan 1996; Oygarden 2003; Fan et al. 2008). Valentin said that gullies not only takes place in silt clay and mountainous or hilly regions but also more globally in soils subjected to loess like European belt, Chinese Loess Plateau, North America and sandy soils example in Sahelian zone, north-east Thailand) or in soils prone to piping and tunneling such as dispersive soils (Valentin 2005)

Without additional information on soil moisture variability, the prediction and interpretation of catchment hydrology is problematic. Piest (2007), after applying soil mechanic principles, maintained that the height of the water table, soil cohesion strength and rate of water infiltration to the soil are contributing factors to gully erosion. Concerned by gully erosion in Northwestern Colorado, Patton and Stumm (1992) observed that the Piceance Creek and Yellow Creek drainage basins show the existence and development of discontinuous gullies, related to unconsolidated soil of the area, on steep segments of the valley floors. In Iowa, USA, Bettis (2010) observed that gullies develop because of a decrease in the erosional resistance and an increase in the erosional forces of the area acting on the land surface. Field and laboratory studies indicate that certain soils like sandy soil of a valley are more prone to gully development than others because of their coarse texture and structure (Bright 2010).

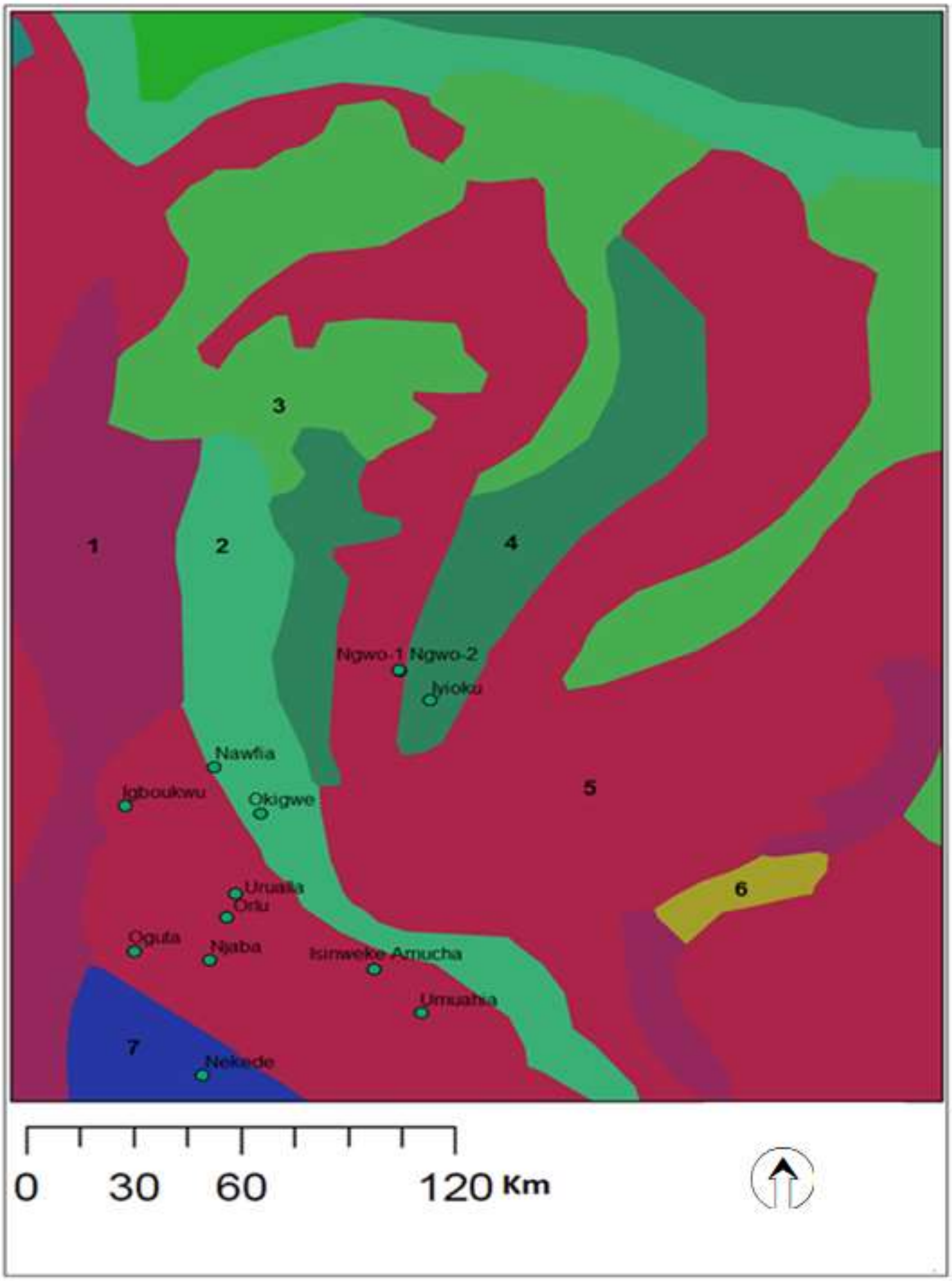


Figure 11: Soil map of south-east Nigeria with overlayed gully points outlined in context (from Harmonized World Soil Database 2012) **see Table 1 for details of soil map**

Table 1: Showing soil name and its description in southeast Nigeria

	FAO-UNESCO Soil name	Description
1.	(Gleysols)	Show hydromorphic properties. Fairly rich soils found on recent alluvia
2.	Fluvisols	Young soil in alluvial deposits associated with river sediments and marine deposits.
3.	Feralsols	Red and yellow weathered soils whose colours result from an accumulation of metal oxides, particularly iron and aluminium.
4.	Nitosols	Intermediate stage of ferralitic weathering on materials of fine or medium texture
5.	Ferralic-Arenosols	Unconsolidated infertile soils form wind-blown or water-deposited sands with very low reserves of nutrients
6.	Cambisols	Recent stage of soil formation and possess a fairly high potential fertility.
7.	Alisols	Red Yellow podzolic soils with high activity of clays

Igwe (2012) grouped soils of southeast Nigeria as mainly ferralic-Arenosols, Fluvisols, Feralsols and Nitosols soils as zones where gully formation mainly occurs, based on the fact that these soils support gully formation **Figure 11**. These soil compositions are deeply weathered which makes them more vulnerable to erosion through run off (Onwumerobi 2002; Igwe 2005). The referenced authors used interviews and measurements to opine that tillage and cropping practices, can lower soil organic matter levels, cause poor soil structure, and result in compacted soil, which contribute to increases in soil erodibility. Decreased infiltration of runoff can be a result of compacted subsurface soil layers (Abegunde et al. 2006). Imasuen and Ibrahim (2011), assessed the remedies to gully erosion in Ankpa metropolis and environs, Kogi state Nigeria. In their study they tested soil samples from gully sites. Particle size and compaction tests were conducted to assess the geologic and hydrologic causes of the gully erosion in the area. The plasticity index in the area revealed that the soils can be considered non-cohesive and non-plastic, ranging from 1.2% to 5.2% plasticity (Chikwelu and Ogbuagu 2014; Onuoha 2008). The plasticity index (PI) of the soil measures the difference in water content of the soils between the liquid and plastic limits. Soils with high PI tend to be clay rich, those with a lower PI tend to be silt rich, and those with a PI of 0 tend to have little or no silt or clay. Sieve analysis indicated that the soil from the Ankpa gully sites were within the medium to coarse grain range with low percentages of clay, indicating non-plastic soil. Soil of this type is easily eroded by runoff and can contribute to both the causes and further development of gullies.

Omon and Oisasoja (2012) in observing the causes of gully erosion in Benin city, Edo state, Nigeria conducted laboratory tests to investigate the effect of Atterberg Limits or consistency limits (Das 2011) on the soil's predisposition to erosion. The Atterberg limits are a basic measure of the critical water content of a fine-grained soil, such as its shrinkage, plastic, and liquid limits. In addition, the referenced study measured *in situ* moisture content of soil, and particle size analysis using sieve and sedimentation tests. Omon and Oisasoja (2012) found that the soil type of silty sand was deemed to be contributing significantly to gullies as a result of the coarse texture of the soil easily triggering gully development. Other studies such as Odemerho and Sada (2002); Ofomata (2009) have also noted the role that coarse textured soil types have in inducing gully erosion. Igwe (2003) remarked that a number of factors, such as the physical and the chemical properties of the soil, influence erodibility. In South-East Nigeria, the long weathering history of the soil parent material could be linked to the gully erosion problem of the area. This weathering history is evident in the dominance of the clay mineralogy by non-expanding minerals and low soil organic matter concentration due to high mineralisation rates and excessive leaching of nutrients. The highly weathered soils contain high concentrations of Iron and Aluminium oxides, making the soil coarse and friable and therefore enabling gully development (Obi and Salako 1995). Inappropriate land use and soil management options are also a common feature of agriculture in the region. Anthropogenic factors often combine to weaken soils to produce severe gullies. The soils are hence loose and slump under high intensive rainfall that renders them easily detachable. Some of the soils have the tendency to slake and form seals under such intense rainstorms thereby resulting in considerable runoff and soil erosion. Igwe (2005), Jenny (2001) and Zoun (2007) noted that gully erosion in South East Nigeria can be linked strongly to the soil structure of the area. The use of heavy machinery for cultivation in some parts of the area has also contributed in loosening the soil particles for soil erosion to take place even with the slightest runoff. Ofomata 2008; Onwumerobi 2002; Igwe 2012 recomemmended soil as a strong factor in gully erosion development of southeast Nigeria. In contrary opinion, (Anejionu 2012; Chigbu et al. 2011 James et al. 2007 and Okereke et al. 2012) are of the view that Population growth has intensified the pressure on land for agriculture and wood logging of developing countries. Stating that land use change is expected to have a greater impact on gully erosion than any other gully erosion factor in southeast Nigeria.

Having observed above that a lot of studies using other methods such as ground measurement, soil tests technique etc as in Jenny (2001); Zoun (2007); Ofomata 2008; Onwumerobi 2002; Odemerho and Sada (2002) strongly agree that soil is an influential factor in gully development. Conversely, this study will make use of Remote Sensing/GIS methodology to test the relationship of soil in gully development in southeast Nigeria. Also this soil dependence will be used as a variable in further statistical analysis of this study.

2.2.5 Slope Dependence

Slopes have been examined in the literature in relation to soil erosion, with several studies stating that slopes are the main influence on gully development (Marquisee 2010; Boardman 2006; Bochet 2004). Igbokwe (2008) observed that in the simplest terms, land located on steep inclines is more vulnerable to water erosion than flat land. The reasons given were that erosive forces, splash, and scour and transport, all have greater effect on steep slopes. Gully erosion is generally accepted as a function of slope attributes (Horst 2003). The slope geometry of hill sides (i.e. whether convex or concave) often contribute significantly to soil loss and gully development. Poesen et al. (2003), in working on gully erosion and environmental change in Leuven, Belgium, recorded that uplands act as a link through which run-off transports sediments down the hill, contributing to the development of gullies. Valley topography is also an underlying factor, as stated by (Teme 2001; Bennard 2012). The steeper and longer the slope, the higher the erosion risk. Gully erosion by water increases as the slope length increases due to the greater accumulation of runoff. Consolidation of small fields into larger ones often results in longer slope lengths therefore increasing erosion potential. This is a direct result of the increased velocity of water, which permits a greater degree of scouring (carrying capacity for sediment). Hughes and Prosser (2012) observed this mechanism of gully formation in Murray-Darling, Australia, where it was noted to be exacerbated by high intensity rainfall. Kim (2006), using RUSLE (Revised Universal Soil Loss Equation) and GIS presented research conducted in Imha watershed in Colorado USA, observed that the mountainous watershed has steep sloping gradients of approximately 40%. Due to this topographical characteristic, most of the watershed is deemed vulnerable to severe erosion. Gully erosion from steep upland areas has also caused sedimentation in the Imha reservoir, deteriorating the water quality and causing negative effects on the aquatic ecosystem. Mat et al. (2009) suggested that Gullies in Okigwe Local Government Area of Imo-State, southeast Nigeria, developed through association with particular slope shapes. Such shapes can be determined accurately from Digital Elevation Models of the area with concave formations in general resulting in more severe gullying (Beshah 2003; Bewke 2003). The concavity of most of the gully catchments coupled with drainage channel termination locations, as well as poor roads and drainage maintenance by the community and government, are deemed to have led to the increased development of gullies.

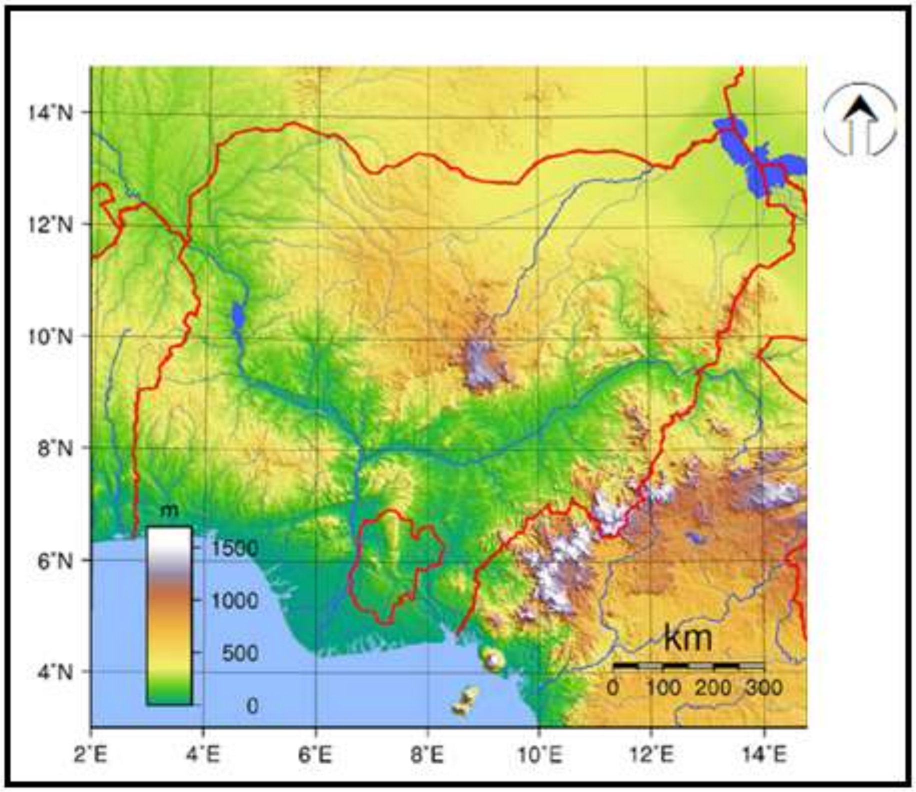


Figure 12:Topographic map of Nigeria with the study area outlined in context

(Panagos, 2011)

In South-East Nigeria, Ofomata (2001), found that there is a positive relationship between relief and soil erosion leading to more pronounced and aggressive gully erosion in areas with valley topography than areas with flat land. In areas like Agulu-Nanka, Njaba, Nekede-Owerri, Iyioku, Okigwe, Afikpo, Ohafia, Umuahia, the gullies can be traced to the natural slope of the topography, while in places the natural slope is further emphasised by human factors such as mineral exploration (Iwu 2012; Abdulfatai et al. 2014; Ekanade et al. 2008 and Ofomata

2017). In assessing and mapping gully erosion hazards in Abia State, Southeast Nigeria, Nwilo et al. (2011) observed that gully erosion sites were well dispersed around false bedded sand-stone geological formations. The slope inclination was ascertained to be greater than 10^{o}, encouraging gully erosion **Figure 12**. Chikwe (2012) stated that the aggressiveness of gully erosion in Agulu- Nanka, and Orlu-Njaba gully sites could be traced to their topographic locations. These gully sites are located at the Agulu Lake and Njaba river head, which have steep slopes providing high runoff to generate gullies. Chukwu (2010), reported the erosion problem of Owerri- Nekede erosion site to the federal government of Nigeria, stating that the problem was made worse by urban developments. The current research suggests that the influence of slope in the area was shown to significantly contribute to the problem at the erosion site, located at the Otamiri river head. Ofomata 2008; Chukwu 2010; Iwu 2012; Chikwe 2012 all pointed out that slope is a strong factor influencing gully erosion development in southeast Nigeria, while other studies such as Anejionu 2012; Chigbu et al. 2011, strongly hold the changes on land-use and cover caused by man as responsible to gully development in southeast Nigeria. The studies pointed out that areas such as Government Reserve Areas, Forest reserves in Imo and Abia states (these areas have valleys and hills) do not have any gully erosion when compared with other areas such as Nekede, Agulu and Nanka, where gullies easily develop due to population pressure.

In the above literature, Ofomata (2001); (Iwu 2012; Abdulfatai et al. 2014; Ekanade et al. 2008 and Chikwe (2012) used other methods such as ground measurement, interviews etc to identify the influence of this factor. This study will use Remote Sensing/GIS methodology to identify this factor and also the identified factor (slope dependence) will be used for further statistical analysis in this study.

2.2.6 Vegetation Dependence

Vegetative cover contributes significantly to reducing the occurrence of gullies (Glade 2003; Brardinoni et al. 2003). Vegetative cover intercepts rainfall, keeps the soil covered with litter, maintains soil structure and pore space, and creates openings and cavities for water to be infiltrated through root penetration (Anka 2004; Holt-Gimenez 2002; Casali et al. 1999). This is best achieved by an undisturbed multistory forest cover. Under special conditions, however, a well-protected, dense grass cover may also provide a similar protection. The potential for gully erosion increases if the soil has no or very little vegetative cover of plants and/or crop residues as these protective elements described previously are reduced or removed. The combination of the plant and residue cover protects the soil from raindrop impact and splash, slows the movement of runoff water, and allows excess surface water to infiltrate (Ritter 2015).

The erosion-reducing effectiveness of plant and/or crop residues depends on the type, extent and quantity of cover. Vegetation and residue combinations that completely cover the soil and intercept all falling raindrops at, and close to, the surface are the most efficient in controlling soil erosion (e.g., forests, permanent grasses). Partially incorporated residues and residual roots are also important as these provide channels that allow surface water to move freely into the soil (David et al.1999).

The effectiveness of any protective cover is also dependent on how much protection is available at various periods during the year relative to the amount of erosive rainfall that falls during these periods. Crops that provide a full protective cover for a major portion of the year (e.g., alfalfa or winter cover crops) can reduce or prevent erosion more significantly than crops that leave the soil exposed for longer periods. Examples of these high exposure crops are row crops, and the erosive effect is maximum during periods of highly intensive, and therefore erosive, rainfall such as during spring and summer (Gulder 2005). Crop management systems that favour contour farming and strip-cropping techniques can further reduce the amount of erosion. To reduce most of the erosion on annual row-crop land, it is suggested to leave a residue cover greater than 30% after harvest and maintain this cover over the winter months (Omali 2010). Another mitigation strategy is to inter-seed a cover crop, for example red clover in wheat, and oats after silage corn (Egboka 1993). This approach has been used to mitigate gully erosion development in Beminda, southern Cameroon Nyom

(2005) where the rate of rill to gully development was reduced from 234 m^2yr-1 to 163 m^2yr-1, and in Awo area in southeast Nigeria Igbozurike (2000) where the rate of gully development was reduced from 345 m^2yr^{-1} to 264 m2yr^{-1}

Posser and Slade (1994), in writing about gully formation in Southeastern Australia said that the reduced vegetation cover made the area susceptible to widespread rapid gully formation. Ahmed and Dinye (2012) stated that St. Kizito's gully site Kumasi Ghana developed after the wide spread fire that removed the vegetation of the area. In general, it is management and protection rather than the type of the vegetative cover which determines the gully control effectiveness. In critical areas, it may be necessary to exclude any use of protecting vegetation but whenever possible, it is desirable to establish a vegetative cover which serves a dual purpose, for example, provision of fodder, fuel wood, or fruit (Madu et al. 2006).

Figure 13 shows a vegetation map of Nigeria. The tropical rainforest in South East Nigeria is being lost to population pressure and increased agricultural activities, the patterns and intensity of forest loss vary according to the type of forest. The majority of the forest reserves in lowland rainforests have lost over 40 % of their area, freshwater swamp forest reserves have lost about 30 %, whilst the reserves in mangrove forests have lost 11 % as a result of population pressure and agricultural activities (Ayanlade and Drake 2015). These environmental changes in the region expose soils to the vagaries of weather and contribute to the escalating gully erosion problems. The implication of these environmental changes is that the soils are frequently subject to different degrees of erosion including accelerated erosion. Vegetation and land use are important factors contributing to gully erosion in South East Nigeria. According to Max, (1998), designing and choosing an appropriate land use by communities can drastically curtail soil erosion.

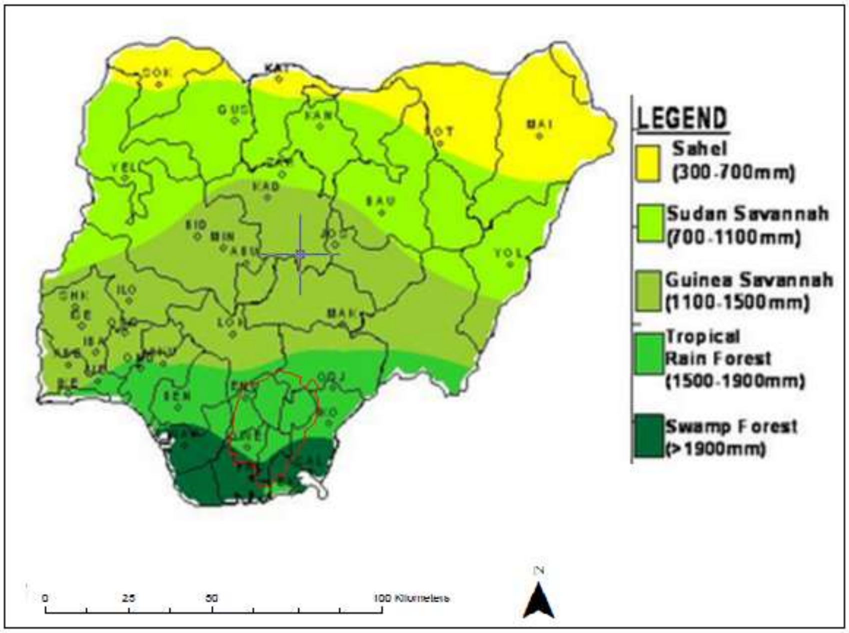


Figure 13: Vegetation map of Nigeria with the study area outlined in context (Iloeje, 2010).

In South East Nigeria gullies mostly develop on soil on which vegetal growth has been disturbed due to infrastructural developments, for example roads and housing developments. Igwe (2005) showed that in the region, gully erosion is connected mainly with land use activity. These include agricultural, mining, road building, urbanisation, industrialisation and general infrastructural development for example some houses in the study are were built across the natural run-off channels without planning. These land use activities deprive the soil surface of its vegetation and contribute directly to sliding, slumping, interrill and rill erosion, and ultimately the most severe case which is gullying.

Onyekwere (2001), using interview methods to study the effect of human impact on ground cover and subsequent erosion, emphasised society's activities in modifying the environment, in particular soil and vegetation, as a major cause of gully erosion. Sharing in Onyekwere's view, Ijeoma and Okey (2005) using remote sensing to study the modification of landcover as the reason for gully development in southeast Nigeria noted that apart from physical factors, a major factor promoting gully erosion in South-East Nigeria is modification of its vegetation cover. This study compared areas with vegetal cover having less than 2% of the area with gullies to areas where there is no vegetal cover which have 12% of the area covered with gullies. In another way, this study will look at the land cover classification for a 30 year period to observe how vegetation is removed over time and its linkage to gully development in southeast Nigeria.

Interview methods, ground measurements etc were adopted by Onyekwere (2001), Ayanlade and Drake 2015 to study the influence of vegetation dependence on gully development. This study will make use of Remote Sensing/GIS technology to identify this factor and further tests its influence in statistical analysis.

2.2.7 Geological Dependence

Many authors are of the opinion that the influence of geology (lithology) on gully erosion processes manifest directly from the character of parent materials whose properties are given by the bed rock (Renard, 1997). Nachtergaele et al. (2002), adopting interview and laboratory tests in his work Prediction of concentrated flow width in ephemeral gully channel, said that in Rio de Janeiro, gullies of the area are linked to the geology, maintaining that chemical contents of soil minerals dominant in the area dissolved with constant rainfall, removing the cementing particles as can be seen in Petropolis gullies. This makes the soil vulnerable to run-off and encourages the development of gullies. The hydrochemical characteristics of South-East Nigeria are very important factors in the cause of gully erosion as a result of chemical weathering (Obiadi et al. 2010). Obiadi (2010) determined that the surface and ground water in the study area are slightly acidic and the shale units generally occur in beds 40-50cm thick alternating with fine sand and siltstone facilitating the breaking down of cements binding rock particles together. Ganjali, et al. (2002), in the Study of effective factors on gully erosion and its zonation in Neyzar region of Qom province Iran, using remote sensing methodology found that apart from slope, aspect and runoff, lithology and land use are the most important factors in gully initiation as can be found in (Wu and Cheng 2005; Vandaele and Poesen 1995).

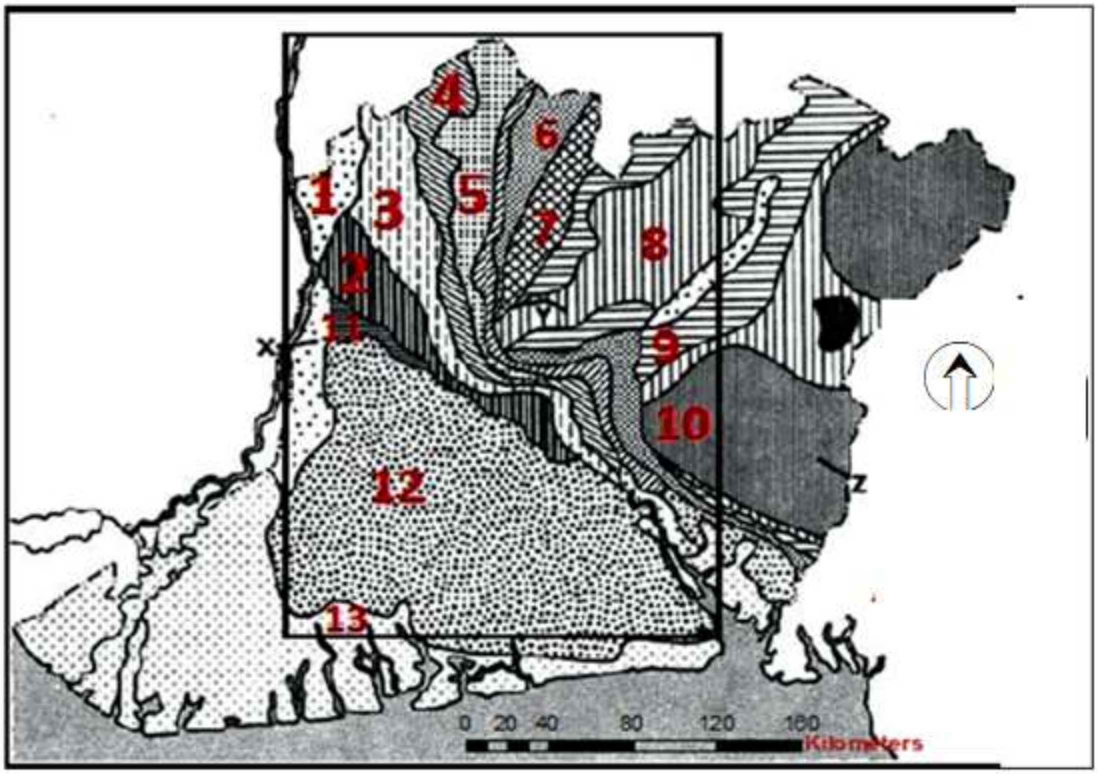


Figure 14: Geology map of southeast Nigeria showing in context

(Nigeria Ministry of Solid Minerals Development 2012) see Table 2 for details of geology map

Table 2: Geological descriptions of southeast Nigeria

Age	Group	Formation	Descriptions
Quaternary	(i) Delta and Alluvium	(1) Niger and Cross River Alluvium	The sediments composing river alluvium include unconsolidated gravel, coarse and fine sand, silt and clays with high groundwater potential
		(13) Delta Formation	Coarse to medium grained unconsolidated sands and gravels with thin peats, silts, clays, and shales, forming units of old deltas.
	(ii) Coastal Plains Sand	(12) Coastal Plains Sand	Coarse and friable cross bedded white and yellow sandstones
Tertiary	(iii) Bende-Ameki	(2) Bende-Ameki Formation	The rocks are clayey with interbedded sand stone and grits

	(iv) Imo Clay-Shales	(3) Imo Clay-Shales Formation	Impervious, unjointed clay-shales with bands of clay, iron stone, and sandstone
	(v) Plateau and Escarpment	(4) Upper Coal Measures	Fine-bedded white sandstones and silt stones, with thin beds of coal, shale and limestone
		(6) False-Bedded Sandstones	Consists of coarse grind white and friable sandstones with bands of shales and grey clays
		(9) Lower Coal Measures	Fine to medium grained white to grey sandstones and shaley stones
		(5) Nkporo Shales	Grey shales and mud shales with sandstone
Cretaceous	(vi) Cross River Plain Group	(7) Awgu-Ndeaboh Shales	Clayey rocks; impervious shales, mudstones and also porous limestone
		(8) Eze-Aku Shales	Deposits of marine condition
		(11) Asu River Group	Dark micaceous shale, fine grained and calcareous sandstone bodies. It is poorly bedded.
Pre-Cambrian	(vii) Basement	(10) Basement Complex	Metamorphic rocks with intrusive granitic bodies

The underlying Geology of southeast Nigeria is shown in **Figure 14**. Ofomata (2001), classified the areas with high potential erosion susceptibility using this. The study indicated that areas of high susceptibility correspond to geological regions of weak unconsolidated sandy formations like the Tertiary recent sediments and Cretaceous sediments, while least susceptible areas are within the consolidated Tertiary sediments, **Figure 14**. In South-East Nigeria the classical gully sites are located in the False-bedded sandstone, coastal plain sands, Nanka and Njaba sands which are under Asu River group and the Bende-Ameki sands under Eze-Aku formation. These are all sandy formations which have more gullies than their shale formation counterparts (Onwumerobi 2009). Gobin (1999), using ground measurement to assess the gully erosion formation in Udi-Nsukka Cuesta, South East Nigeria, observed that ravine and gully formations were influenced by a combination of infrastructure, geohydrology, topography, vegetation and land use. This is in keeping with World Bank Technical reports on the causes of gully erosion in Enugu state, South-East Nigeria (World Bank 2011). The report states that the general topography and geology of the zone made the state highly prone to gully erosion. Gullies are found in areas underlain by loose Ajali and Nsukka geological formations, such as the scarp slopes of Udi Escarpment. There are strong relationships between gully formations, expansion and geomorphology as well as with the underlying rock types of the area (World Bank 2011).

In the same vein, Egboka et al. (1990), using a methodology of interviewing and ground measurement, identified that instances of gullies and land sliding in South-East Nigeria may be a result of susceptible geological formations, derived substantially from the palaeo and neo-tectonic features. Such formations can create seismic effects which initiate movement on marginally stable slopes, hence encouraging gully development. Kenneth (2002), studied the phenomenon in detail, emphasising the role of geology, vegetation cover, lithology, and structural stability of the soil as being the major factors that bring about gully erosion in South-East Nigeria. It was stressed in Ofomata (1998) that the main contributing factor causing soil erosion is not society; rather, the physical factors, Ofomata is of the strong opinion that no matter the contribution to gully erosion initiation, if the physical causes do not support its formation, gullies will not develop. Ofomata stated that gully erosion formations in south-east Nigeria result from physical causes, linked to soil type, slope, topography and geology. Ezezika et al. (2011), Uche et al. (2006), Godsun (2007) and Chuk (2010) further agree that gully formation in south-east Nigeria is initiated by the geological and topographical nature of the area, but then counter that the severity is complicated by societal contributions. These works raise the question that if Ofomata (1998), were indeed right, then the question must be asked as to why these gully erosion formations were not present 100 years ago in a period of low population pressure in comparison to recent times. Gullies have been associated with the post-colonial era, as apparent from the gully development of abandoned coal sites and as a consequence of the introduction of heavy machinery in agriculture (Nwankwo 2010). In trying to understand the changes linked to the physical causes, anthropogenic causes are discussed in the next section.

2.2.8 Anthropogenic Activities that Influence Physical Process to Cause Gully Development

As suggested in the previous section, some authors have deduced that in spite of the natural and physical controlling factors of gully erosion, human impact plays a major role in the development and location of gully formation. In this section the influences on gully formation from an anthropogenic stand point are presented. In the Northern hemisphere including many countries of Europe, Giordano et al. (1991) have shown that among the factors encouraging gully formation are anthropogenic activities. Those contributing to gully erosion comprise overgrazing, over-cultivation, mono-cultivation, settlement expansion, increased exploitation of natural resources, building of roads, construction of dams and irrigation projects, large scale open cast mining, burrowing and digging, environmentally reckless engineering work, clearing of vegetation for agriculture, deforestation and other unsustainable agricultural and engineering practices (Mrabet 2002; Jahantigh et al. (2010); Igbokwe (2008); Sidorchuk and Torri (2002). Similarly, Nyssan (2002), following a study in Ethiopia using local information, garnered from interviews and *in situ* measurements on erosion rates, stated that the main causes of gully erosion are road construction and wood logging practices, where it was discovered that wood logging has reduced the vegetal cover of the area to 77%, this can as well be found in Valentin et al. (2004); Vanwalleghem et al. (2005); Martinez-Casasnovas (2003). Collectively they support the theory that the rural poor are dependent on natural resources for survival and hence poverty is a major driver for gullydevelopment, through wood logging for fuel, bad agriculture practices and methods of extracting raw minerals. In the work of Terranova et al. 2009, using RUSEL (Revised universal soil loss equation) and GIS methodology it was observed that human impacts on the environment have made the Calabria region of southern Italy particularly prone to intense gully erosion. Through the use of interviews and measurements Clarke (1992) in Welkom area South Africa, observed that negative government policies of redistribution of land ensured that 42% of the people live on 13 % of the land (the "homelands"). This overcrowding has resulted in severe erosion. As the land became increasingly degraded and thus less productive, subsistence farmers were then forced to further overuse the land. The intensive agriculture and overgrazing that followed caused more pronounced gully degradation.

In the same vein, Boardman and Foster (2008), in Karoo South Africa, observed that evidence of relatively recent landscape degradation is ubiquitous and has been noted in reports, diaries, and articles for over 100 years in Midwestern United States and Australia where gully systems have been attributed to farming practices and in particular to the introduction of large numbers of domesticated sheep and cattle. This livestock contribute to destabilising hill slopes and contributing to gully formation. Such behaviour can be associated with Udi hills Enugu, southeast Nigeria, where gullies follow the foot march of cattle and sheep (Nweze 2008). This has also been the observation of Sirvio & Hargrave (2004) in Taita Hills and also by Maerker (2001), using agrohydrological modelling systems in examining gully erosion in Mbuluzi river catchment Swaziland, South Africa.

Most of the gully erosion research works done in Nigeria, most importantly in south-east Nigeria are linked to bad agricultural practices, population explosion and its consequences. Population growth has intensified the pressure on land for agriculture and wood logging in rural areas of developing countries, forcing farmers to resort to cultivating easily eroded hillsides. Rapid deforestation and shifting cultivation have increased as a result (Anejionu 2012; Chigbu et al. 2011).

Exemplified by recent examples from all over the world (Shalaby and Tateishi 2010; James et al. 2007; Okereke et al. 2012) Valentin et al. (2004) states that land use change is expected to have a greater impact on gully erosion than climate change. Ehiorobo and Audu (2012), agree with this theory and report that many gullies have developed as a result of inappropriate land use, poor termination of drainage outlets that can initiate gully, inadequate storm drainage facilities and in some cases, a lack of available and appropriate drainage facilities (Valentin et al. 2005; Choxt 2007; Greg et al. 2004).

Though, mineral exploration provides livelihoods to the people of South-East, Nigeria such as crude oil exploration and exploitation, sand stone, sand, granite, coal, limestone, quartz and clay mines, but they have exacerbated gully development in the area (Chigbu et al. 2011; Aigbedion, and Iyay 2007). In trying to link this factor, Abegunde, et al. (2006), through structured interviews with the affected people, pointed out that the gully erosion in south-east Nigeria began to creep into the region following Nigeria`s oil boom of the 1970`s, which helped to create more forest destruction and dugout pits during explorations. These activities have adverse impact on land use and land cover. The area is characterised by abandoned mining ditches, mine ponds, mine dumps and mounds which may have become the trigger to gully erosion in the area (Jonathan and Joshua 2013). They clearly maintain a view that nature was there before man came to explore and exploit it. In the works of Nduji et al. (2008), Nwankwo (2010) and Chukwu and Okeke (2012), the reported evidence suggests that if there is no human interference on the natural environment, gullies may not develop.

Nwankwo (2010) used ground measurement to trace the genesis of these gullies in southeast Nigeria and pointed out that even though the area receives more rain than other areas, gully erosion was rarely found prior to the colonial era. Igbokwe, (2010) agrees with Nwankwo (2010) maintaining that society’s activities in the area are the source of the problem. In his view, Olabonde (2002), however, agreed that factors identified as causing gully erosion in south-east Nigeria, do not work exclusively or in isolation. Rather, several factors operate together in most places where gully erosion is identified; this is exemplified in more spectacular and sometimes monumental features that gully erosion produce. As seen in the Agulu- Nanka **Figure 15** and Okwudor- Amucha areas of south-east Nigeria (Okeke 2007)

Figure 15: Part of Agulu-Nanka gully, southeast Nigeria (Igbokwe et al. 2008)

Since tropical uplands are typically shallow and fragile in structure (Nwankwo 2010), they are easily eroded. Productivity may decline but may not be noticeable until the topsoil has been depleted and the infertile subsoil exposed (Ananda et al. 2003). Society's uneducated decisions regarding the land are one of the main reasons why gully erosion is significant across South-East Nigeria (Poeson, et al. 2007). South-east Nigeria is densely populated extending from Onitsha to Ikot Ekpene, **Figure 16**. The people of the region overly depend on valuable oil palm gardens (Dike 2002). Following this, Okocha, (2008) using interview on the communities and *in situ* gully measurements in the study of gully formation in southeast Nigeria discovered that some gully erosion going on at Okigwe, Umuahia, Onitsha and Enugu urban centres resulted from buildings being built across topographic contours, runoff channels and areas prone to gully devastation.

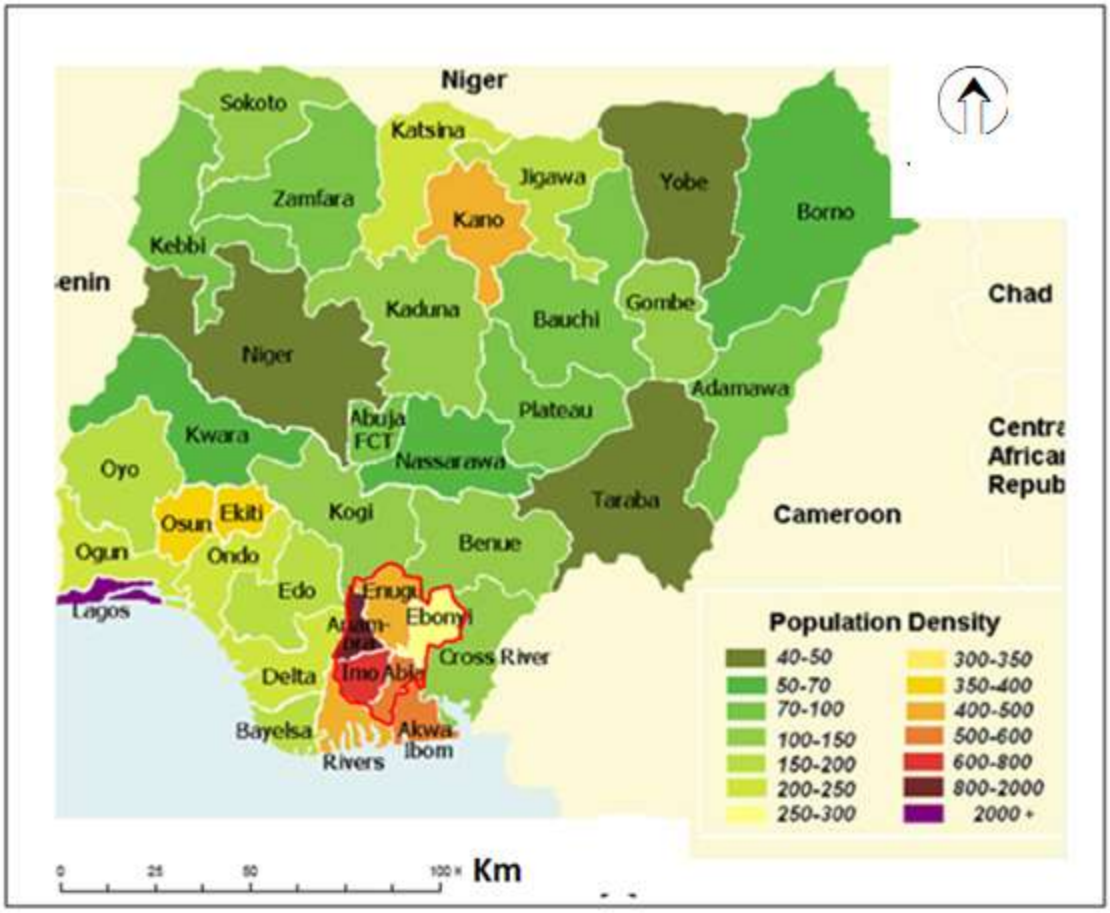


Figure 16: Population density map of Nigeria (people per sq. km of land area) with the study area outlined in context. (Iloeje 2010).

Most urban residents live in informal settlements and the effect of rapid growth in urban areas may include; poverty and environmental degradation (United Nation Development Program 2012). In 1962, the population of southern Nigeria was 24 million, (National Population Commission 2014). From southern Nigeria, south-east Nigeria was calved out, and according to the 1991 census, its population was 10,765,977 people. By 2006 the census reported a population of 16,390,557. By 2011 estimates suggest 18,902,315 people with a population density of about 2000 persons per square km (National Population Commission, 2014) also see **Figure 16**. This recent population surge could be associated with the serious environmental degradation in the area. It is not necessarily because the population is increasing but, that out of necessity, the majority of the population depends on unsustainable methods of agriculture which inevitably exerts more pressure on the land.

This was expertly what Mbaka and Onyeka (2012) found when trying to assess Gully Erosion in Awka Town, Anambra State, Nigeria. In the referenced study using unstructured interviews and incorporating satellite image analysis remote sensing technology, it was observed that during the period 1991 to 2000, a rapid increase in population and extent of built up areas took place. This high increase could be attributed to an influx of civil servants and other migrants when Awka town became the State capital in 1991. The quantity of tarred roads and streets increased while undeveloped land and open space witnessed significant decline. The implication of this growth, and consequent outward expansion, as well as deforestation of the forest woodland of Awka town catchment areas, was for an increased area of impervious surfaces which generated higher runoff than infiltration during rainfall events; consequently, accelerating gully formation. Bridget et al. (2010) opined that the problem in Awka was not the influx of people, rather how those new buildings were constructed without following urban planning guidelines.

Occurrences such as in Awka town are mostly very common throughout the geographical region of South East Nigeria. Omuti (1999), used interview and observation method to observe that settlement evolution and the degradation of physical environment in Auchi Edo state, Nigeria, was as a result of growth in settlement which leads to degradation of the landscape. Elaborating more on that, Uche (2008), using the same methodology, observed that the relationship between erosion and population concentration, can be noted in areas like Agulu-Nanka, Orlu, Amucha, Njaba, Mbaise, Umuahia, Onitsha and Enugu areas of South East Nigeria. These areas have the greatest population concentration and contain greater density of gullies per area. That was the reason Onakhoraya (1994) pointed out that the problem is not the population but how the population manages their environment.

Anejionu 2012; Chigbu et al. 2011, Okocha, (2008), Omuti (1999), Chukwu; Okeke (2012) and (Okeke 2007) used methods such as interviews and ground measurements to identify the influence of anthropogenic dependence in gully development. This study will make use of Remote Sensing/GIS methodology to observe the influence of anthropogenic dependence (in vegetation loss) on gully developemt and further use it for statistical analysis.

2.3 Gully Prevention Methods

Preventing the formation of a gully is much easier than controlling it once it has developed (Njoku 2012). Therefore, if areas prone to gully formation are not prevented and stabilised, gullies develop and become longer, larger and deeper as time goes on. Prevention is also more economical and easy to deal with than controlling because structural measures are considerably more expensive than preventative measures. An example can be found in Nekede gully, southeast Nigeria, where it has cost both World Bank and the federal government of Nigeria over $5million to control the gully.

The Food and Agricultural Organisation, (2015), listed some measures of gully control as: (a) Proper land-management practices **Figure 17.** These include prevention of forest fires and illegal wood cutting in plantations and natural forests, control of grazing, revegetation of open and grass lands and maintenance of soil fertility and stability on land which is under agro-forestry or agriculture. It also requires control of road construction and mining, and the immediate stabilisation of moderate sheet and rill erosion, and incipient gullies in forest, rangeland and cultivated areas before they develop into gullies. This method has been in place in Queensland Australia since 1950, to prevent gully development. Zund and Payne (2014) reported that in Queensland Australia after construction works, to prevent gully development, some Management options are adopted which include a combination of improving the vegetation cover in the contributing catchment by reducing grazing pressure at critical periods, maintaining tree cover and revegetation. This has been successful when compared with areas without any management practice. The United States of America adopted this measure in Gullaya, and parts of Colorado, among others, to mitigate gully development in areas that are prone to gullying (United Nations Development program, 2015). In southeast Nigeria, many gully researchers like Igwe (2012); Okereke (2012); Igbokwe et al. (2010) and others, have advocated for this method as a very veritable method to prevent gully development in the area. Their recommendation was based on the government reserve areas that are well managed compared with other areas that are left under the care of the public which has dots of gully development.

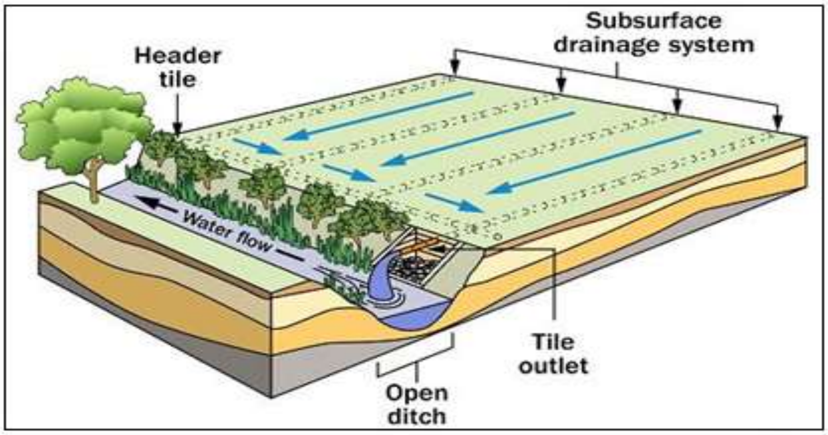


Figure 17: Land management to control runoff (Veen 2010)

(b) Retention and infiltration of surface water **figure 18**. Proper land-management practices are important, so also, specific slope-treatment measures, such as retention and infiltration ditches, terraces, wattles, fascines and staking. All of these should be carried out above areas prone to gullying, and in the eroding area, to reduce the rate and amount of surface run-off. These also decrease the cost of structural gully-control measures. These methods were found effective in the Eastern Nile of Ethiopia (Eastern Nile Subsidiary Action Program 2012). Equally, this has proved effective on rice terraces in Indonesia to prevent gully erosion (Nekatet 2006). This also was done in Cotonou Benin Republic at Sungai Farm land where grasses and short trees are deliberately allowed to help retain and reduce the level of runoff in the area (Kerekou 2012)

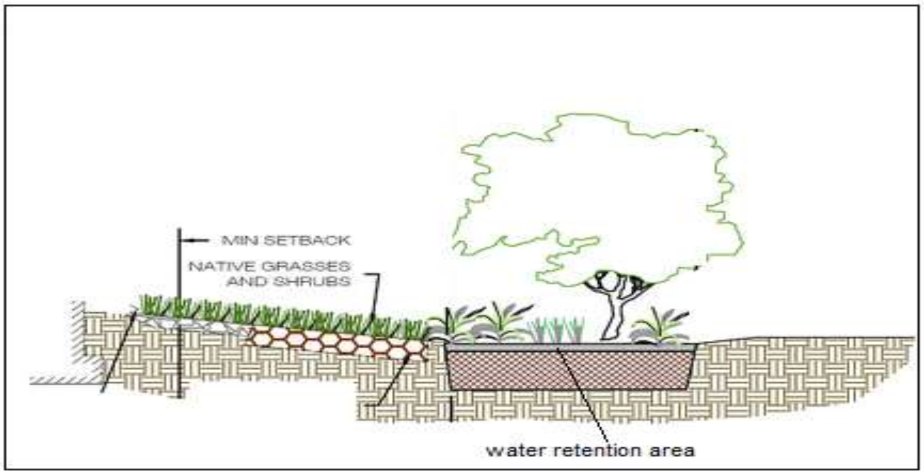


Figure 18: Runoff retention (Veen, 2010)

(c) Diversion of surface water above the gully area. Diversions constructed above the gully area direct run-off away from gully heads, and discharge it either into natural waterways or vegetated watercourses, or onto rock outcrops and stable areas which are not susceptible to erosion, **Figure 19**. Surface water must not be diverted over unprotected areas or it will cause new gullies. In some gully sites of Nite mile, Amucha and Abiriba, in southeast Nigeria, this method was used to stabilise further incision and widening of the gully areas (Iwu, 2012). In gully prevention and control, Igbozurike (1989), equally listed some measures to be adopted. These include construction of run-off catch-pits, construction of bunds, construction of sufficient channels, and construction of embankments and dams.

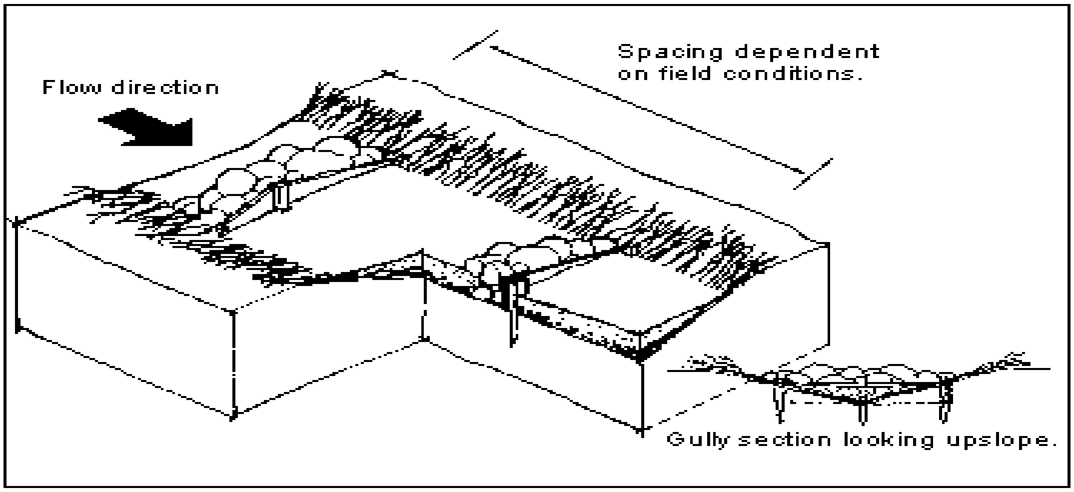


Figure 19: Diversion of surface runoff and prevention of gully prone areas with embankments (Igbozurike, 1989).

2.4 The Application of Remote Sensing in Gully Erosion Assessment

Assessment of gully erosion can be conducted in two categories; ground-based measurements (supported by air-photo interpretation) and remote sensing assessment (supported by ground-work), which are based on different models. Although ground based methods are the most accurate in practice (Hudson 1993; Loughran 1989), for example using Cellular Automation Evolutionary Slope and River (CAESER), measuring gully erosion rates at multiple locations is generally expensive and time-consuming. Standard equipment is not commonly available (Stroosnijder 2005). The CAESER method was used to model the effects of changing flow regime, gully sediment supply, and riparian vegetation on the morphology of the braided Waitaki river, New Zealand (Coulthard et al. 2013) and measurement results may vary under similar conditions (Nearing et al. 1999). Ground based measurements are mostly used for assessing the role of a specific erosion factor, for model development, or for validation purposes, but rarely for spatial evaluation. Some examples using ground measurements do exist, Thomas at el. (1994) in Landscape sensitivity to rapid environmental change in humid tropical areas which is attributed to anthropogenic contributions; Vente et al. (2008) in the assessment the contributions of slope and soil to gully development of Mulka hill gully in southern Ghana. Obinna (2013), used ground based methods (Gully Thermoerosion and Erosion Model- GULTEM) to assess gully erosion hotspots in south-east Nigeria. Obinna pointed out that gully factors such as soil, slope and rate of rainfall runoff where responsible for the gully intiation and development in southeast Nigeria. Igbokwe, (2008) also used this method to highlight soil and gully erosion areas with different degrees of susceptibility to landslide in Oko area of south-east Nigeria. In predicting the rapid changes of gully morphology, Nickson and Laflen 2001, used the Limburg Soil Erosion Model- LISEM to model the sediment transport of Onyema hill gully in southern Nigeria and discovered that slope and high run-off influence the transport of the sediment transport while Lancast (2004) also used this method for assessing gully development in Polakwani South Africa, incorporating in the model are rainfall, interception, surface storage, infiltration, vertical movement of water in the soil, overland flow and channel flow. The result was used to mitigate the effects of runoff and erosion of the area.

Image-based analysis is proving to be a practical approach for erosion assessment over large inaccessible areas. This is especially applicable to regions with excessive gullying, given variability in potential size, shape, and occurrence (Knight et al. 2007 in large-area, high-resolution remote sensing based mapping of alluvial gully erosion in Australia’s tropical rivers and Ezeomedo et al. 2013 in Mapping and Analysis of Land Use and Land Cover for a Sustainable Development Using High Resolution Satellite Images and GIS. This is also applicable to the gully monitoring scenario due to the dynamic nature of gully-affected landscapes. This description largely describes gully occurrence in southeast Nigeria.

Data extracted from remotely sensed imagery have been used to provide specific information for policy makers to enable reclamation of degraded areas like gullies and landslides (Nwilo, et al. 2011 and Okereke, et al. 2012). Recent advances in satellite technology, GIS, and digital image processing, have led to the development of new techniques for semi-automatic and/or automatic gully detection (Nweze 2011 and Osadebe and Akpokodje 2007).

Remotely sensed imagery such as aerial photos, low-altitude aerial photos (e.g., from drones/unmanned aerial vehicles), satellite imagery (multispectral, and synthetic aperture radar), and Light Detection and Ranging (Lidar) data have been utilised to map gully erosion features using several approaches (James et al. 2007). These methods include manual image interpretation, photogrammetry using stereo-photos or stereo-images, and semi-automatic/automatic feature extraction using pixel, sub-pixel, or object-based image analysis (OBIA with field validation) as was utilised by (Adesina 2010 and Shalaby 2007).

The contribution of remote sensing to gully erosion research, based on aerial photo interpretation techniques, dates back to the 1940s (Chalapathi 2015). Gully erosion assessment by aerial photo interpretation and photogrammetric techniques continued largely unchanged for decades, with the studies limited to visual image interpretation (Langran 1983; Stromquist et al. 1985). Examples of this approach can be seen in (Schiefera and Gilbert 2007; Westoby et al. 2012). However, aerial photos have traditionally been collected for smaller regions of interest as can be found in the work of Casanovas (1996); Chuqun (2008); and Nnaji (2008). The collection of Earth observation data has developed over time from aerial photography to multispectral, hyperspectral, Lidar and SAR (Synthetic Aperture Radar). Now, the increasing availability of space borne data with suitable spatial (<1 m) and spectral information (400-1000 nanometre), swath widths ranging from 10 km to 3000 km and frequent revisits, allows the detection of irregular instances of land degradation. Until recently, pixel- based image analysis has been the main method to extract spatial information about gullies (Metternicht et al.1998; Vrieling et al., 2007). However, the selection of adequate training pixels (a key element for a successful classification) requires in-depth knowledge of the study area and careful analysis of the separability of spectral signatures (Reis 2008; Laliberte and Rango 2009).

In addition, spectral heterogeneity of the environment is affected by variability in moisture, organic matter, and mineral content. This strongly affects the performance of multi spectral image classifications. Furthermore, the spatial resolutions of the traditional Earth observation satellite platforms, such as those on-board Landsat, SPOT, ASTER, IRS, ALOS and ENVISAT, are only sufficient to identify large to medium sized gullies (10 meters and above in length) (vrieling and Rodrigues 2004). Although pixel based classification can find possible erosion/gully pixels, the ambiguity of whether a feature is a gully or not requires contextual analysis, hence there is a need to use advanced image processing methods that incorporate contextual information into the analysis. This research work will make use of both Pixel based and Object based image analyses to resolve this problem in a multi modal data analysis framework.

Technical advances in space borne remote sensing, have created new possibilities for research in earth surface processes, including gully erosion. These advances include the provision of higher spatial and temporal resolution, development and extension of digital imaging technology, and improved data integration with GIS. With growing availability of high resolution imagery (HRI), a shift from traditional pixel methods has been necessary. The analysis of objects, as opposed to individual pixels, is more appropriate to address the heterogeneity of the landscape, and more suitable for knowledge driven analyses akin to visual image interpretation. In object-based image analysis (also called object oriented analysis) the information content of an object (relatively homogeneous and meaningful segments in the image) is used to classify the gullies by integrating the contextual information in the image analysis, which is a step towards replicating the human visual interpretation process (Navulur 2007).This method has been used to detect gully affected areas in the Region of Taroudannt, Morocco (Oltmanns et al. 2014) and in Beiyanzikou Catchment of Qixia, Shandong, China (Wang et al. 2014). The results indicate that OBIA can effectively extract information of gullies; average range difference between points field measured along the edge of gullies and classified boundary is 0.3166 m, with variance of 0.2116 m and the erosion area and volume of two gullies are 2141.6250 m2, 5074.1790 m2 and 1316.1250 m2, 1591.5784 m2, respectively, providing a new method for the quantitative study of small gully erosion. (Wang et al. 2014). Wang work has proposed an accuracy assessment method based on the adjacent distance between the boundary classified by remote sensing and points measured by RTK-GPS along the shoulder line of gullies

Since gullies are the result of hydro-geomorphological process, digital elevation models (DEM) and their derivatives have been used as additional data during analysis. DEMs used in gully analysis have been largely derived from remote sensing data (d'Oleire-Oltmanns et al., 2013; Wang et al. 2014). Numerous gully susceptibility studies, trying to identify areas of gully incision, have been developed using slope gradient and critical drainage area relations derived from DEM (Montgomery and Dietrich, 1992; Patton and Schumm 1975; Poesen et al. 1998).

Some gullies may appear fresh and active while actually being very old and stable (Valentin 2004). Assessing gully dynamics may assist in understanding gully formation and spatiotemporal evolution. This is very important as this will be utilised in this research to unravel the real causes of particular gullies in southeast Nigeria from inception and improve understanding of gullies in general. Visual stereoscopic analysis of aerial photos and satellite images (Nachtergeale and Poesen 1999), pixel-based satellite image analysis (Vrieling and Rodrigues 2004), pixel/object-based analysis of data from airborne Lidar data and low altitude unmanned imaging platforms are efficiently used to measure and monitor changes in gully or gully systems. However, measures to stabilise gullies have to be designed for the entire area requiring detailed erosion extent maps at landscape or regional scale. This is one of the cardinal points of this research presented as part of this thesis. As it is not practical to acquire HRI for a larger area (although large swath is available) because of high cost; it is proposed instead that use is made of freely available medium resolution satellite imagery to extract gully features. Although it is possible to map gully extent, it is not possible to quantitatively assess the magnitude of the soil loss using the presented methods. Nduji (2008), Igwe et al. (2012) and David (2014), used freely available satellite imagery (Landsat) to classify land-use and land-cover and quantify gully extent in a single particular year, but similarly were unable to obtain annual loss of soil extent or volume. In the same vein, Reis (2008) analysed Land Use/Land Cover Changes using remote sensing and GIS in Rize, North-East Turkey. A supervised classification method was applied to Landsat images acquired in 1976 and 2000 to determine gully extent. This classification approach was also utilised by Igbokwe, et al. (2008) in comprehensive landcover and landuse mapping of the states of the southeast area of Nigeria. This was conducted with the aim of depicting the spatial distribution of gully sites in the area. For gully monitoring, Shalaby (2007), used the same method for mapping and monitoring land-use and gully erosion changes in the Northwestern coastal zone of Egypt. In the study, maximum likelihood supervised classification and post-classification change detection techniques were applied to Landsat images acquired in 1987 and 2001. Also, Selvam (2012), used remote sensing and GIS Techniques for land use and gully erosion monitoring and mapping of Tuticorin Coast, Tamilnadu India. The study integrated field data for accurately mapping landuse of the study area and a maximum likelihood classifier was applied to classify the Landsat satellite images. Six major landuse classes were identified and mapped for the study area. Ehiorobo (2012), utilised GPS with Total Station Surveys, Remote Sensing and Geographic Information System (GIS) in monitoring the morphology and land degradation processes within the Queen Ede Catchment Basin in Benin City Nigeria.

Although these studies mentioned above such as CAESER, GULTEM, LISEM and Landscape processes modelling at multi-dimensions and scales, have demonstrated good techniques for particular gully erosion assessments, they are less realistic and not practical when working in larger areas with high density complex gully features. Areas such as southeast Nigeria with such complexity have the added complication of often being inaccessible for field measurements (Teeuw 2007)**.** Due to the difficulties involved in ground validating and collecting new measurements in the SE Nigeria region, the research presented in this thesis will combine the use of pixel and object-based analysis of data as well as vectorisation and quantification of Gully patterns. The focus will be trained on developing an improved method for gully assessment, monitoring, concentrating on areal extent and rate of gully change over different time periods. The methods and framework proposed will be considered generic and transferable, allowing application to complex gully systems in other regions of the world. There are similar methods that were utilised by Vrieling and Rodrigues (2004); Reis (2008); Laliberte and Rango (2009); Nweze (2011); and Osadebe and Akpokodje (2012), but their work did not monitor gully change over different periods of time.

2.5 Limitations of Analysed Literature

Having highlighted and analysed the published literature on gully erosion, this study identified clear limitations with existing works. It is these limitations that this framework and methodology presented in this thesis aims to address. The limitations include a lack of tracking historical development of gullies; statistically correlating rainfall patterns with observed gullies over a defined period of time, and monitoring landuse and landcover changes during this time period. No research study has been conducted in Nigeria to this level of detail using remote sensing and landuse classification to allow application of a monitoring framework across the entire region. Other more basic limitations associated with Nigerian gully studies include the lack of use of Nigerian soil maps to analyse soil as a factor of soil erosion.

This study will resolve these limitations and equally address the existing problem that very little detailed work has been undertaken to ascertain the main contributory factors causing gully development in South East Nigeria, particularly regarding historic development. This study aims to improve on this current scenario by examining the current state and past dynamics of gullies in the region over time and incorporating *in situ* measurements of identified gully coordinate points acquired during field work. In addition, use will be made of land-use and land-cover points from selected sites and multi modal remote sensing imagery to detect areas where gully erosion exists, to what extent, and at what rate. Based on substantial evidence from information obtained from site visits, the climatic condition of the study area, and other research works carried out in south-east

Nigeria on gullying, this study will focus on gullying due to overland flow as the predominant type found in south-east Nigeria. Gully erosion in southeast Nigeria is one of the most challenging environmental problems. Degradation of sediments in the area has both on-site effects, such as loss of soil fertility and lowered water holding capacity, and off-site effects, such as siltation of reservoirs and lakes (Tamene and Vlek 2007).

The major contribution to knowledge is that low budget remote time series analysis will be performed for the first time on established gullies in West Africa. Equally, anthropogenic and physical contributions to gully development will be evaluated and analysed to ascertain the level of their contributions. This will be done by ways of land cover analysis and rendering of Digital Elevation Models (DEM) to detect changes on the land surface. This study will focus on the time period of 1986-2015 and will additionally incorporate the analyses of meteorological conditions in southeast Nigeria and the relationships with soil. These additional analyses will allow observation of environmental and climatic conditions which are changing or existing and may correspond with gully extent and rate of erosion variations at the 14 studied gully sites. The study will make use of Nigerian soil maps to identify the type of soil prevalent in the area of study and identify its relationship with gully erosion formation in the study area.

In order to carry out these objectives, an essential and widely applicable, low cost method of gully identification and monitoring is required. This, in conjunction with assessment of the landscape in terms of land cover and the changes over time, will help application on a regional to national scale.

2.6 Rationale of the Study

The devastation caused by gully erosion in southeast Nigeria is very poorly quantified, in spite of a series of studies carried out by researchers. What is required is a method allowing a regional to national analysis which can be obtained through the use of low cost medium resolution remote sensing data as proposed in this thesis. Understanding the development and dynamics of major gully sites through the methods proposed in this study will also allow preventative measures to be enacted to reduce the need for future intervention. This gully preventive masures will be nipped in the board when gully development and change over time have been well understood.The problems associated with gully erosion are immense and include; loss of life and houses, infrastructural collapse and loss of agricultural land. The extent, role, and development of gullying in the studied region remains unmapped, unabated and unresolved.

2.6.1 Knowledge Gap

As indicated by the literature review, the knowledge gap lies in the limitations of other research works to fully understand empirically the way studied gullies have developed over time. In addition, methods presented have not been consistent or produced any clear "one method suits all" methodology. It could also be added that experts have not considered temporal development over long enough periods to understand how and why gullies have developed in regard to the local landscape. This research work will provide the facility to do something that no research work on gully erosion has done previously by methodically tracing and tracking gully development from early stage onset to mature stage through the use of remote sensing and GIS. The methods presented are here used to classify landcover and vectorise/quantify gullies to determine rates of change and identify what predominant environmental conditions are exacerbating gully formation in the area. It is anticipated that appropriate control and mitigation may be applied to slow and reverse gully erosion effects upon application of the proposed quantification and monitoring methods, with also potential use for identifying areas of high risk or threat. Potentially the most significant aspect of this study is the low cost of implementing the methods, clearly addressing a societal need in low GDP countries.

Therefore, this study will provide a framework for tracing and tracking gullies from early development to maturity to determine the causes, and allow detection and quantification of extent and rates of erosion in gullies in Southeast Nigeria. It will additionally provide a process for use as an early warning indicator of areas at risk of gully development, which is done by observing the same senerios responsible for gully development in the area. It is expected that the findings will inform local government policies and be available for decision making purposes in other regions affected by this phenomenon. The output of this study in terms of the contribution to knowledge and the presented monitoring methodology will serve primarily as a management tool to inform the application of protective measures while essentially requiring minimal financial input.

2.6.2 List of the Contributions to Knowledge

Achieving the principal aims of this investigation will lead to original contributions to knowledge that are summarised in the following list:

Development of a methodology to trace and track gully development as a potential consequence of environmental variability and land-cover change. Monitoring gully development from early stage to maturity.

1. Regional monitoring of gullies through comparing and contrasting low budget remote sensing and classification methods (Pixel and OBIA), using Landsat and Google Earth imagery.
2. Displaying and evaluating the potential for fusing Landsat and Google-Earth imagery to overcome missing or unusable data in the Landsat record.
3. Tracing and utilising rainfall patterns to observe the development of gullies over a study period.
4. Using ALOSPALSAR image change detection to determine forest degradation associated with anthropogenic encroachment as a possible precursor to gully development.
5. Use of remote sensing to obtain which of the gully factors identified contributes to gully development more than others.
6. Providing a low cost framework to incorporate the proposed methods for gully monitoring and quantification for specific application to low GDP countries.

3 Data Acquisition and Sources

As mentioned in previous sections this thesis is developed with the aim of using satellite remote sensing to explore and evaluate the impact of environmental changes as triggers for gully formation in south-east Nigeria. The importance of this subject lies in the proposed methodology of employing past satellite images to study gully development. The research methods presented aim to determine the causes while providing a low budget method for gully analysis and monitoring.

To enable gully monitoring in response to environmental change, particularly regarding land-cover, remote sensing data is an obvious tool to use. For this study it is a key and essential input. Remote sensing data is an excellent and reliable tool due to the cost effectiveness of the data and its relevant application and accessibility to an area of Nigeria with low GDP. Out of all available remote sensing methods the immediate availability and extensive temporal coverage of the Landsat data archive make this the ideal candidate for data provision. Landsat is used in this study to enable initial investigations. Data has been available through the Landsat data continuity mission for ~40 years (Short, 2011). This temporal period provides sufficient data for the purposes of this study which will examine the years 1986-2015 due to the free availability of Landsat data during this period (Teeuw et al. 2012) but also most of the studied gullies developed within this time period. The temporal coverage effectively allows the monitoring of the gullies in question from formation to present day in a way that ground measurements have not been able to match. In this study the Landsat archive will be supplemented by Google Earth images, from Landsat and Copernicus at 30m and Digital Globe images of between 2 – 3m resolution/pixels available over some selected gully sites. This will be especially useful for monitoring those gullies that are under the cover of forest, those that are smaller than the Landsat image resolution/pixels (30m × 30m) and those that have developed more recently. Some of the Google Images have higher resolution/pixels than Landsat Images and have the ability to cover most of the inadequacies of Landsat images as highlighted above. Images acquired from the Radar satellite system ALOS PALSAR (Rahman and Sumantyo 2007) was are also incorporated into the study to compare with the classified Landsat images, to check for the reliability of result obtained and for Mapping dynamics of deforestation and forest degradation in southeast Nigeria. Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) is used for topography analysis of the study area.

3.1 Landsat Images

The Landsat program is the longest running satellite program for acquisition of satellite imagery of Earth. On July 23, 1972 the Earth Resources Technology Satellite was launched (National Aeronautics and Space Administration 2011). This was eventually renamed Landsat, (Short 2011). The Landsat MSS (The Multispectral Scanner System) recorded data in four spectral bands of green, red, and two infrared bands. The most recent system, Landsat 8, was launched on February 11, 2013. The images, archived in the United States and at Landsat receiving stations around the world, are unique resources for global change research and applications in agriculture, cartography, geology, forestry, regional planning, surveillance and education; among others (National Aeronautics and Space Administration 2003). Landsat has been used successfully for monitoring land formation and land-use changes in works such as Metternicht and Zinck (1998) and Vrieling (2006) in which Landsat was used to detect and map changes in erosion features and eroded areas, topography, soil properties, vegetation cover, and management practices. The latest studies mentioned have been able to incorporate the use of the Multispectral Scanner Sensor (MSS) and Landsat Thematic Mapper (TM) bands in their studies. Landsat 8 **Figure** 20 has been used extensively since its launch in 2013 with studies such as (Wang 2013; Van et al. 2014) relying heavily upon its output.

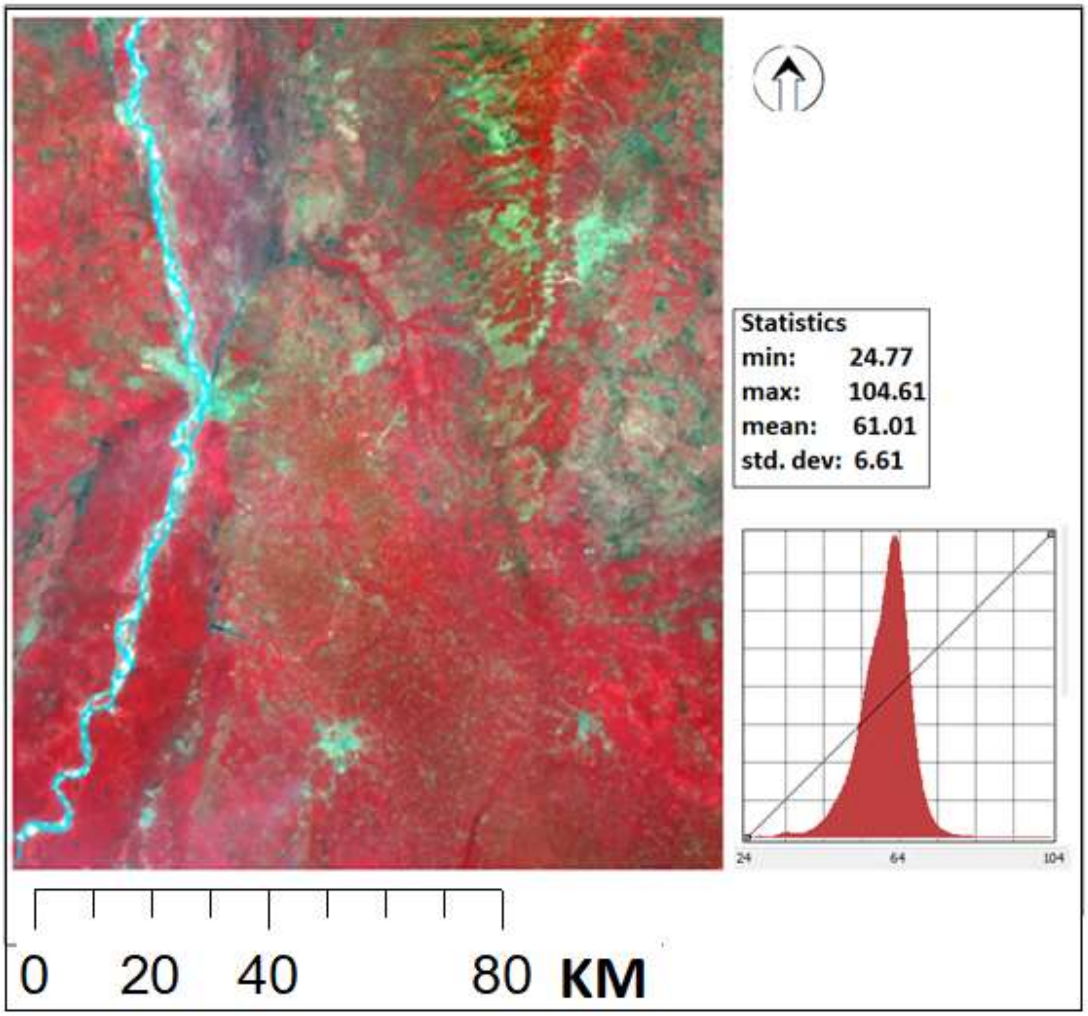


Figure 20: 2015 Colour Infrared Landsat Image of southeast Nigeria with band combination of 5, 4, 3 for Landsat 8 and 4, 3, 2 for Landsat (scene ID, path and row 188055, 188056, 189055, and 189056). Mosaicked and cropped to leave only the region of interest. (USGS 2015)

The MSS and TM bands are used in select studies such as Nduji, (2009); Nweze, (2008); and Matternicht and Zinck, (1998). The MSS consists of 4 bands with, 60-metre resolution. Many of the newer images (Images dated March 1 1984 or later) are from the Thematic Mapper, a newer scanner carried on Landsats 4 (Clark 2006) and 5 (McDowell 2013) or from ETM+ data, (Enhanced Thematic Scanner Plus), on Landsat 7 (McDowell 2013). These sensors have 30-metre resolution and with more bands than MSS, but the images are all comparable and work on the same principles (Campbell 2008). More details in **Appendix I**

3.2 Synthetic Aperture Radar (SAR)

SAR is a side-looking radar system that generates a high resolution image of the Earth’s surface for remote sensing application. It is an active system that uses the microwave region of the electromagnetic spectrum (Chang 2011). The available wavelengths considered for radar are from approximately 1mm to 1m. SAR can penetrate clouds due to very low energy attenuation, making it useful for collecting data in areas of bad weather, persistent fog or smoke (Tian 2011). This is of particular benefit in tropical areas in which optical images are often hampered by persistent cloud cover. SAR is an active system, meaning it does not rely on external energy sources, for example it does not rely on solar energy (Mishra and Mulgrew 2007). This additional benefit allows uninhibited data collection 24 hours a day independent of daylight. SAR discriminates features according to roughness, shape and orientation which are related to the backscatter and polarizations. These properties give it a different methodology for identifying features. Advantages over optical remote sensing are apparent when observing ice, ocean waves, soil moisture, vegetation mass, man-made objects such as buildings and most geological structures. For each of these structures additional information is provided by radar which can be used independently or complementary to optical datasets. Using interferometric techniques SAR can be used to generate DEM (Digital Elevation Model). This has been used most prominently to create the output of the Shuttle Radar Topography Mission (SRTM) now providing 30m horizontal resolution data equivalent to Landsat (Schneider 2006). The accuracy of elevation data obtained from SAR allows for detection of minute changes in the landscape (Carabajal and Harding 2006).

3.2.1 Alos Palsar

The Advanced Land Observing Satellite (ALOS) Phased Array Type L-band Synthetic Aperture Radar (PALSAR) **Figure 21,** was launched from Tanegashima, Japan, on 24 January 2006 by the Japanese Aerospace Exploration Agency (JAXA) on an H-IIA rocket. In Japan the system is known as DAICHI (McCurry 2007). The satellite contains three sensors that were used for Earth monitoring, cartography and disaster monitoring. ALOS data has been used to analyse several disaster sites (Susuki et al. 2012). Images of the devastated Japanese coast following the 2011 Tohoku earthquake and tsunami were among the last major contributions from ALOS, which was declared dead in orbit by JAXA on 12th May, 2011 and on 24th May, 2104 ALOS 2 or Daichi 2 was launched (Japan Aerospace Exploration Agency 2015). The ALOS PALSAR, high resolution system operated on a maximum bandwidth of 28 MHz and centre frequency of 1270 Mhz (23.6 cm) The different modes have different bandwidths. The higher the bandwidth the better the image resolution. The observation modes are described below;

Fine Mode: This observation mode is most commonly used under regular operation. Its maximum resolution/pixels of 7m is one of the highest available from L Band SAR (for comparison, SAR onboard JERS-1 (Rosenqvist et al. 2004), a previous L-Band sensor, was about 18m pixel). Fine resolution mode typically gives 10 m spatial resolution in both range and azimuth over 70 km of swath width. Significant studies such as (Margono 2012) and (Joshi et al. 2015) took advantage of this resolution.

ScanSAR mode: ScanSAR mode enables scanning off-nadir angle from 3 to 5 times (scan by the swath of 70km) to cover wide areas from 250km (70 miles' x 3 miles) to 350km (70 miles x 5 miles). For comparison, swath width of SAR onboard JERS-1 was about 75km. The ScanSAR mode offers more than 250 km width of SAR images at the cost of spatial resolution (100 m) but when an optimised orbit is used; one could revisit the same target area in less than five days (Amante and Eakins 2009). Studies such as (Pearson et al. 2014) and (Potapov et al. 2014) benefited from the use of the larger swath width to map tropical forest change assessment in Mapping the worlds intact forest landscapes and in Peru.

Polarimetric mode: PALSAR possess data transmission and receiving capabilities in both horizontal and vertical polarisation. In addition, PALSAR can switch from horizontal to vertical polarization and vice versa at respective transmission pulse enabling four polarizations by doubling simultaneous polarization, a function called full polarimetry (Caccetta et al. 2010). The resolution of Polarimetric mode is 30m on a 30 km swath, which gives a complete polarization scheme (HH/HV or VV/VH) (Rosenqvist et al. 2004)

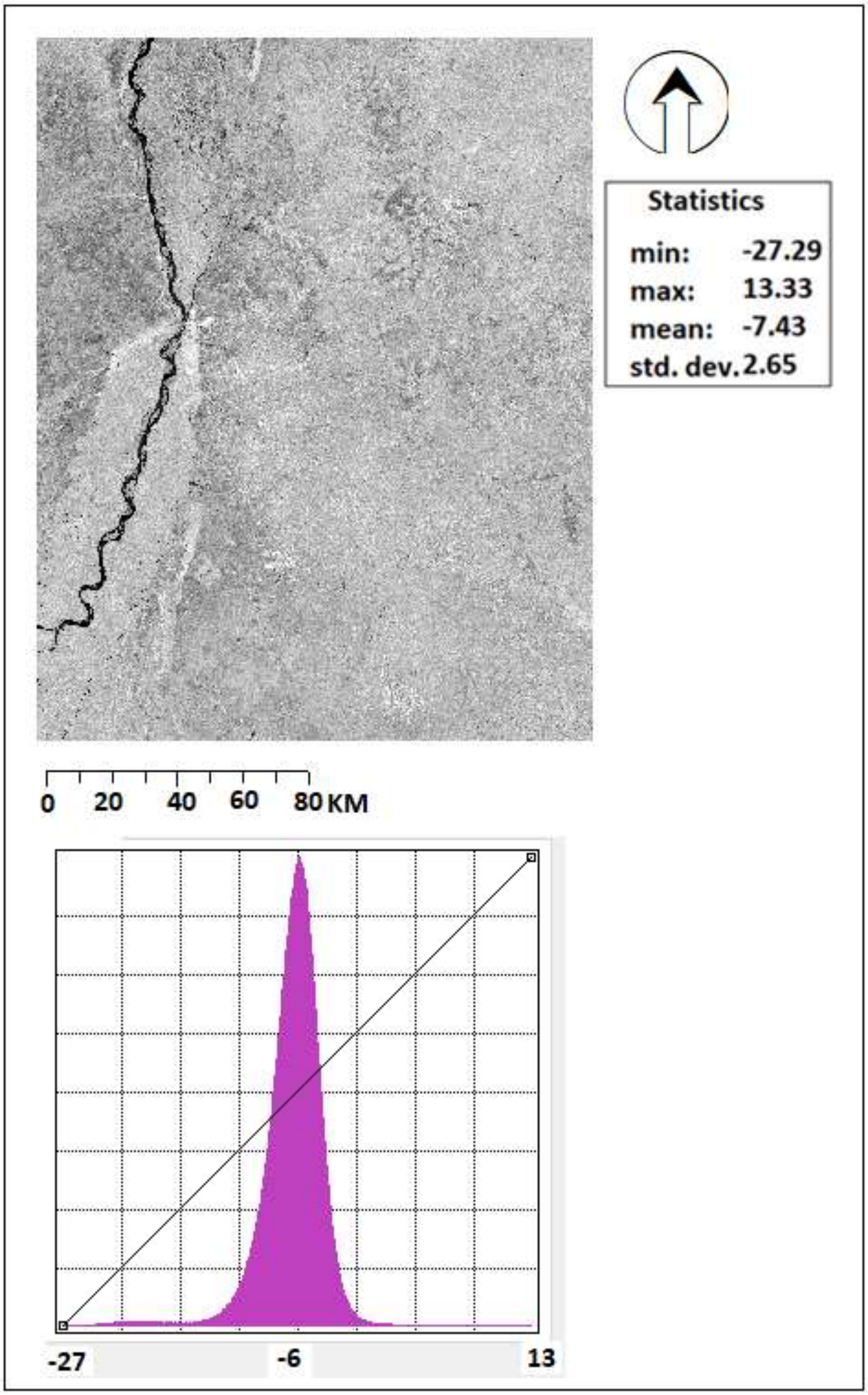


Figure 21: 2008 ALOS PALSAR image of southeast Nigeria. (JAXA 2014)

3.3 Google Earth (from Landsat of 30m and DigitalGlobe QuickBird of 2 – 3m pixels)

Google Earth is a virtual globe map and geographical information program. Google Earth displays satellite images of varying resolution of the Earth's surface, allowing users to see things like cities, houses, roads and other geographical features. In mapping **Figure 22,** Google Earth has assisted cartographers, Geographers and other Environmental Scientists in mapping activities. For example, Gilad et al. (2012), used Google Earth to study the gullies of The Great Barrier Reef. Google Earth assisted in mapping out sensitive areas and areas that have low satellite resolution. Also, a risk map for gully locations in central Queensland, Australia was mapped out with the aid of Google Earth (Eustace et al. 2011). McInnes et al. (2011) used Google Earth and other satellite images to map gully extent in the West Gippsland region (Victoria, Australia). Google Earth aided the study in getting the extent of the studied gullies. It is observed that Google Earth images have been used to map out gully erosion sites in Imo state southeast Nigeria where Google earth images and ground truth were used to confirm gully spots and maps were then generated with vital spatial datasets on the spatial distribution and development of gully erosion in Imo State (Amanbagara et al. 2014).

Figure 22: 2015 Google Earth of southeast Nigeria (Google Earth image 2015)

3.4 Shuttle Radar Topography Mission (SRTM) DEM

The White House made announcement On September 23, 2014, that the highest-resolution topographic data generated from NASA's Shuttle Radar Topography Mission (SRTM) in 2000 was to be released globally by 2015. This announcement was made at the United Nations Heads of State Climate Summit in New York. Since this announcement was made, the schedule was accelerated, and all global SRTM data have been released. Lower-resolution SRTM topographic data having 90-meter pixels were released publicly in 2003 for many parts of the world, providing a global standard for many applications. The new data increase the detail to 30-metre pixel spacing, now revealing the full resolution of the world's landforms as originally measured by SRTM **Figure 25 section 4.2.1** (National Aeronautics and Space Administration 2014). Since the release of the 30-metre resolution in Africa, the Digital Elevation Model has been used in topographical mapping. For example, calculating and analysing terrain is the study of soil/ gully erosion, hydrology, geographical locations and changes (Mayomi et al. 2016; Ikusemoran et al. 2014; Mayomi et al. 2014; Dalil et al. 2016) Since the release of this 30-metre resolution, there is improvement in horizontal and vertical accuracy, reduced presence of artifacts and a better and realistic water body values (Mispan et al. 2015). A recent research Yue et al. (2015) revealed that on mountainous and rugged terrain, the SRTM data set can be more accurately represented on the ground than the Aster version 2 elevation model. In case of estimating area, SRTM underestimated the Domli Dam point, Pakistan while ASTER DEM overestimated the area (Ehtesham et al. 2016). In calculating and analysing terrain in the study of soil/ gully erosion, hydrology, geographical locations and changes (Mayomi et al. 2016; Ikusemoran et al. 2014; Mayomi et al. 2014; Dalil et al. 2016), all used SRTM DEM. Even though some work suggested that ASTER version 2 DEM is better than SRTM DEM (Moulatlet et al. 2015), The study area of this study will make use of SRTM DEM based on the ground points comparison with ASTER DEM **Table 3** showing that SRTM data elevation points were better than the ASTER data in 3 points out of the 4 observed points.

Table 3: Comparison of elevation points of ASTER and SRTM DEMs in the study area

Reference object	Reference point	Ground Elevation point from GPS	Aster Elevation point	SRTM Elevation point
Lokpanta hill peak	5°54'50.66"N 7°23'15.31"E	348m	255m	365m
Onitsha river shore	6° 8'37.34"N 6°45'16.63"E	22m	19m	23m
Ogui Layout	6°12'24.82"N 6°49'55.62"E	110m	111m	112m
Ogwu MTN mast	6°29'35.09"N 7°18'0.55"E	216m	213m	217m

3.5 Nigeria Soil and Geology Maps

The soils in Nigeria are classified into various zones; but the focus are those found in south-east Nigeria in the research areas of this study **Figure 11 section 2.2.4.** The soil map was acquired from new version of Harmonized World Soil Database from where the Nigeria Ministry of Lands and Surveys derived the current soil map of Nigeria. The soil of the study area is discussed in three zones

Southern belt of forest soils: Soils in this zone broadly represent those of the humid, tropical forest climate zones of the south where the wet season is long, the Harmattan season is short and forest cover is dense. Local soil types depend largely on parent rock (Adegbola 1979). Where the underlying rocks are granite or clay, the soil is a rich clayey loam (Ofomata 1998). The forest soils yield cocoa, oil palm, rubber and they are of considerable importance in Nigerian agriculture (Adegbola 1979).

Interior zone of laterite soils: This zone is made up of sands and clays. They are grey to black clays poorly drained and seasonally flooded forming the “Fadama” (Aregheore, 2009). Soil in this zone is deeply corroded, generally sticky and impervious to water and has low fertility (Iloeje 2001). When the virgin forest on them is cleared it reduces the fertility further, thus making available soil of little agricultural value (Adegbola 1979). When the soil is exposed to the surface, it becomes as hard as brick and for this reason, the soil here is more suitable for road paving and wall construction than for farming. However, not only laterite soils are found in this zone (David 1997).

Zone of alluvial soils: These soils are found on the flooded plains of rivers or on deltas, or along the coastal flats. This zone extends from the coastal inland and runs along the valleys of the Niger and the Benue rivers, thus cutting across the vegetation zones. The soils found in this zone do not depend highly on climate and vegetation for their formation (Iloeje 2010). The underlying parent rock is the most important factor in their formation. Soils in this zone are characteristic of fresh-water soil of grey to white sand, grey clay and sandy clay with humid topsoil (David 1997). Another group consists of brownish to black saline mangrove soils, with a mat of rootlets (David 1997). The south-east soil map was acquired from Nigeria’s Federal ministry of Lands and Survey, Abuja Nigeria. This ministry is in charge of land related matters like solid minerals, land acquisition, maps of different kinds in Nigeria. The geology map of southeast Nigeria was acquired from Nigeria Ministry of Solid Minerals Development produced in 2015 (Offordile 1976). It was published by Nigeria Geological Survey 2005-2012 in a scale Map 1:250,000. The soil data represents an independent variable for use in further statistical analysis to determine its influence on gully formation and erosion rates.

3.6 Southeast Nigeria Rainfall Data

The rainfall data of the study area was obtained from Nigeria meteorological Agency (NIMET). The study area is rainforest area with rain almost all the months of the year, with June to July and September to October recording highest monthly rainfall data. The rainfall data was made available from the archived rainfall data from NIMET office. The rainfall data for the year was recorded by calculating the monthly rainfall average for that year.

3.7 Field Data

Ground validation field work was conducted with Handheld Garmin Global Positioning System (GPS) Recievers with accuracy of within 10m (the accuracy was determined by the use of PDOP {Positional Dilution of Precision} values). The best PDOP values are obtained by one satellite directly above the receiver and three others evenly spreed across the sky (Parkinson 1996). This was carried out in June/July 2013 to determine the validity of areas initially identified as gullies using remote sensing data. The choice of field season was made because it is the peak of the rainfall that produces runoff in the study area and to observe insitu gully development. This was different from the choice of season for satellite data that was obtained during dry season to avoid cloud and other weather artifacts that occur during rainy season. The gully points were located using, Easting and Northing locations, and GPS measurements. The location of the gully measurement was determined by the nature of the gully regarding accessibility. Some were measured from the centre, some by the side and some at the gully head, see **Table 4**. The field work was also used to determine Land-cover of the local area, nature of topography of the study area and visual analysis of some of the gully sites. All data acquired were used in the landcover classification process, topographical analysis, and general gully site analysis. In measuring and obtaining the information needed, youth leaders from each community helped to acquire data needed by acting as a guide ensuring villagers did not interfere in the process of the work.

Table 4: Observed Gully points in UTM (32N) coordinates from the field and the side of gully where points were picked. R=Right, L=Left and G=gully. Coordinates in Universal Transverse Mercator (UTM)

	Gully Name	Easting(m)	Northing(m)	Gully Side		Gully Name	Easting (m)	Northing (m)	Gully Side
1	Agulu	287006.7	671828.8	South	21	Nkwere1	285500	633512	North
2	Nanka	280249.2	676632.2	South	22	Nkwere2	285633	633384	South
3	Ukwulu	275812.1	693160.8	East	23	Amaigbo	285656	633251	East
4	Ejemekwu	224276.5	587335.4	North	24	Ehime	310800	628052	North
5	Umuaka	283306.3	641559.8	East	25	Isinweke	310821	628074	East
6	Nkpor	268550.4	655853.7	South	26	Onicha	310826	628045	East
7	Njaba	279040.32	630127.83	South	27	Umuderim	310928	628052	West
8	Ideato	285272	649271	North	28	Iyioku	330452.05	705080.71	East
9	Ihiala	279806	644590	South	29	Umunomo	310528	620814	South
10	Umuchieze	301901.00	620430.00	West	30	Dikenafai	294019	640235	West
11	Obodoukwu	286075	644712	East	31	Umuezike	294015	640077	South
12	Umuaka	285669	633719	West	32	Umuowa	293843	640186	South
13	Umuezike	285730	633612	West	33	Amobia	293895	640248	East
14	Okigwe	290963.48	672395.90	East	34	Igboukwu	259322.32	674641.62	East
15	Orlu	283044.05	642487.15	North	35	Isinweke	317475.49	627455.20	West
16	Amucha-2	285607.00	633615.00	South	36	Nekede	277394.78	596903.36	North
17	Ngwo-1	323446.00	713518.00	North	37	Ngwo-2	323245.00	713784.00	West
18	Oguta	261516.24	632542.9	South	38	Oraukwu	275009.01	674335.22	South
19	Umuahia-2	328458.00	614902.00	North	39	Urualla	285138.93	649246.3	North
20	Nawfia	280062.58	685792.43	East	40	Obosi	259322.32	674641.62	North

4 Methodology and Analysis of Data

This study adopts remote sensing and GIS methodologies in processing the satellite data. This involves Landcover classification, study area DEM analysis, gully area analysis and Analysis of forest degradation and deforestation of the study area.

4.1 The Methodology Work Flow Chart

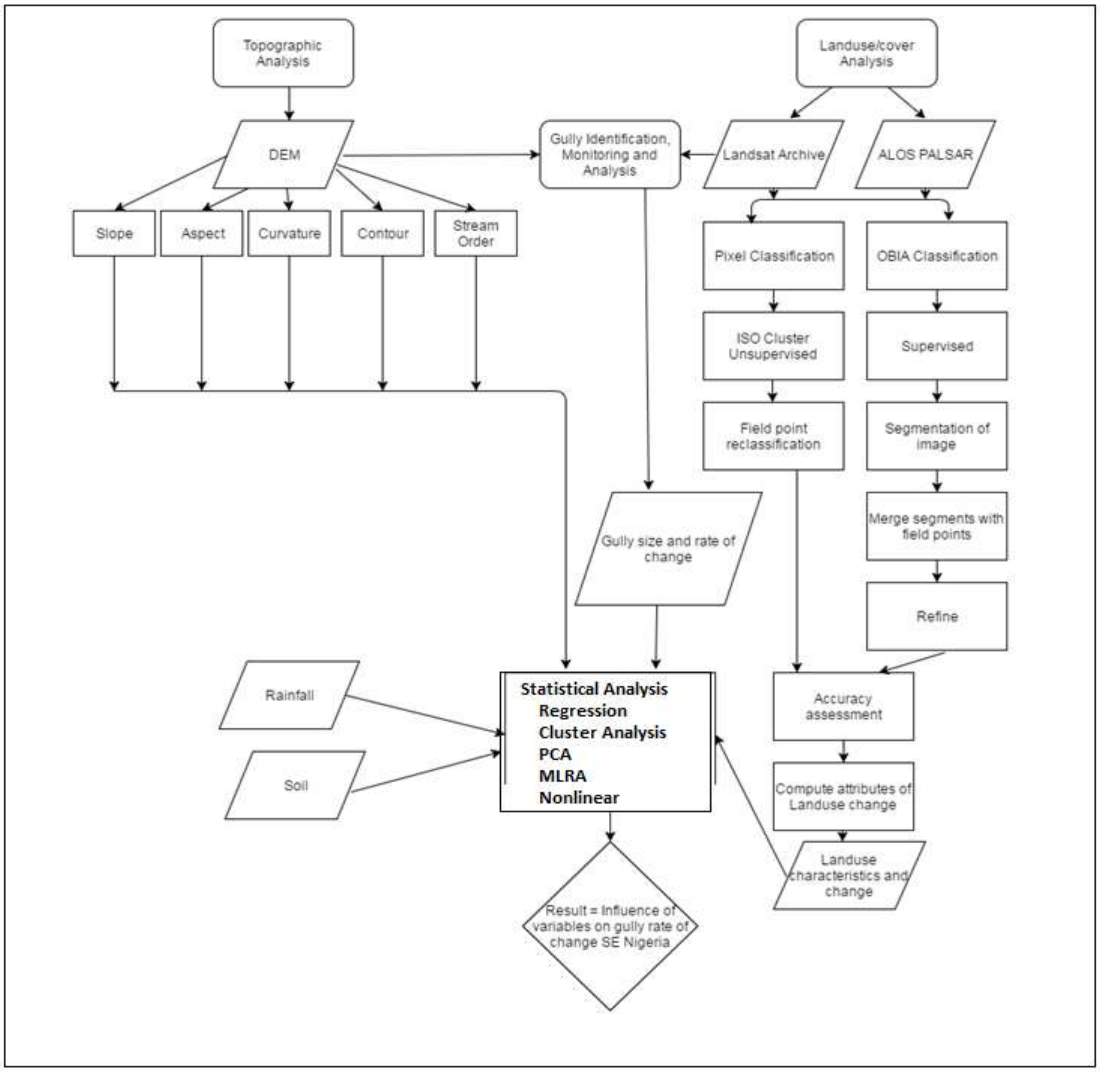


Figure 23: The methodology work flow chart

4.2 Preprocessing of Data Used

In the case of this study, the remote sensing data used in this research were acquired from Landsat images from December 1986, 1987, 1988, 1989, 1990, 1991, 1992, 1993, 2000, 2001, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012 and 2013, 2014 and 2015. Attempts to compile a complete annual data set were impeded by unavailability of Landsat images in the study area from 1994 – 1999. During this time period the data was not available, not because of cloud cover, but because of data acquisition issues within this period. The study area is found in the tropical region where the presence of cloud cover is extremely common throughout the year (Iloeje, 2010). Images were then chosen from the month of December during the Dry season when the sky is mostly cloud free. The use of Landsat is warranted for several reasons. It is observed that no other current or planned remote sensing system, public or private, fills the role of Landsat in global, regional environmental change research, or in civil and commercial applications (National Air Space Agency, 1999). The Landsat archive contains data spanning over 40 years (Lee and Liu, 2001) and continues to be collected through Landsat 8 launched in February 2013. The spatial resolution of Landsat Images from 1986 onwards is 30m x 30m, and is applicable for the study area, as the study area covers a very large area of about 57,758.034Km2. Previous research by Nduji (2008), observed that studying the development of large gully through time is well suited to the use of Landsat images. The data have been used in other related studies such as Okereke et al., (2012) and Manandhar, (2009).

A common error occurring in Landsat data acquired after 2003, SLC-OFF, was corrected using Focal Analysis in the software package Erdas Imagine. The error occurred as a result of a failure of the Scan Line Corrector (SLC) onboard the Landsat 7 Enhanced Thematic Mapper (ETM) sensor on 31 May 2003. Since that time all Landsat ETM images have had wedge-shaped gaps on both sides of each scene, resulting in approximately 22% data loss (Zhang, et al. 2007). The processing technique applied to correct for this error has the ability to fill gaps in each band with data from the closest pixel values not affected by SLC-OFF

Figure 24. It does this by calculating their standard deviation and mean values, with a method known as Gap-filling Landsat 7 SLC-off (Chen et al. 2011). The error does not exist for Landsat 8 data. Each Landsat 7 band acquired in the month of December 2003 to 2013 that was used in this study were subjected to Gap-filling to fill the SLC-off data. The bands are Bands 1, 2, 3, 4, 5 and 6. The choice of these six bands area were they distinguish land cover and land use from one another, and measure ways they change over time (Bahadur 2009).

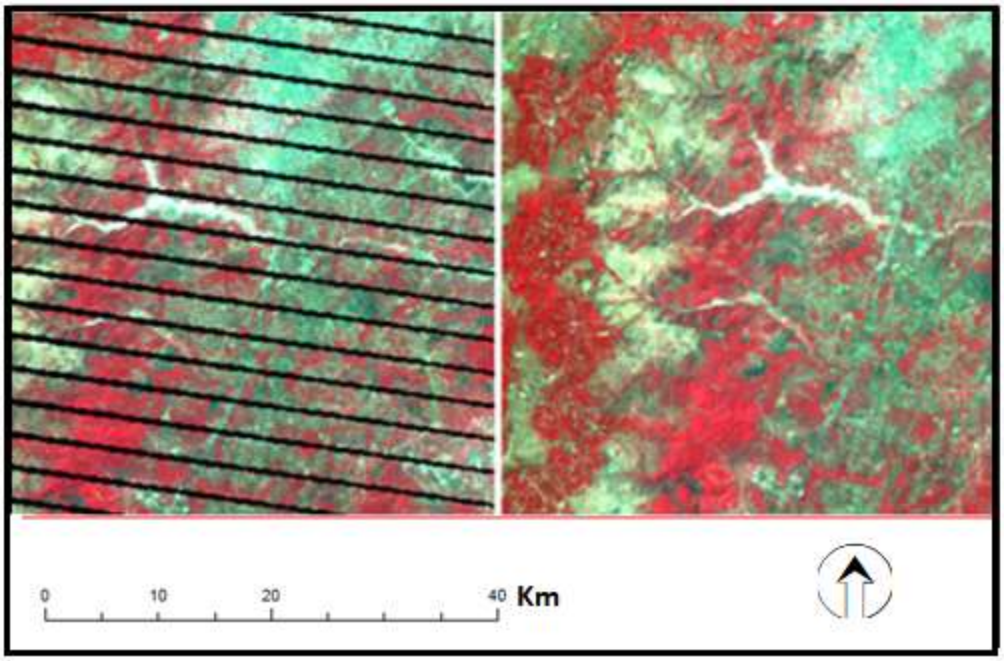


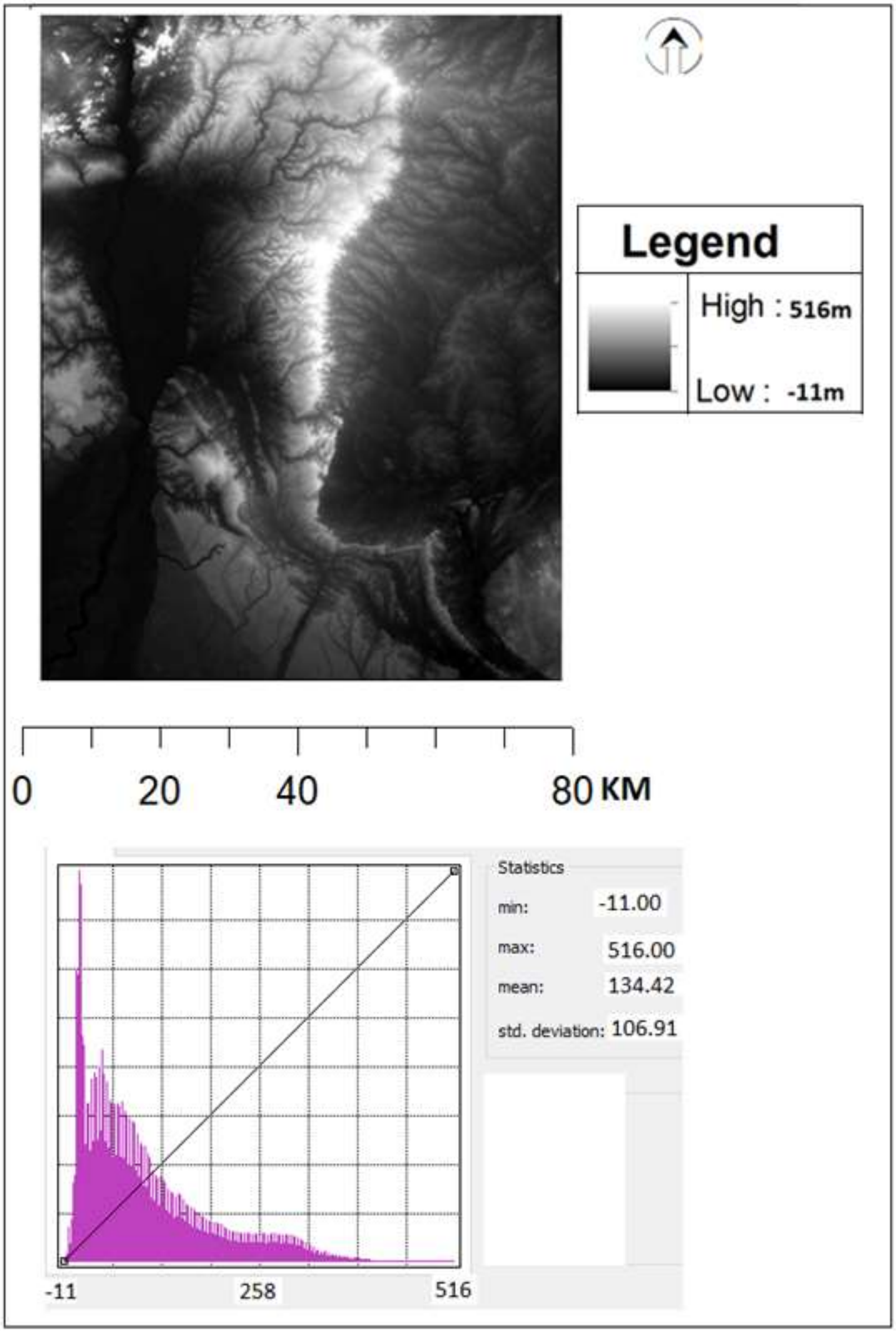
Figure 24: colour infrared Landsat 7 SLC-OFF data before and after correction (December, 2013) with band combination of 4, 3, 2. (USGS 2013)

A very large percentage of Landsat imagery are severely contaminated by aerosols, clouds, loud shadows, and other artefacts. The removal of the effects of aerosols, clouds and cloud shadows can make Landsat images more useful. This procedure for retrieving surface reflectance is usually called atmospheric correction (Liang et al. 2001). However, to maximize the usefulness of the data from a multitemporal point of view, an easy-to-use, cost-effective, and accurate radiometric calibration and correction procedure are needed. The atmosphere effects the radiance received at the satellite by scattering, absorbing, and refracting light; corrections for these effects, as well as for sensor gains and offsets, solar irradiance, and solar zenith angles, must be included in radiometric correction procedures that are used to convert satellite recorded digital counts to ground reflectances (Chavez 1996). Using recent Remote Sensing software like Geomatica, and Envi 5.1, there is automatic calculation of all the parameters like sensor type, acquisition date, solar zenith, solar azimuth and automatic detection of all the band set-up which calculates the offset and gain of the bands for reflectance values (Masek et al. 2012). The formula for atmospheric calculation is in attached in Appendix XI. Atmospheric correction was performed in this work also allows for accurate mosaicking by properly aligning of two adjacent Landsat images, which can be used for image classification and other measurements. After preprocessing of the images, the four scenes of the study area (scene ID, path and row 188055, 188056, 189055, and 189056) where mosaicked (Mosaicing is the process of combining multiple, individual images into a single scene) and cropped to leave only the region of interest (ROI, southeast Nigeria).

The preprocessed Landsat images where used for image classification for land-use and land-cover analysis and other measurements. In addition, preprocessed 2008 and 2009 ALOS PALSAR images were used to classify the Land-cover of the study area to compare directly with the results of processes enacted on Landsat 2008 and 2009. This quality analysis was done to check the reliability of Landsat images for their ability to be used for Land-use and Land-cover classification particularly relating to gullies and forest environments. The L-band SAR observations of the ALOS PALSAR (Phased Array L-band Synthetic Aperture Radar) data have resolution of 10m which is higher than Landsat image resolution and therefore potentially more accurate in defining land classes.

4.2.1 SRTM (DEM) for Topographical Outlook of the Study Area

In order to obtain the structure and contribution of topography to the development of gullies in the study area, SRTM (USGS DEM) images were used. This study will use newly released 30m X 30m SRTM data of the study area acquired from Shuttle Radar Topography Mission dataset (Jarvis et al. 2008). This dataset was chosen to get a recent topographical outlook of the study area to enable qualitative and quantitative analysis of the gully sites. The DEM were downloaded and cropped to the area of interest **Figure 25**. The elevation values ranges from low = -11m to high = 516m. This elevation data from each of the 14 studied gullies which includes hillshade, slope gradient, slope aspect, slope curvature, contour of the area, cross profile and gully stream order, represent an independent variable for use in further statistical analysis to determine its influence on gully formation and erosion rates. These DEM rasters used in this analysis were processed and calculated with spatial analyst tools of GIS software (ArcGIS, Erdas Imaging etc).



Statistics

min: -11.00

max: 516.00

mean: 134.42

std. deviation: 106.91

Figure 25: An SRTM DEM image of the 57,758.034km2 study area, cropped to Area of Interest Black represents low elevation (USGS 2016)

4.2.2 Google Earth Images for Gully Analysis

Google Earth images were used in order to aid analysis of gullies hidden from view in the Landsat images due to vegetation cover (Almeer 2012), weak spectral signatures, or because of the low spatial resolution of the Landsat image compared to the specific images sourced from Google Earth (Martinez-Casasnovas, 2003). Google Earth images **Figure 26** were downloaded and gully edges were digitized using the polygon tool from the Google Earth for digitization and quantification of the gully areas, starting from the first available year, 2006, to 2015 to act as a supporting dataset to the Landsat archive. Some of the gullies that are found in Landsat images are as well found in Google Earth images and they were digitized and measured to compare with Landsat measurement.

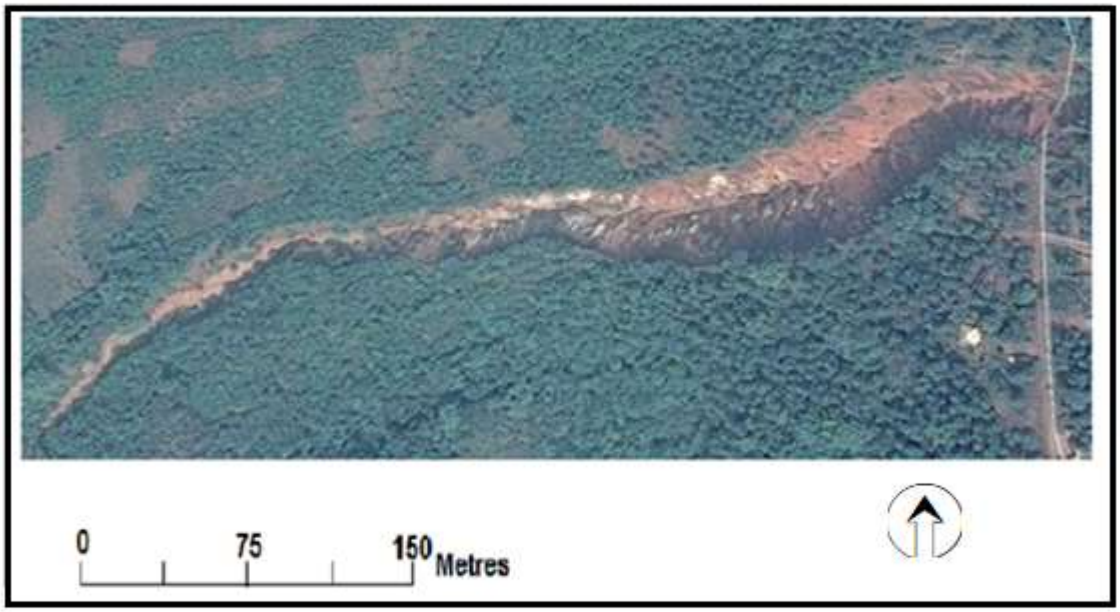


Figure 26: 2015 Google Image of Urualla gully site, SE Nigeria. (Google Earth image 2015)

4.3 Land-cover Classification of the Study Area

Land cover classifications were deduced from Landsat and ALOS raster data by ISO Cluster Analysis, a form of unsupervised classification for pixel oriented and supervised for OBIA oriented. The Iso Cluster algorithm is an repetative process for computing the minimum Euclidean distance when allocating each candidate cell to a cluster. The process starts with casual (arbitrary) means being assigned by the software, one for each cluster (the number of clusters will be dictated by the analyst) (Valls and Bruzzone 2005). Iso Cluster Analysis was chosen because the algorithm separates all cells into the user-specified number of distinct unimodal groups in the multidimensional space of a multiband raster. Also, to provide the sufficient statistics necessary to generate a signature file for better classification (Environmental Systems Research Institute 2011).

These unsupervised and supervised classifications were assisted using the 40 gully points and 60 other land-use points picked during field work. Five classes were chosen to represent the land based on the Land-cover types of the study area. The classes identified were 1. Water, 2. Vegetation, 3. Agriculture, 4. Urban-Land and 5 Gully/Open-Land. Accuracy Assessment was done with Google Earth to extract 100 KLM points from the classified data which gave between 80% to 93% accuracy. This was checked with the 100 Random points extracted from the classified data; at the location of each random point, a land-cover of that part using Google-Earth was used to compare it with the land-cover of the classified raster. Google-Earth was used because it has better resolution than Landsat image and the features can be better observed (Virginia, 2011).

The missing Landsat data from 1994 – 1999 were obtained by calculating the linear interpolation by connecting two adjacent known values of 1994 and 1999. The Linear Interpolation method used here is shown in equation (2) to estimate the value of a function between two known values. This method allowed land use changes to be classified with respect to time. This method was also used to obtain values for missing data during the vectorisation and quantification of the specifically observed gully sites. Linear Interpolation is a method used to determine a present or future value factor when the exact factor does not appear in either a present or future value table. Linear Interpolation assumes that the change between two values is linear and that the margin of error is insignificant. Although the fluctuations in data are not shown to follow an exact linear pattern over the course of the study a linear relationship best fits the data and so is used here. If the two known values are (x_1, y_1) and (x_2, y_2), then the y value for some point is:

$$y = y_1 + (x - x_1)\frac{y_2 - y_1}{x_2 - x_1} \quad (2)$$

Pearson's correlation was then employed to statistically analyse the correlation between the vegetation class and Gully/Open-Land class for every image collected within the study period. This reveals whether the continuous removal of vegetation is correlated with the development of Gully/Open Land found in the study area. All classes are then correlated with one another to determine all patterns.

4.3.1 Pixel-based Unsupervised Classification

Traditional per-pixel approaches deliver results for landform analysis that usually depend entirely on the information of individual pixels (Vrieling et al. 2007). Only the spectral information is used for the classification. Other information, such as Blaschke (2010), that implicitly exists within the data is not considered because according to Blaschke (2010), as long as pixel sizes remained typically coarser than, or, similar in size to the objects of interest, emphasis will be placed on per-pixel analysis or sub-pixel analysis. Therefore, the main difference with traditional per-pixel approaches and utilizing an object-based image analysis approach, is the explicit incorporation of neighborhood, distance and proximity parameters.

In the past decades, pixel-based classification procedures have been the main image processing means that has been used in land-cover classification. Traditional supervised classification and unsupervised classification processes incorporated into work such as Rozenstein and Karnieli (2011); and Elmahboub et al. (2009) to determine land-use are all based on the single pixel. That is, the overall objective of image classification procedures is to automatically categorise all pixels in an image into land cover/Land-use class. Normally, multispectral data are used to perform the classification, with the spectral information for each pixel utilised to correspond closely to a unique landuse class spectral response.

Table 5: 100 Land cover Reference points picked during field work for classification including 10 water bodies, 10 vegetation points, 10 Agricultural sites, 20 Urban-Land, 40 gully points and 10 open land points. Coordinates in Universal Transverse Mercator (UTM) 32N in metres.

	Water		Vegetation		Agriculture		Urbanlands		Gully/openlands	
1	Easting	Northing	Easting	Northing	Easting	Northing	Easting	Northing	Easting	Northing
2	249051.80	668301.08	242242.67	612665.61	313630.93	612977.27	258117.18	677498.35	279040.32	630127.83
3	251728.02	674842.78	244253.75	636120.10	311748.20	597285.04	255287.40	679038.10	290963.48	672395.90
4	248622.19	690974.92	263274.20	610116.70	285191.74	593573.81	255566.00	683415.95	283044.05	642487.15
5	255669.06	690682.26	362306.96	623084.92	264435.22	625154.44	249066.23	684693.94	317475.49	627455.20
6	255287.20	688135.79	334826.53	628112.91	241985.43	584011.35	248440.35	671230.06	323446.00	713518.00
7	254920.40	631383.87	373144.22	694922.60	253881.57	599585.59	269436.39	665710.93	285272	649271
8	300361.36	559809.56	415271.20	731544.55	259743.07	650627.86	285198.02	607294.05	279806	644590
9	334974.77	532246.18	355263.52	628088.00	226561.18	661508.64	278506.70	606482.95	301901.00	620430.00
10	290913.62	607951.48	341569.58	608975.99	235133.22	725631.48	316693.54	564932.77	392694.24	620722.95
11							333739.87	610956.43	330452.05	705080.71
12							370122.68	619696.68	259322.32	674641.62
13							285428.59	686073.78	317475.49	627455.20
14							287770.90	688388.04	277394.78	596903.36
15							271846.27	663928.87	323245.00	713784.00
16							338311.02	606044.64	285138.93	649246.3
17							378839.87	595535.94	280062.58	685792.43
18							287718.55	665973.35	283044.05	642487.15
19							288989.72	665118.14	285607.00	633615.00
20							323114.07	757361.93	323446.00	713518.00
21									261516.24	632542.9
22									328458.00	614902.00
23									280062.58	685792.43
24									285500	633512
25									285633	633384
26									285656	633251
27									310800	628052
28							**Openland**		310821	628074
29							Easting	Northing	310826	628045
30							328458.00	614902.00	310928	628052
31							237810.79	750349.61	330452.05	705080.71
32							392694.24	620722.95	310528	620814
33							266803.74	627071.18	294019	640235
34							279184.92	629967.73	294015	640077
35							233787.52	619482.15	293843	640186
36							387224.82	633648.49	293895	640248
37							236224.82	742358.14	259322.32	674641.62
38							246492.69	785412.45	317475.49	627455.20
39							311003.71	610305.22	277394.78	596903.36
40							315576.62	608822.26	323245.00	713784.00

Table 6: Accuracy Assessment and validation of Field work points and pixel Landsat Classification

		2013 Field work				
2013 pixel Landat class	Water	Vegetation	Agric	Urbanland	Gully/openland	Raw Total
Water	9	0	0	0	1	6
Vegetation	0	8	2	0	2	12
Agric	0	2	8	0	0	10
Urbanland	0	0	0	19	1	20
Gully/openland	1	0	0	1	46	48
Column Total	10	10	10	20	50	100
Overall Accuracy = 90/100 =90%						

Table 7: Accuracy Assessment and validation of Field work points and OBIA Landsat Classification

		2013 Field work				
2013 OBIA Landat class	Water	Vegetation	Agric	Urbanland	Gully/openland	Raw Total
Water	10	0	0	0	1	6
Vegetation	0	8	2	0	1	11
Agric	0	2	8	0	0	10
Urbanland	0	0	0	19	1	20
Gully/openland	0	0	0	1	47	48
Column Total	10	10	10	20	50	100
Overall Accuracy =92/100 = 92%						

For the study area of south-east Nigeria, land use classification was deduced from the raster data by ISO Cluster Analysis, a form of unsupervised classification. ISO Cluster is used because the standard deviation within each cluster, and the distance between cluster centers is calculated and if one or more standard deviation is greater than the user-defined, Clusters are split but are merged if the distance between them is less than the user-defined threshold (Mather and Koch 2011) as can be found in the results shown in **Figure 27**. The number of classes used for unsupervised classification were 60 classes, 10 representing each band because there are 6 Landsat bands (Virginia Geospatial 2011). This was assisted using the 100 land-cover points picked during field work **Table 5**, which include 10 water bodies, 10 vegetation points, 10 Agricultural sites, 20 Urban-Land, 40 gully points and 10 open land points **Figure 27**. This was reclassified into 5 classes using level of inter-class similarities for the unsupervised approach.

Five classes were chosen to represent the land based on the Land-use/Land-cover types of the study area. The classes identified were 1. Water, 2. Vegetation, 3. Agriculture, 4. Urban-Land and 5. Gully/Open-Land. These were used to reclassify the ISO cluster classification **Figure 28**. Accuracy Assessment and validation of Field work points and pixel Landsat Classification gave 90% success **Table 6.**

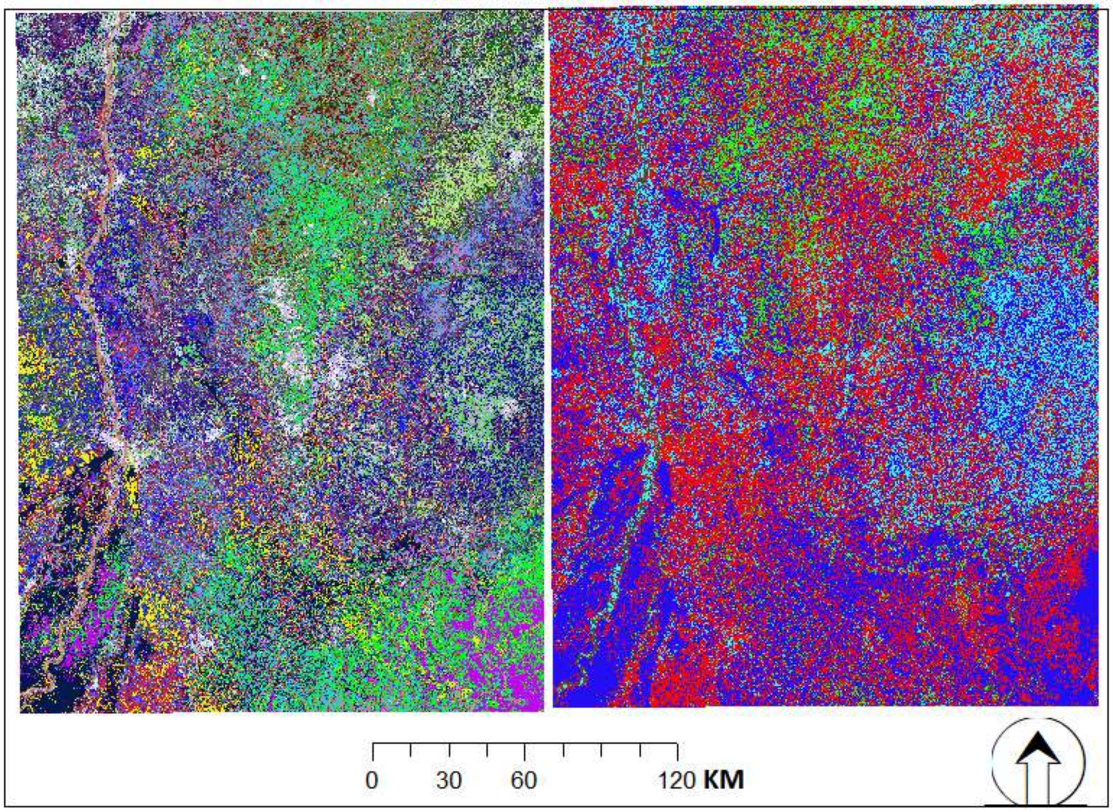


Figure 27: Example of (a) Landsat 2009 and (b) ALOSPALSAR 2009 ISO Cluster unsupervised classification of the study area (the different colours represent various Identified spectral values of the pixels which were reclassified in **Figure 28**

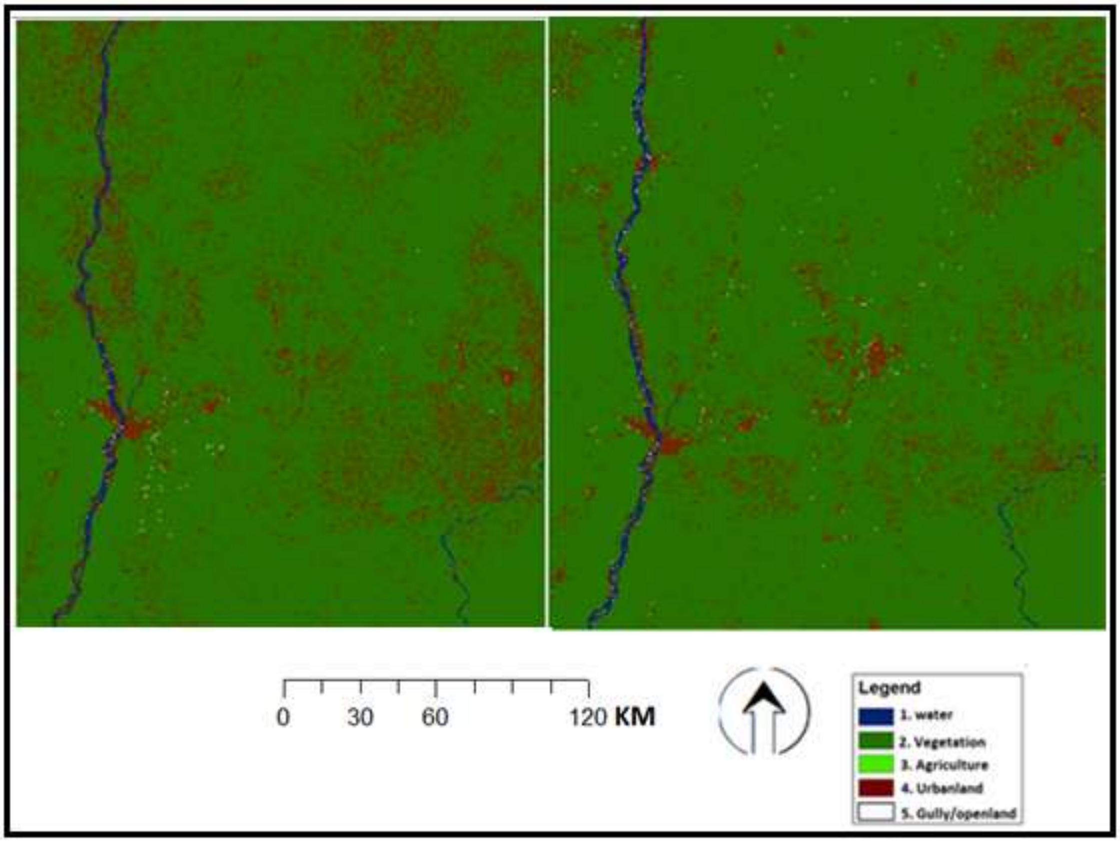


Figure 28: (a) and (b) Example of the result of Reclassified images of Landsat 2008 ALOSPALSAR 2008 images of the study area. (Vegetation class is dominant, but when expanded on a GIS software the hidden classes can be clearly observed)

4.3.2 Object Based Image Supervised Classification (OBIA)

As pixel-based classification approaches only rely on spectral per-pixel values, the idea of object-based image analysis (OBIA) enables the incorporation of additional analytical aspects, including geometry, broader context, and more refined expert knowledge. According to Blaschke (2010) and D'Oleire-Oltmanns et al. (2014), OBIA produces relatively common regions, in regard to any homogeneity criterion. In recent years, OBIA has become a successful new methodology (Blaschke 2014), that goes beyond the per-pixel approach. Although still using pixel information, through the grouping of pixels, additional features can be addressed such as the homogeneity of a region, within-region variation or differences to neighboring objects. The regions are typically generated through segmentation based on one or more criteria of homogeneity in one or more dimensions. In addition, and sometimes of even greater advantage than the diversification of spectral value descriptions of objects, is the additional spatial information for objects (spatial topology, geometric descriptions).

In general, the object-based classification process is based on multiresolution segmentation and knowledge-based classification of the segments. Object-Based classification starts by segmenting the image into meaningful objects which is determined by per-pixel analysis, or even sub-pixel analysis, **Figure 29**, and considers each pixel as a separate object. Subsequently, adjacent pairs of image objects are merged to form larger segments. The merging decision is based on the local homogeneity criterion, describing the similarity between adjacent image objects. This was based on the 100 land-use/cover training samples **Table 5** which was examined by looking at the histograms to check the normalization of training data as well as the pixel value ranges and check for overlap. The pair of image objects with the smallest increase in the defined criterion is merged. The process terminates when the smallest increase of homogeneity exceeds a user-defined threshold. Therefore, a higher threshold will allow more merging and consequently bigger objects, and vice versa. The homogeneity criterion is a combination of colour (spectral values) and shape properties (a combination of smoothness and compactness). The resultant segments act as image objects which can then be classified.

Classification following image segmentation is necessary, which as implemented with eCognition Developer 8 GIS/Remote Sensing software. Usually classifying means assigning objects to a certain class according to the class's description (this is based on segmentation result, in which image was segmented based on the mean spectral values of the segments). In the Object-Based classification approach, the classification description is knowledge-based which accounts for not only the spectral properties but also shape and size characteristics, context, and texture information, **Figure 30.** The Frame of knowledge base for the analysis and classification of image objects is the so-called class hierarchy. The objects then become assigned (classified) according to whether they have or have not met these properties (classification rule) which is the feature analyzing tool

SEaTH (SEparability and THresholds) that identifies these characteristic features of the object with a statistical approach based on 100 training objects from the field work (Maglines et al. 2008). These training objects represent a small subset out of the total amount of image objects and should be representative objects for each object class guided by the 100 land-cover points. Gao et al. (2007) made use of SEaTH in classification of Land-cover in a forest area in Mexico, also, Shackelford and Davis, (2003) equally set classifying rule in a combined fuzzy pixel-based and object-based approach for classification of high-resolution multispectral data over urban areas.

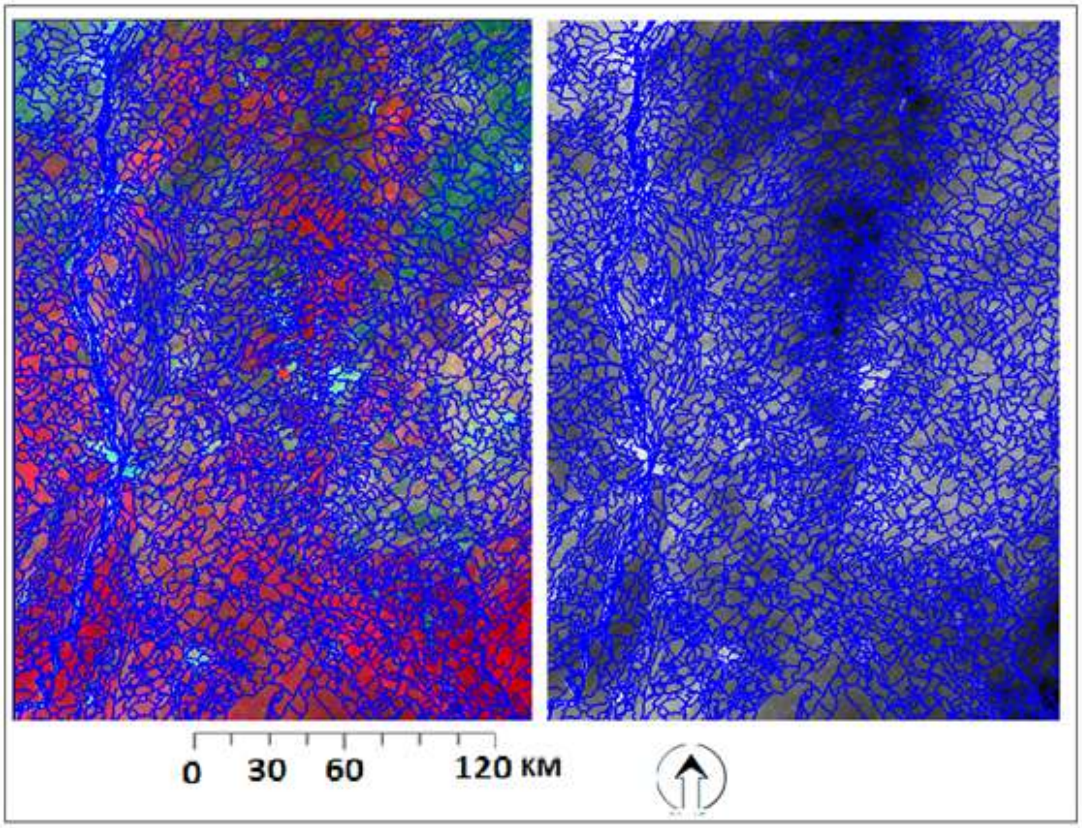


Figure 29: (a) and (b) Year 2009 OBIA Image Segmentation of Landsat and Year 2009 OBIA image segmentation of ALOSPALSAR of images of the study area

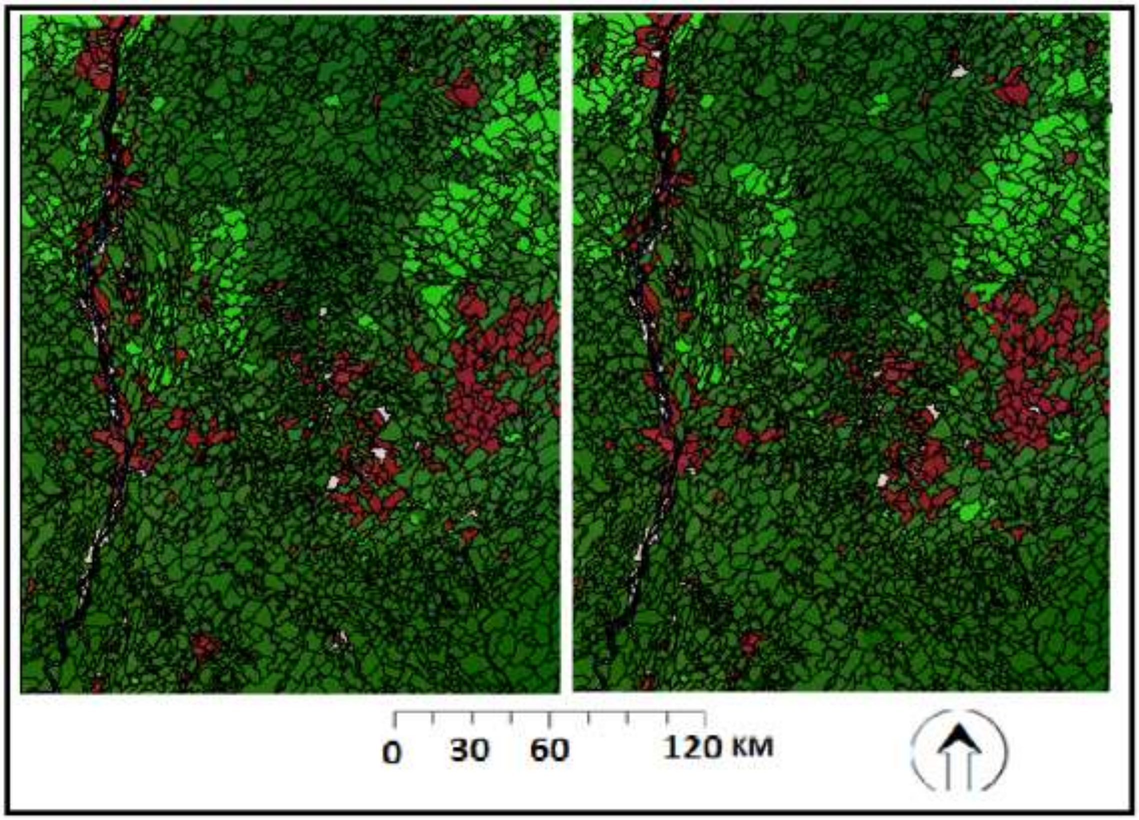


Figure 30: (a) and (b) shows result of object-oriented classification of Landsat of year 2009 and ALOSPALSAR of year 2009 images of the study area

In trying to understand the effect of local environment on the gully sites and not simply the regional variations, the classified local environment of 10km X 10km area around each of the 14 gullies were also used for both Pixel and OBIA classification to calculate the correlation between the classes. The central point of the gully was used as the centre of the 10km x 10km classified region helping to determine whether the same environmental variables are influencing gully development on both spatial scales. This classified local environment of 10km X 10km around the 14 gully sites represents an independent variable for use in further statistical analysis to determine its influence on gully formation and erosion rates. Accuracy Assessment and validation of Field work points and OBIA Landsat Classification gave 92% success **Table 7.**

4.4 Extracting Gully Test Sites for Analysis

Visual interpretation has long been a common method for detecting individual gullies from aerial photographs and satellite images. Some early examples are the interpretation of the one of the earliest photo image of Canadian Halifax Citadel of 1892 (Nicholson, 2003) where . Good examples being Nachtergaele and Poesen (1999) and Martinez-Casasnovas (2003). There have been many examples of Landsat, in particular, being used as the primary data source to extract information about Gully sites, some of them include (Shalab 2007; James et al. 2007; Zinck et al. 2001; Marakanye et al. 2012; Nduji, 2008; Okereke et al. 2012). In a similar manner, the Landsat archive will be used in this study to review and quantify the development of 4 of the 14 specific gully sites from 1986 to 2015. These are listed in **Table 8** with some visual examples shown in **Figures 31 and 32**. The extracted information about the other 10 gully sites were done using downloaded Google images. The reliability of the Google images for this process was rechecked using extracted information from the 4 main gully sites, comparing with Landsat images. The 14 gully sites chosen for further analysis were the ones that can be observed visually both from the satellite and the Google Earth images used. Other gullies were covered by trees and buildings or deemed spectrally not good enough for analysis.

This methodology of vectorization and quantification of gully pattern is chosen among other methods because GIS software such as ArcGIS and also Google Earth have the ability to calculate the size of the gully authomatically after manually picking the pixel of the edges of the gully through digitisation and the area calculated and compared with other years under review. This method of digitization and quantification of Gully sites from the Satellite Images has been used by many Environmental scientists. Shalaby (2007), traced the gully patterns and monitored land cover changes in the Northwestern coastal zone of Egypt, using Landsat Images. Mararakanye, and Nethengwe (2012), equally utilized this approach in mapping areas devastated by gullies in South Africa. Nduji (2008), used this method in mapping and monitoring gully erosion sites in Nigeria. Also this method can also be found in Hofle et al. (2013); and Taruvinga (2008) among others.

Table 8: The 14 Gully sites identified with their corresponding coordinates in Universal Transverse Mercator (UTM) in metres

	Gully Name	Easting	Northing		Gully Name	Easting	Northing
1	Njaba	279040.32	630127.83	8	Iyioku	330452.05	705080.71
2	Okigwe	290963.48	672395.90	9	Igboukwu	277896.15	676839.85
3	Orlu	283044.05	642487.15	10	Isinweke	317230.61	622463.35
4	Amucha	285607.00	633615.00	11	Nekede	277394.78	596903.36
5	Ngwo-1	323446.00	713518.00	12	Ngwo-2	323245.00	713784.00
6	Oguta	261516.24	632542.9	13	Urualla	285138.93	649246.3
7	Umuahia	328458.00	614902.00	14	Nawfia	685792.43	280062.58

Figure 31: Revegetating and Active paths of Iyioku Gully site

Figure 32: Active gully-walls of Njaba Gully site

Some of the 14 gully points (see **Table 8)** observed in the field are not visible in the Landsat satellite images. The humidity of the study region and consequent vegetation cover often obscures ground visibility due to close to 100% canopy coverage. This problem has previously been reported in studies undertaken in the Eastern Cape Province of South Africa by Martinez-Casasnovas, (2003) who discovered the limitation in identifying gullies using satellite images. The work only made use of clearly identified gullies that can be observed on hill tops, areas with reduced forest, and gullies on grass lands.

Individual erosion events such as the large gullies of Iyioku, Okigwe, Njaba and Igboukwu are easily identifiable from satellite imagery due to their sheer size and the inability of vegetation to establish full canopy coverage over the sites. The analysis of these gullies and 10 others provide a significant contribution to this study and represent the extent of visually obtainable data. The chosen gullies are identified as Gully sites Iyioku, Okigwe, Njaba, Igboukwu, Orlu, Isinweke, Amucha, Nekede, Ngwo1, Ngwo2, Oguta, Umuahia, Urualla and Nawfia. Their coordinate details can be found in **Table 8** in Section **4.4.** Their identification as gully sites within the remote sensing imagery is possible partly due to distinct spectral properties but also as a result of unique shapes, subsoil exposure and typically reduced vegetation cover. Most importantly they are identifiable due to the clear spatial structure of rills and gullies. The clearly identified gullies used in this study is to reduce the occurrence of unwanted commissions during the classification process. This may subsequently lead to minor omissions in the classification process and are clearly identified as a limitation of the process. Visually detectable gullies include those observable on hill tops, areas with reduced forest, and those exposed on grass lands and open areas.

Of the four large gullies initially analysed using Landsat data, the identified gullies of Iyioku and Okigwe were chosen due to their popularity as research areas (Nduji 2008) and for being subjected to government and Agency interventions (Okereke 2011). In comparison, Njaba and Igboukwu were chosen due to their relative youth which have calculated volumes size in 1986 of 38286m^2 and 27008 m^2 when compared with Iyioku and Okigwe with 1316860m^2 and 157543m^2

respectfully and the little or no government or agency intervention enacted. The further 10 gully sites were chosen due to their more recent development and their ability to be identified clearly from the Google earth image archive. The 14 main gully sites that were identified based on their coordinates and spectral values were digitised as shape files manually. An example can be seen in **Figure 33 and Appendix III.** This process was carried out where possible for each gully, for each of the 30 years of Landsat images (except 1994-1999 values that were estimated with linear interpolation because of non availability of Landsat data) and 10 years quality Google Earth images available for the study sites. Area estimates were then calculated in each case for the 14 gully sites to enable time series analysis and change detection. A total of 216 shapefiles were created using this process. To validate the use of the Google Earth image archive alongside the Landsat data, and as a form of quality assurance, the gullies were vectorised using both Landsat and Google Earth data for a sample of 3 of the 4 main gullies of Iyioku, Njaba and Igboukwu sites for the available years of 2006 - 2015. The Okigwe gully was not part of this process because Google Earth still has Landsat image covered on the area location of the gully. Pearson's correlation was conducted to determine if the gully area from Landsat correlates with gully area from Google Earth. Each gully was identically identified using the two different data sources at the 95% confidence level. For each gully examined a significant positive correlation ($p<0.05$) was shown with the lowest correlation being 0.723. **See Appendix V Table 95 - 97** for data output. The 14 gully area size, rate of change per square metre and absolute rate of change per square will be used in this study for further statistical analysis to determine how they are being influenced by other anthropogenic and environmental factors in gully formation and erosion rates.

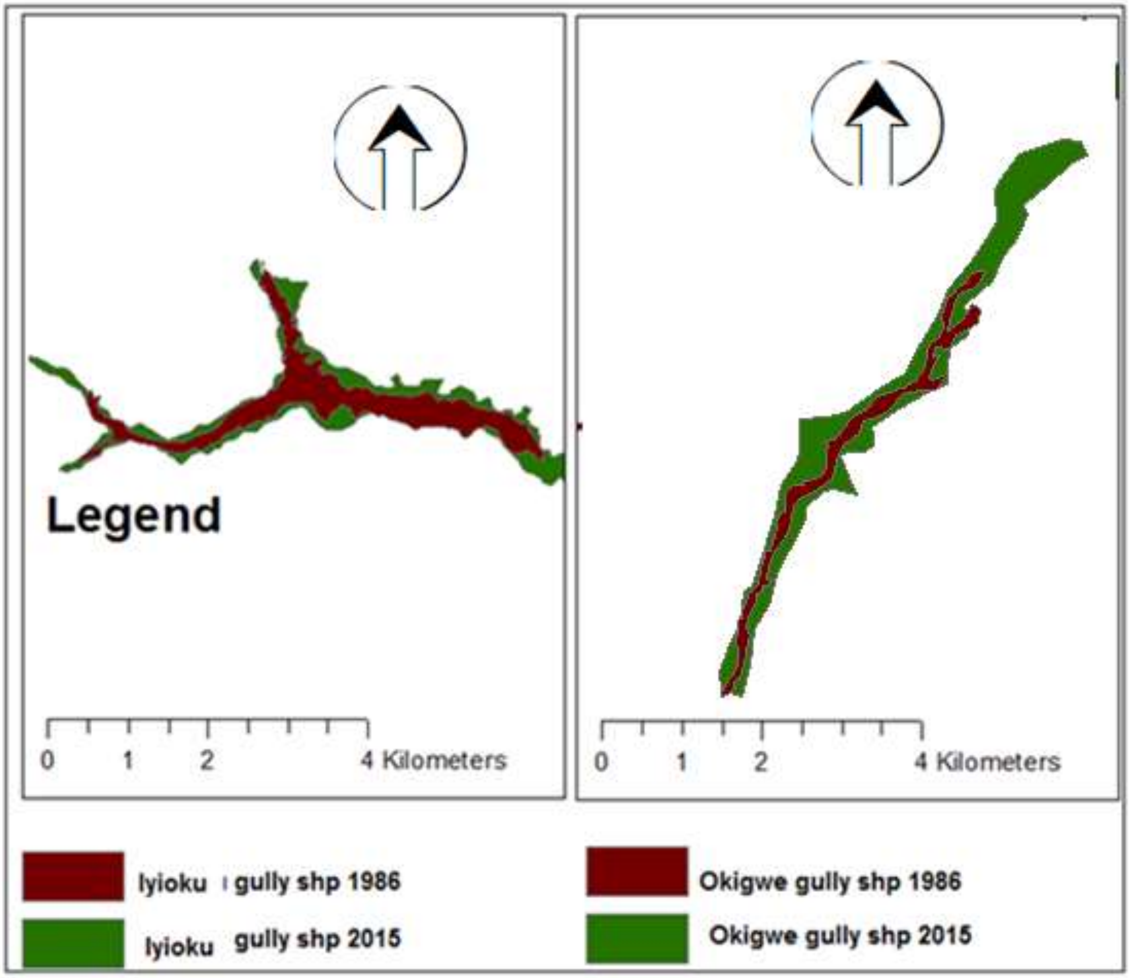


Figure 33: (a) Iyioku Gully shapefile 2015 overlaid by 1986 shapefile and (b) Okigwe Gully shapefile 2015 overlaid by 1986 shapefile

4.5 Rendering of Digital Elevation Model (DEM) to Detect Changes in the Study Area

One of the most important factors affecting gully erosion by water is topography (Lal, 2001). Digital elevation models (DEMs) have been commonly used in geographic information systems (GIS) for representing topography and for extracting topographical and hydrological features for various applications, including soil erosion studies (Gorokhovich 2006). Topography is a crucial surface characteristic in soil erosion modelling, and soil erosion studies use a digital elevation model (DEM) to derive the topographical characteristics of a study area (Datta and Helmer, 2010).

In the landscape, the topography determines the behaviour of the surface runoff, the phase of the hydrologic cycle that is most directly associated to the water erosion, and requires a rigorous and effective analysis throughout its entire extension. This is made possible with the use of digital elevation models (DEM) (Oliveira, 2013). The analyses developed using a DEM allow: visualisation of the model in planar geometric projection. From southeast Nigeria DEM, grey scale images, shaded images and thematic images, the conducting of profile analyses, and generating derivative maps, such as steepness and exposure maps, drainage maps, contour maps, slope maps, and aspect maps were all generated for analysis. Very importantly, elevation points were generated from the southeast Nigeria DEM, the data represents an independent variable for use in further statistical analysis to determine its influence on gully formation and erosion rates.

4.5.1 Analysis of Slope of the Study Area

The steepness of slopes is a factor of primary importance in the dynamics governing land evolution. It has a direct effect on surface runoff, drainage density, and soil erosion (Dramis and Gentili, 1977). For this reason, slope steepness plays a crucial role in the creation of maps to show erosive process susceptibility in any given area. In specific cases this may indicate areas of gully erosion. Therefore, steep slopes promote high runoff velocity and consequent rill and gully initiation (Valentin et al. 2005).

In the classical sense, slope is the rate of maximum change, in z-value, between two points. The slope raster can be calculated in two types of units, degrees or percent (percent rise). The percent rise can well be understood as rise divided by the run, multiplied by 100. Consider triangle B below. When the angle is 45 degrees, the rise is equal to the run, and the percent rise is 100 percent. As the slope angle approaches vertical (90 degrees), as in triangle C, the percent rise begins to approach infinity **Figure 34**. (Environmental Systems Research Institute 2015).

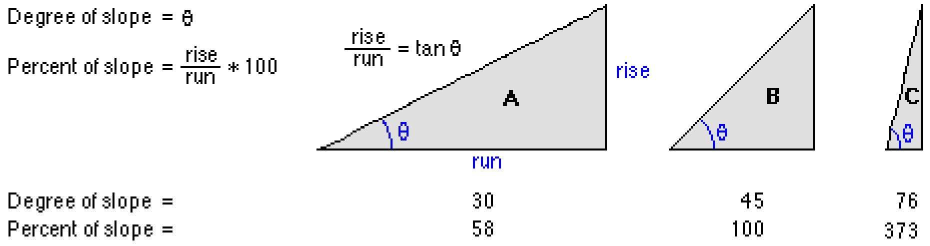


Figure 34: Degree and percent of slope (Environmental Systems Research Institute 2015).

The direction the plane faces is the aspect for the processing cell. The lower the slope value, the flatter the terrain; the higher the slope value, the steeper the terrain. Calculating how steep slopes are, is very important to anticipate and predict the direction and energy of runoff contributing to the causes of gully formation of the study area with the obvious influences on potential and then kinetic energy.

In this study, slopes derived from the DEM are divided into 5 classes, according to the level of their steepness. Slopes are calculated in angular degrees (0-90) or in percent which is a measure of vertical rise over horizontal run. The slope was calculated in Degrees and classified with the range of slope values of 0^0 - 10^0, 10^0 – 20^0, 20^0 – 30^0, 30^0 – 40^0 and 40^0 and greater with gully points overlaid to obtain a decision on where gully erosion could be developing and where flooding is taking place. Essentially they indicate high ($>40^0$), medium ($20 < x < 40^0$), and low ($<10^0$) gradients (Burrough, and McDonell 1998). Each pixel indicates the maximum slope calculated from 8 calculations within a 3x3 moving window.

Hill shade of the study area was generated from the DEM, creating a shaded relief from a surface raster by considering the illumination source angle and shadows. This reveals the graphical nature of relief of the study area **Figure 35**. The Slope tool is most frequently run on an elevation dataset. This slope data represents an independent variable for use in further statistical analysis to determine its relationship on gully formation and erosion rates.

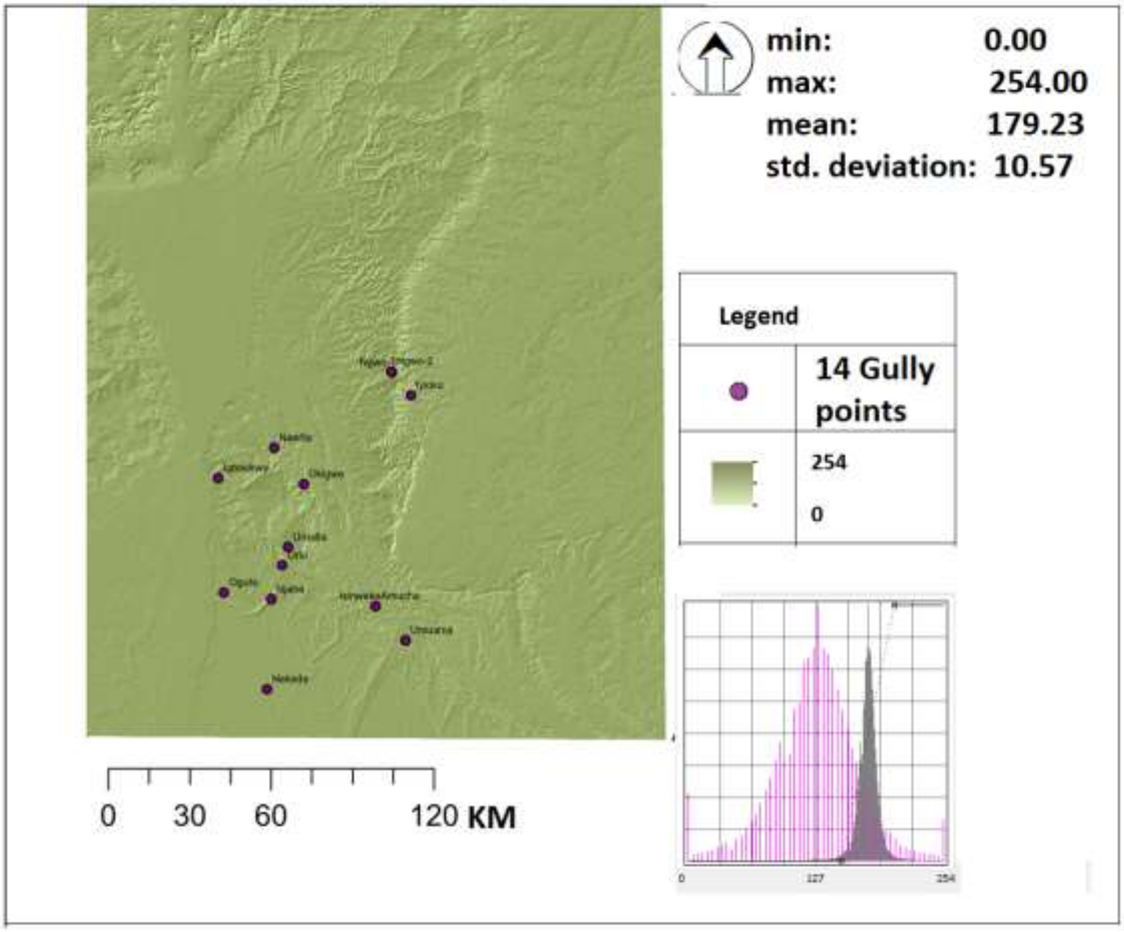


Figure 35: Hill shade map of the study area showing the structure and nature of the landscape

4.5.2 Nature of Slope

The concave or convex nature of the slope is examined to support the gradient data and to offer an additional environmental variable as part of the analysis. This information is generated using the DEM of the study area. The primary output is the curvature of the surface on a cell-by-cell basis, as fitted through that cell and its eight surrounding neighbours within a 3x3 window. Curvature is the second derivative of the surface, or the slope-of-the-slope (Environmental Systems Research Institute 2015). Slope plan curvature has been investigated with respect to its effect on gullies through triggering and development. The term curvature is theoretically defined as the rate of change of slope gradient or aspect, usually in a particular direction (Wilson and Gallant 2000). Plan curvature is described as the curvature of a contour line formed by intersecting a horizontal plane with the surface. The influence of plan curvature on slope erosion processes is through the convergence or divergence of water during downslope flow.

There are two optional output curvature raster, the profile curvature is in the direction of the maximum slope, and the plan curvature is perpendicular to the direction of the maximum slope. A positive curvature indicates the surface is upwardly convex at that cell. A negative curvature indicates the surface is upwardly concave at that cell. A value of 0 indicates the surface is flat as can be shown in **Figure 53 section 5.1.4**. In the study of Plan curvature and landslide probability in regions dominated by earth flows and earth slides, Ohlmacher (2007), observed that Statistical analysis of plan-curvature and landslide datasets indicate that hillsides with planar plan curvature have the highest probability for landslides in regions dominated by earth flows and earth slides in clayey soils. Godwin (2013) observed, in the study of gully development in Edo southern Nigeria, that most of the gully sites in the area are found on concave slopes. In the work of Rahman and Hiura (2004), it stated that with a smooth average slope, sediment transport is reduced on a concave slope as a result of localized sedimentation, but increased on a convex slope due to the gradient of the steepest portion.

Slope curvature was used by Lee et al. (2004) as a landslide-related factor to map landslide susceptibility in the Korean Peninsula. Upwardly concave slope curvature was associated with higher landslide susceptibility (Lee et al. 2004). Kukemiks and Saks (2013) observed in Landslides and gully slope erosion on the banks of the Gauja River between the towns of Sigulda and Ligatne that the results show that landslides and gullies are more frequently found in convex curvature than in concave curvature.

Any cell that exhibits a slope must, by definition, be oriented in a known direction. This orientation is referred to as aspect. Aspect is also considered an important factor in sensitivity studies of erosional Processes (Maharaj 1993; Gazette et al; 1999; Nagarajan et al; 2000). As it shows where the slope is facing which helps to determine where runoff is flowing from. Aspect is expressed in degrees from north ranging from 0 to 360. The aspect of a slope can indirectly influence gully erosion processes, because it controls the exposition to several climate conditions (duration of sunlight exposure, precipitation intensity, moisture retention, etc.) and the vegetation cover (Cevik and Topal 2003; Pulice et. al; 2009). Consequently, slope and aspect can play a prominent role in environmental degradation and in the formation of pedo-regolithic cover. The aspect map of the study area was classified into ten classes: flat, N(0 -22.5), NE (22.5 – 67.5), E (67.5 – 112.5), SE (112.5 – 157.5), S (157.5 – 202.5), SW (202.5 – 247.5), W (247.5 – 292.5), NW (292.5 – 337.5 and N (337.5 - 360) **Figure 52 Section 5.1.3**. On this basis, the aspect classes of the southeast Nigeria region highlight a fairly homogeneous distribution.

4.6 Analysis of Forest Degradation and Deforestation of the Study Area

To analyse the impact of freely available L Band SAR data on efforts to monitor the degradation of forests in proximity to gullies, ALOS PALSAR data was used. Although not released as open source data the data is available free of charge upon request through various data streams but is limited by regional location. The use of the L-Band data in this scenario acts as a precursor to the potential use of future data sources such as the NASA NI-SAR L-Band mission (Yu and Saatchi 2016). This mission, due for launch in 2020, will operate an open data policy similar to that currently employed by the LandSat mission. Such availability will make the SAR data an integral part of any low budget landcover analysis methodology, particularly regarding the condition and extent of forest canopies. The strengths of the SAR data lie in the existence of relationships between the backscatter levels and the forest biomass, as well as structural variations. In this study the ALOS PALSAR data is employed to determine the degradation of forests via a change detection analysis to complement the theories exposed regarding the loss of vegetation and the emergence of gullies, and confirmed by the Landsat landcover analysis.

Synthetic Aperture Radar images acquired by the ALOS PALSAR system are used here to analyse forest degradation in the regional study area. Images from the years 2007, 2008, 2009 and 2010 were used for this purpose to map dynamics of deforestation and forest degradation in the study area. Understanding these dynamics increases knowledge of the level and amount of forest removal taking place. It will also help determine whether it is one of the influential factors responsible for gully development in the study area.

As surface moisture can vary radar backscatter, and decrease the contrast between forests and bare-ground, dry-season scenes were acquired from the phased array L-band Synthetic Aperture Radar sensor in August for each study year from 2007, 2008, 2009 and 2010 with The Tropical Rainfall Measuring Mission (TRMM). TRMM was a research satellite designed to improve the understanding of the distribution and variability of precipitation within the tropics and the dataset became the space standard for measuring precipitation (National Aeronautics and Space Administration 2016). This was utilised by Jackson (2001) and Zhu et al. (2011) in obtaining data for analysis of the rainfall erosivity factor based on Tropical Rainfall. In the same manner, ALOS data for this analysis were obtained based on the report of the least moisture in the soil from (TRMM).

Since terrain can significantly impact image projection and backscatter, scenes were terrain-corrected and radiometrically calibrated using the 30m resolution Shuttle Radar Topography Mission dataset (Jarvis et al. 2008). They were then converted to backscatter (co-polarized σ^0 HH and cross-polarized σ^0 HV) and mapped at 15m resolution in UTM projection (Shimada et al. 2009). Speckle, which is inherent in radar images (Woodhouse 2006), may be problematic for accurate disturbance detection. The images were moderately despeckled using the Enhanced Lee Filter (Lopes et al. 1990) with a 3× 3-pixel window to retain textural information (Joshi et al. 2015).

Image pixels were then made to have an average of 30m resolution via multi-looking as a compromise to reduce the noise (speckle), but to continue to allow the detection of small-area disturbances and enable comparability with Landsat-based deforestation datasets (Asnera et al. 2010; Hansenetal 2013; Joshi et al.

2015). To reduce any remaining variability in backscatter unrelated to anthropogenic disturbances, images were calibrated to the base year (2007) by adjusting pixel values by the difference in average backscatter over a 510 × 510m window. This procedure was chosen since it showed reasonable adjustment over known forest/non-forest areas from the field study, that is able to distinguish and differentiate forest and non-forest areas.

4.7 Calculating the Maximum Gradient of the Slope at the 14 Specific Gully Test Sites

Gradient represents how much the elevation is changing in a given distance. A contour map is generated from the DEM data of the study area; this is used to calculate the geographical gradient of the slope of the vectorised 14 gully sites of Iyioku, Okigwe, Igboukwu, Njaba, Orlu, Amucha, Ngwo1, Ngwo2, Oguta, Umuahia, Isinweke, Nekede, Urualla, Nawfia gully sites example is found in **Figures 36 and 37 and Appendix II**. The Gradient was calculated by change in field value divided by the Distance. The field value refers to the difference in elevation between the highest point in the gully site and the lowest point around the gully site. The highest point was selected from the last contour line to gully-head and the lowest point was selected from the last contour line to gully-tail end around the gully area. This will be used to determine the "Rise difference” in elevation from the top to bottom and “Run" is determined by horizontal distance from the highest elevation to the lowest (Wenner 1989; Desmet et al. 1999)

This was calculated to derive the gradient of the slope of each of the 14 gully sites. For example, Iyioku Gully site, the highest elevation was 250m while the lowest elevation was 150m, the vertical difference being 100m, the horizontal distance between the highest and the lowest elevation was 6618m All of the 14 gullies gradient are well tabulated in **Table 10.** The values derived were not used for further statistical analysis rather DEM derived values were used. This was done to reveal the nature of geographical contours and the relationship with the 14 gullies.

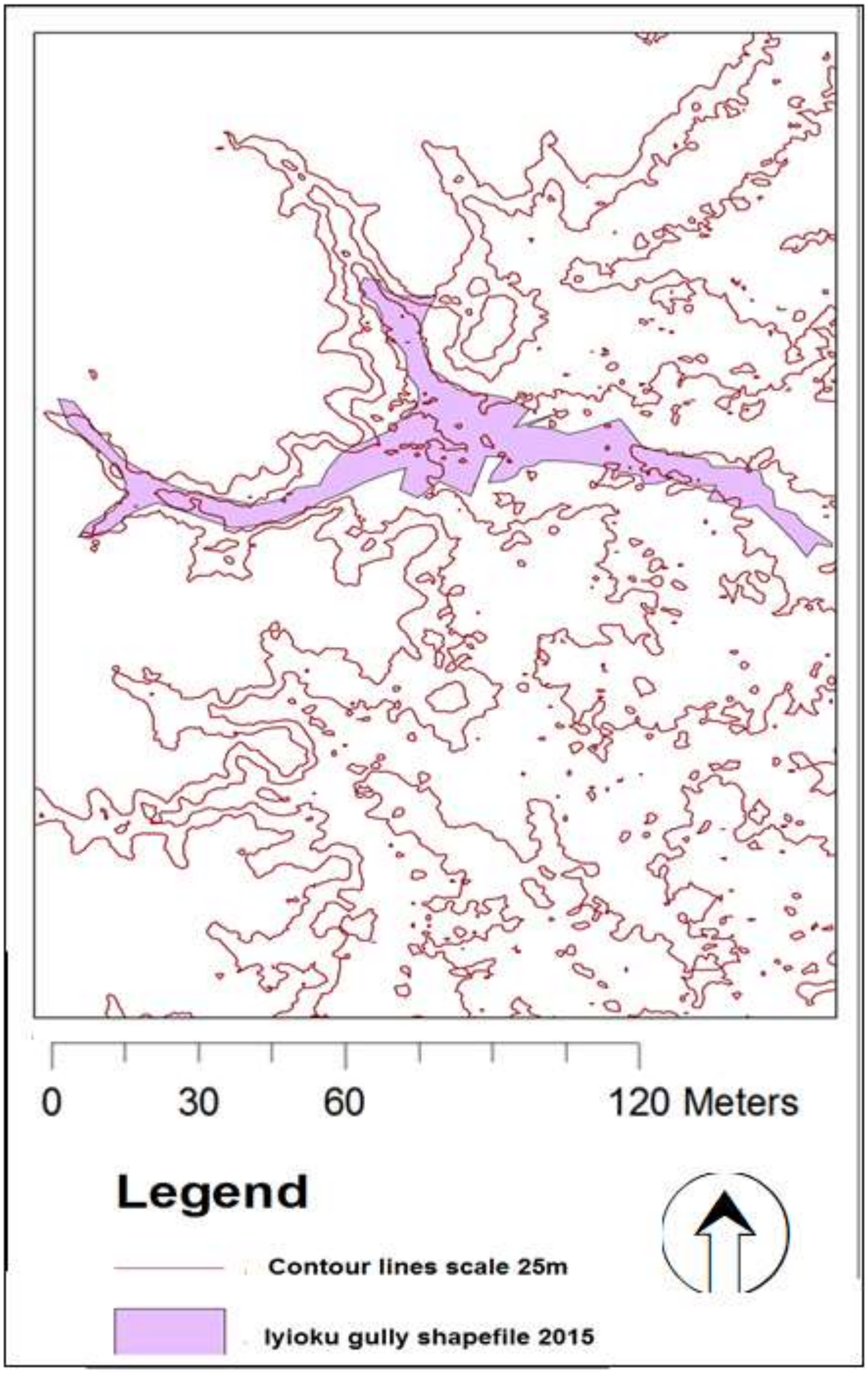


Figure 36: Displayed Iyioku vectorised gullies of year 2015 on the contour map of the study area with contour interval of 25m

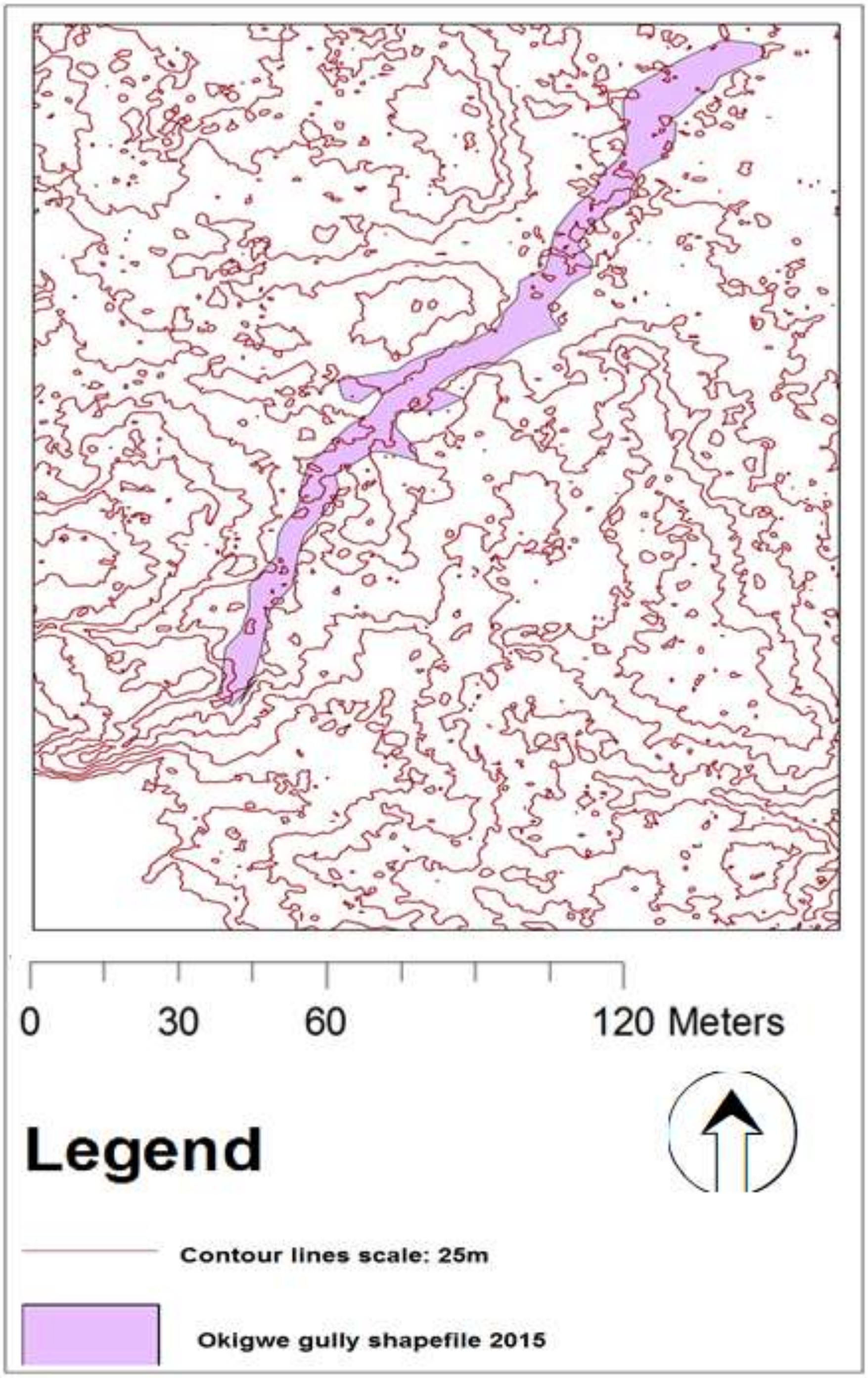


Figure 37: Displayed Okigwe vectorised gullies of year 2015 on the contour map of the study area with contour interval of 25m

4.7.1 Classification of the Drainage Pattern of the Study Area

The drainage pattern of the study area was calculated to observe the rate of run-off contribution in gully formation. The flow Accumulation was calculated from the flow direction to reveal the hierarchy (order) of the drainage that contributes to the gully formation. The hierarchy order moves from 1 which could be a very small underground or surface flow to the highest number which could be a surface water flow.

Drainage patterns explain the pattern and ways the streams, rivers and lakes formed and flow, which is governed by the topography of the land, whether a particular region is dominated by hard or soft rocks, and the gradient of the slope (Zhang and Guilbert 2012). Drainage patterns are classified on the basis of their form and texture according to slope and structure. Their shape or pattern develops in response to the local topography and subsurface geology. Dendritic type of drainage system is found on the topography of the study area. In a dendritic river system, tributaries of a main river join together in a shape analogous to the twigs of a tree (Lambert, 1998). Drainage pattern is arranged in orderly manner which is called stream order. Stream order is used to define stream size based on a hierarchy of tributaries **Figure 38.**

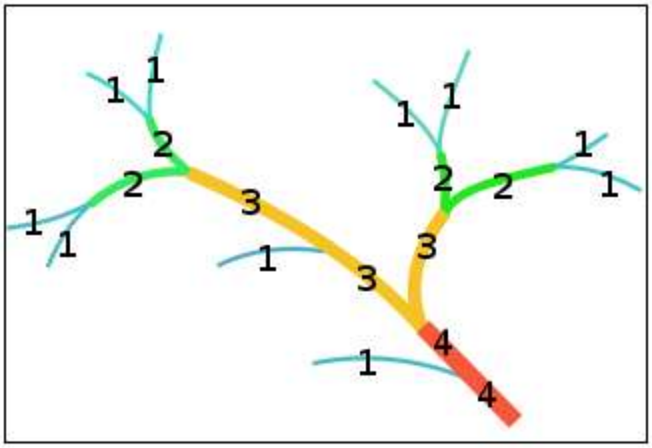


Figure 38: Diagram showing the Strahler stream order(Devroye and Kruszewski 1995)

The flow Accumulation takes flow direction raster and calculate the pixels that do have the highest number of pixels with the highest amount of water cumulating within that area. It creates a raster of accumulated flow into each cell, each will have a value representing the numbers of cells which will flow into that cell as shown in **Figure 39**. This data stream order represents a dependent variable for use in further statistical analysis to determine its influence on gully formation and erosion rates.

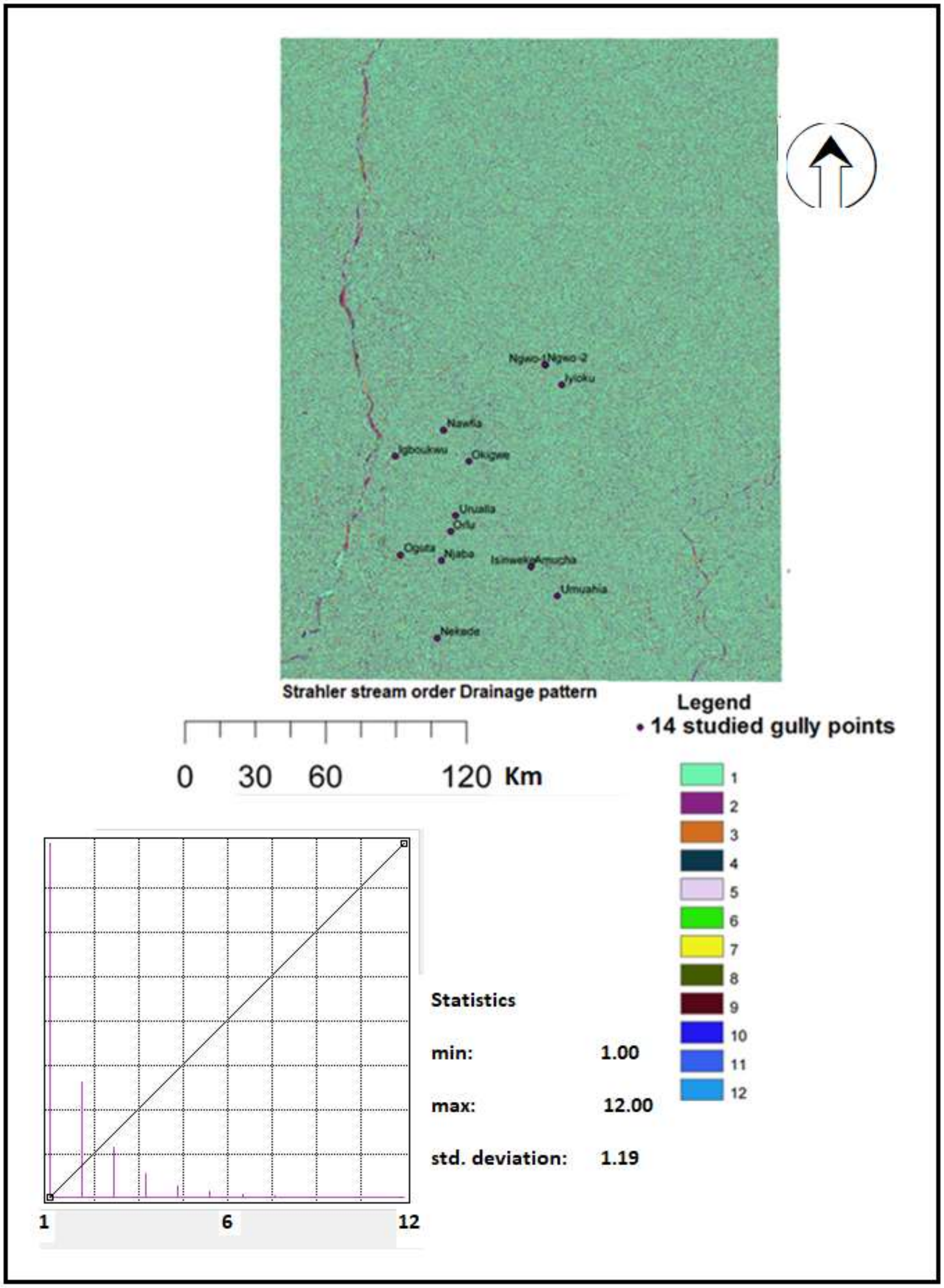


Figure 39:The Strahler stream order Drainage pattern of the study area overlaid by the gully points. From 1 to 12 are stream sizes based on a hierarchy of tributaries in the study area. The cell value shows that stream 1 are more in number than others

4.7.2 Creating Profiles using a DEM-channel Cross Section

The cross profile of the gullies is carried out using the DEM of the study area to measure the depth at the centre of the gully and to obtain the shape of the gully **Figures 40 - 46.** The purpose is to show the level of gully incision, gully dept and shape, where the flat bottom could be reduction in gully incision and V-shape could mean that the gully incision is still active. The approach is similar to that taken by (Soms 2011; Ehiorobo et al. 2012; Casali. et al. 2006). Resolution is restricted to the spatial resolution levels of the SRTM data.

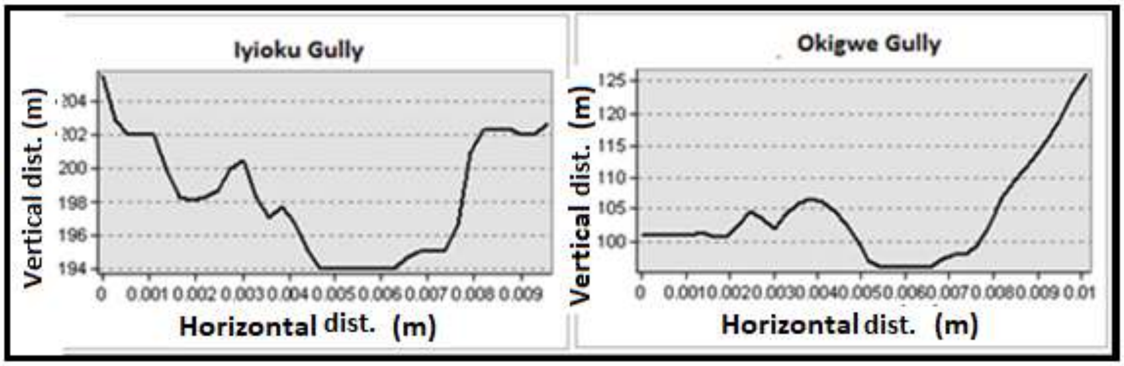


Figure 40: Cross profile of the Iyioku and Okigwe gullies in metres

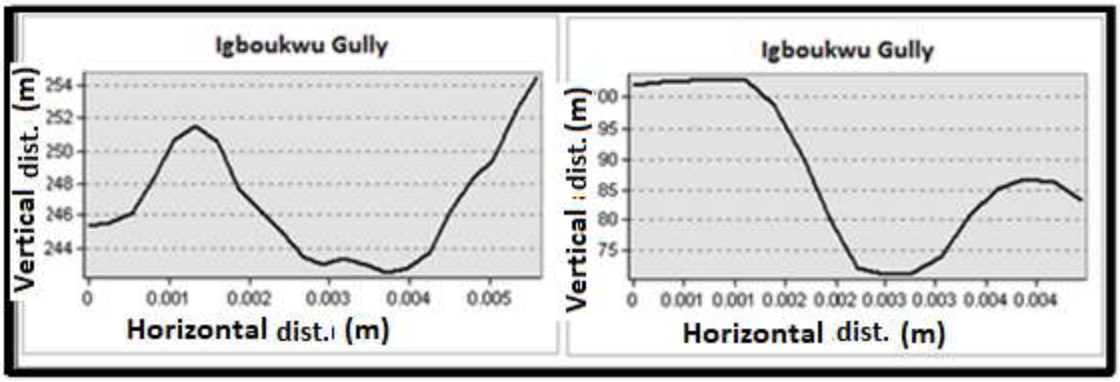


Figure 41: Cross profile of the Igboukwu and Njaba gullies in metres

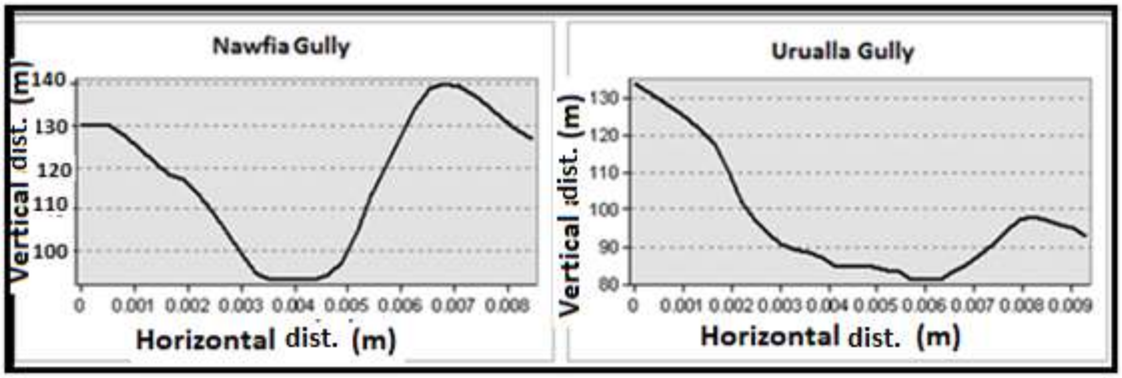


Figure 42: Cross profile of the Nawfia and Urualla gullies in metres

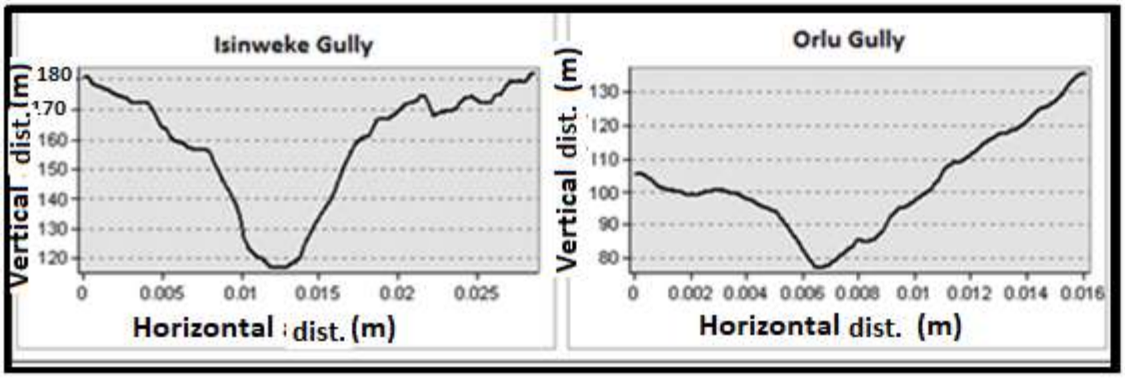


Figure 43: Cross profile of the Isinweke and Orlu gullies in metres

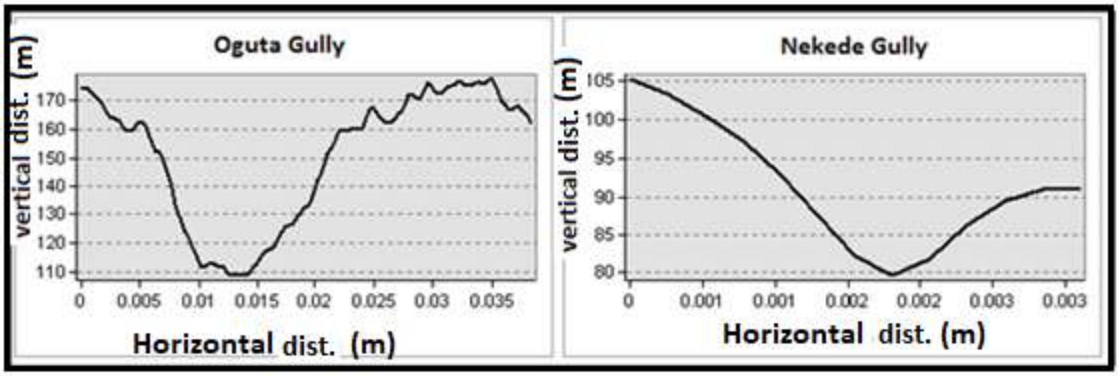


Figure 44: Cross profile of the Oguta and Nekede gullies in metres

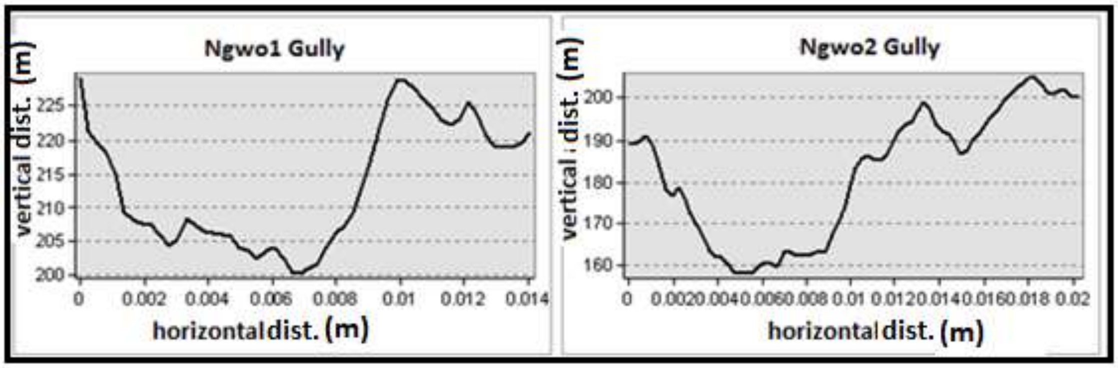


Figure 45: Cross profile of the Ngwo1 and Ngwo2 gullies in metres

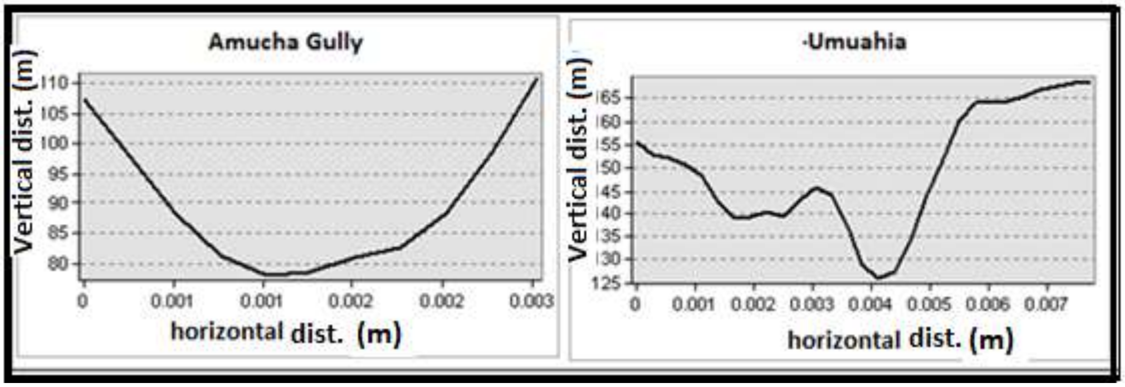


Figure 46: Cross profile of the Amucha and Umuahia gullies in metres

4.8 Analyses of Historic Meteorological Data and Development of Gullies in Southeast Nigeria

Southeast Nigeria is largely located within the rainforest region (Iloeje 2010). Total rainfall pattern is high with mean rainfall per year from 1986 to 2015 of 2134mm/yr, and the intensity, duration and amount of rainfall in conjunction with other specific gully influences, contribute to determine how soil will be removed from areas via gullying (Wood 2013). The rainfall pattern of the study area is determined in this study from the rainfall data from the 6 weather stations in southeast Nigeria **Figure 47**, obtained from Nigeria Meteorological Agency (NIMET). The data collected is on a regional scale due to the lack of distributed monitoring stations which leaves the spatial resolution of the data lacking. It is therefore difficult to analyse the rainfall locally to each gully. The method of rainfall collection was obtained from agency in Nigeria responsible for weather report and prediction (NIMET) similar to that used in Adejuwon (2012); and Ogungbenro and Morakinyo (2014). The method of rainfall estimation is adequate for this study's purpose because it will contribute among other observed factors in this study to know its effects on gully formation and development in the study area. Its main impact will be on a regional rather than local level. Similar approaches have been taken in Igwe (2012) and Igbokwe et al. (2008) with encouraging results. The data for the region is shown in **Table 9.** This data is used in this study to identify relationships between gully development across the region and locally to each gully. The rainfall data represents a dependent variable for use in further statistical analysis to determine its influence on gully formation and erosion rates. In the choice of rainfall data from NIMET, other methods of obtaining rainfall data from the study area were considered, for example Tropical Rainfall Measuring Mission (TRMM) was considered but the data was not complete and did not have rainfall data from 1986 to 1997 and would only partially inform the study.

Table 9: Total Rainfall pattern of southeast Nigeria in mm per annum (Nigeria Meteorological Agency, 2016)

Year	Total Rainfall mm	Year	Total Rainfall mm
1986	1618	2001	1556
1987	1504	2002	1777
1988	2008	2003	1845
1989	1782	2004	2088
1990	2010	2005	2807
1991	2083	2006	1672
1992	2500	2007	1399
1993	1654	2008	2689
1994	1609	2009	1729
1995	2471	2010	2623
1996	1827	2011	2001
1997	1907	2012	3794
1998	2086	2013	2871
1999	1988	2014	2857
2000	1675	2015	3604

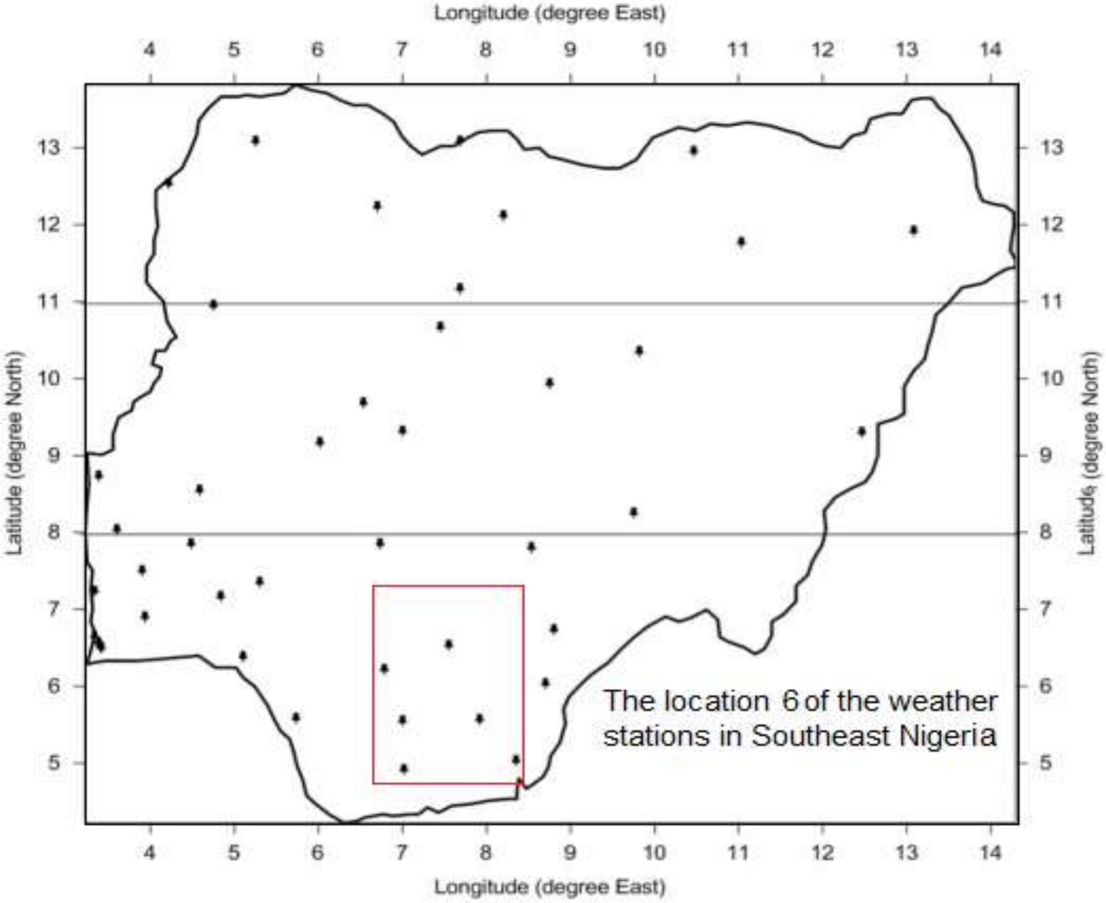


Figure 47: : location of the 6 weather stations of Southeast Nigeria with the study area outlined in context (Ogungbenro and Morakinyo 2014). (the weather stations are between 75km to 119km to each other)

4.9 Multi-variate Statistical Analysis of Gully Factors

In determining the weight of influence each of the environmental factors contribute to gully development in the study area, multi variate statistical analysis is performed. The factors employed in statistical analysis are the following with more in depth descriptions provided below. These variables such as soil, vegetation loss, slope, elevation and gully stream order have been identified in some of the studies of gully erosion in southeast Nigeria by Ofomata 2002; Onwumerobi 2002; Igwe 2012; Igbozurike 2000; Egboka 1993. This study using Remote Sensing/GIS technology observed these variables could be contributing to gully development and therefore were subjected for further statistical analysis. Gully area and rate of gully are controlled by the 5 variables mentioned above and as well subjected to further statistical analysis to observe their relationship with the 5 variables above.

1. Soil
2. Vegetation loss
3. Slope
4. Gully area
5. Yearly gully change in metre squared per square metre
6. Elevation
7. Gully stream order

4.9.1 Variables and their Justification

The choice of these variables are hinged on the location of gullies in the study area and recommendations from other studies as being very influential in gully development. Many studies such as (Abdulfata et al. 2014; Parnwell 2011; Arash et al. 2011; Poesen et al. (2003) agree that these factors are the drivers of gully development. In the justification of the choice of the data, some vegetation in 2014/2015 were lost and the study wants to know if it is responsible for the yearly gully change in metre squared per square metre of each gully locally. Equally the analysis of other contributing factors to understand the role being played in the size of the gully with yearly gully change in metre squared per square metre in 2015 and the local environmental factors. The Cluster Analysis, PCA, MLR and Nonlinear statistical analysis were used to compare with the data from 2009/2010 and 2006/2007 of vegetation loss, yearly gully change in metre squared per square metre and 2015 gully area with other environmental factors. The study would have used 1986/1987 and 2000/2001 data but the model could not run because the data was not enough and some of the data produced zero. This is because by then the study could only recognise 4 gully sites of Iyioku, Okigwe, Njaba and Igboukwu which are not enough to run the model. The PCA model does not run when the data for analysis are not enough (Hatcher and Stepanski 1994). Also, when the data is not equall, the Cluster Analysis and MLRA will be reporting error message in the model.

All the values of the 7 variables that were used for further statistical analysis were normalised, Normalisation is important in Cluster Analysis, PCA, Multiple Linear and Nonlinear Regression Analysis since they have different base units of measurement for example, the soil value was obtained from nominal classification value scale and equally, they are variance maximizing exercise, because the analysed result obtained from PCA, Multiple Regression Analysis have different variance values. They project the original data into directions, maximize the variance and equally explain how the data relate to each other (Xu 2012).

4.9.1.1 Soil

Considering the nominal nature of some variables, such as soil, alterations were necessary to enable their use in the conducted statistical analyses. As the nominal soil classification it was classified according to its reported level of weathered soil, unconsolidated sandy sediments and whether the soil is deeply weathered. These were given ordinal values with 1 being Low, 2 Medium and 3 High (Retallack, 2001). These soils were divided into 3, namely Ferralic-Arenosols soils (deeply weathered, unconsolidated sandy sediments and friable soils) = 3, Feralsols and Nitosols (Less deeply weathered with sandy sediments) = 2 and Gleysols and Fluvisols = (hydromorphic properties and recent alluvial deposits, = 1. The soil map was overlaid by 14 gully points to observe the soil types on which each gully was located in terms of the 3 soil classes.

4.9.1.2 Vegetation Loss Variable

Vegetation loss is the amount of loss of vegetation in a year, obtained by subtracting amount of vegetation cover of the preceding year from the subsequent year. To determine vegetation loss on the local scale to each gully the classified vegetation value for each year (1986 – 2015) was used to subtract from the preceding year. For example, 1986 classified vegetated area was (8650865m^2), which was subtracted from the year 1987 vegetation area value of 7749875m^2 to get vegetation loss value of 900990m^2. This was repeated for each year and the values were obtained for vegetation loss of that year. At the local scale the vegetation loss over the time period 1986 to 2015 could be determined for each gully as well as for the 57758603400 m^2 (57,758.034km^2) study region as a whole. The value used for each of the 14 gullies in statistical analysis was the last value (pixel count) of the local scale vegetation Loss (vegetation Loss value for 2014-2015). For example, Iyioku (351987 – 321823) and the vegetation Loss is 30164 pixel count. The 2014/2015 value was chosen because it represents the current vegetation loss for the study period (Castillo et al. 1997). The vegetation loss data for 2006/2007 and 2009/2010 were also used to compare result.

4.9.1.3 Slope and Elevation Variables

Slope values were obtained by extracting the value of exact location point of each gully on the slope map of the study area. Consequently, this was how Elevation points were generated from the elevation map of the study area. The choice of gully reference points selected from slope and elevation values were got from the location of the field gully points (the gully points were picked from the gully sides depending where it is accessible). The elevation and slope points were selected based on where the gully points picked from the field were located which were picked at the gully head. For example, Iyioku has an elevation point of 250m and slope of 28^0.

4.9.1.4 Gully Strahler Stream Order.

These values were obtained from the drainage pattern of the study area; this drainage map displays the Strahler stream order where the gully points where overlaid to obtain the stream order values for each gully. The values were used as the variable for gully order. This variable was identified by some studies as having influence in gully development (Carey et al. 2015; Swanson 1989).

4.9.1.5 Gully Area, Rate of Gully Change and Rate of Yearly Gully Change in Metre Squared Per Square Metre

Gully area is the calculated size of the gully on a particular year. Each of the gully area values for the 14 gullies used in multivariate statistical analyses are obtained from the 2015-year data. This is because it represents the current gully area value of that gully from 1986 to 2015. Gully rate of change is a ratio between a change in one variable relative to a corresponding change in another. The yearly gully change in metre squared per square metre value is also obtained for all the 14 gullies. The yearly gully change in metre squared per square metre value is also obtained from the value of 2014/2015 yearly gully change in metre squared per square metre, which was got by dividing the yearly gully rate change by gully area. For example, Iyioku gully has gully rate of change for 2014/2015 as 83558m^2 which was divided by 2015 gully area of 1701881m^2 which gives 0.049m$^{2.}$ (yearly gully change in metre squared per square metre) .The values were obtained for 2006/2007 and 2009/2010 for Iyioku other 13 Gullies and their yearly gully change in metre squared per square metre obtained for the analysis (Dalil et al. 2016). It is important to note here that yearly gully change in metre squared per square metre was used to look at how 14 gullies have been eroding per m$^{\wedge 2}$yr^{-1} which represent both big and small gully and as well could be having similar yearly gully change in metre squared per square metre.

4.10 Multivariate Analysis as Empirical Analysis Techniques

This section discusses several multivariate techniques that are frequently used in Environmental management and change research. This section describes three methods for exploratory spatial data analysis in terms of data reduction, structure detection and classification, namely cluster analysis, Principal Component Analysis and Multiple Linear Regression Analysis**.** Multivariate analysis (MVA) techniques permit the use of more than two variables to be analysed at once. Multivariate Analysis can be used to process the data in a meaningful way by exploring how variables relate to each other. It can be used to summarise the strength of the linear relationships between each pair of response variables using the Correlations table, identify dependencies and covariance matrices. The multivariate analysis conducted in this study includes: Cluster Analysis, Principal Component Analysis (PCA) and Multiple linear regression.

Figure 48 shows an ordering for the different empirical analysis techniques for analysis of gully variables. This diagram is not intended as a 'simple' decision tree for selecting the appropriate method for this study. The diversity in data structures and research objectives conditions make a careful analysis of the requirements of the method necessary for this study. Furthermore, different methods can be used at the same time or sequentially within one analysis to better explore the data structure.

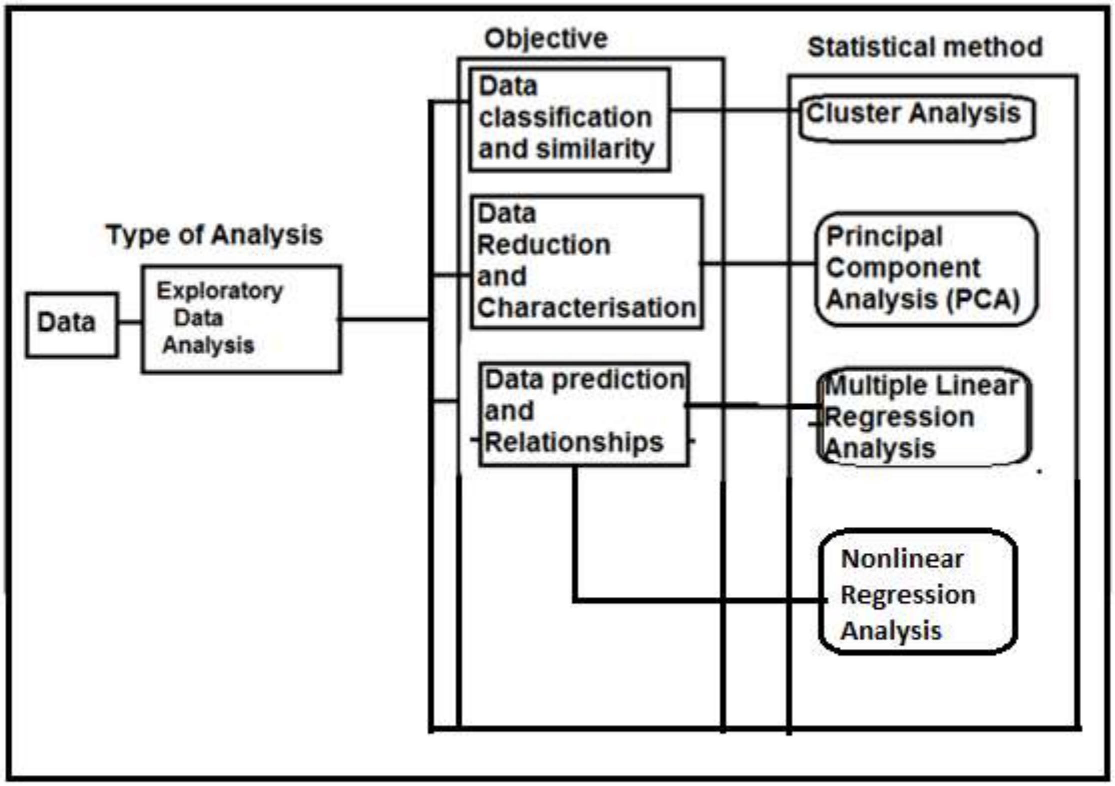


Figure 48: Classification of empirical analysis techniques based on objective and data structure of the study

The main uses of exploratory data analysis techniques are related to data reduction and structure detection. These methods aim (i) to reduce the number of variables; (ii) to describe the underlying structure between variables in the data; and (iii) to classify variables into groups. Principal component analysis (PCA) and Multiple Linear Regression Analysis are applied as data reduction and prediction methods and cluster analysis for classification and similarity of data. This is useful in Environmental Management analysis like gully erosion because land use change is often assumed to be influenced by a large set of driving and conditioning factors (Lesschen et al. 2005). PCA is suited to exploration of the structure of interrelationships between these different driving factors.

4.10.1 Cluster Analysis

Cluster Analysis is the grouping of a set of variables in such a way that variables in the same group (called a cluster) are more related to each other than to those in other groups or clusters. Essentially there will be high intra-group similarity levels, and low inter-group similarity levels to distinguish the clusters. The goal of cluster analysis is to identify the actual groups objects or variables belong. A general question posed by researchers in the pursuit of understanding relationships is how to organize observed data into meaningful structures, that is, to develop arrangements. The joining or tree clustering method uses the dissimilarities (similarities) or distances between objects when forming the clusters. Similarities are a set of rules that serve as criteria for grouping or separating items. Among the clustering techniques, Hierachichal cluster analysis was chosen because Hierarchical Clustering can give different partitionings depending on the level-of-resolution the researcher is looking at and makes several merge/split decisions, equally, hierarchical is good for small datasets as in the case of this analysis.

In this study, cluster analysis was used to at look at yearly gully change in metre squared per square metre in relation to other 6 variables (Vegetation loss, soil, slope, elevation, gully stream order and gully area) for all the studied 14 gullies.. Investigating similarities in yearly gully change in metre squared per square metre and other gully variables help to determine if the the variables show similarity and relationship to yearly gully change in metre squared per square metre. Again, cluster analysis will be used to look at the yearly gully change in metre squared per square metre in relation to rainfall pattern and vegetation area loss for the 30 years for the four major gullies and 10 years for all the 10 gullies under review to group years with same eroding power together. The approach is similar to the work of Feng et al. (2016) to assess the dynamic assessment of forest resources quality at the provincial level in China which revealed that Chinese forest resources during the 8th NFI could be grouped into four clusters according to the provincial administrative region. Another study, Parente et al. (2016), used Cluster Analysis to assess the influence of dataset characteristics, fire prevention policy decisions, weather and climate. A concluding finding was observed that the significant role of the weather on days when fires were active was confirmed for all small, medium and large fires. Results confirmed the influence of the dataset's characteristics reaching the outcome. Köbrich et al. (2003) used cluster analysis for the typification of farming systems, to be used for the reconstruction of representative farm models. The farming system typification was applied for a region in the coastal mountains of Chile. A data set of 67 farmers with 25 different farming system variables was collected. A hierarchical cluster analysis was applied on the seven retained factors. A dendrogram was constructed to show the sequence by which the observations and clusters were merged. Line C was defined as the cutting line, which resulted in five clusters (farms 1–27, farms 28–50, farms 51–57, farms 58– 61 and farms 62–63).

4.10.2 Principal Component Analysis (PCA)

The analysis of multivariate datasets requires some statistical techniques like Principal Component Analysis to reduce their dimensionality. PCA has the ability to replace the original variables by a smaller number of derived variables, the principal components. These are linear combinations of the original variables (Jolliffe 2014). The main purpose of principal component analysis is to obtain a minimal number of independent linear combinations (principal components) of a set of measured variables that represent as much of the variability in the original variables as possible, equally can be used in Correlation between the original variables and the factors, and the key to understanding the underlying nature of a particular factor. This approach was applied in this study to demonstrate the reactions of the variables and their contributions in gully formation and development of the study area. The application of Principal Component Analysis was not utilised by any of the analysed literature in my study area but has been used in such studies as Yu et al. (1998) for the analysis of effective dimensionality of environmental indicators and Vajcnerova et al. (2011) in evaluating the quality of a tourist destination. The application in this study will help determine significant variables in relation to gully area and development rates of change.

Principal Component Analysis was used to determine similarities between the gully influencing variables observed. The main aims of PCA are data reduction and Interpretation (Dien et al. 2005). In the principal component analysis (PCA), account will be taken of components with eigenvalues exceeding 1, how much variability is described by the significant components and of how variables relate in terms of their variance descriptions provided by the most significant components. Using these data similarities between variables will be identified.

Principal Component Analysis was used to extract the most contributing variable in all the gully factors and how all variables relate to one another (Tekana 2014). The factorability of correlation matrix of Eigenvalue should be 1 or greater which shows that variable could be significant in the description of the model (Joliffe 1986). Therefore, factors having higher Eigenvalue explains the variables better and show they contribute or relate to each other.

4.10.3 Multiple Linear Regression

Multiple linear regression is the most common form of linear regression analysis that is used as a predictive analysis, which explains the relationship between one continuous dependent variable from two or more independent variables (Freedman 2009). Multiple linear regression attempts to model the relationship between two or more explanatory variables and a response variable.

Multiple linear regression (MLR) is used in this study to determine how specific factors such as, Vegetation loss, Slope, Soil, elevation, gully stream order, gully area and yearly gully change in metre squared per square metre, influence gully area development. MLR could be used to model the impact that each of these variables has on gully area development in terms of absolute area and rates of change. MLR fits a linear equation to observed data. Every value of the independent variable x is associated with a value of the dependent variable y. The multiple linear regression equation is as follows;

$$\hat{Y} = b_0 + b_1X_1 + b_2X_2 + \ldots + b_pX_p \quad (3)$$

where $\hat{Y}$ is the predicted or expected value of the dependent variable, X_1, X_2, X_3, X_4 through X_p are p distinct independent or predictor variables, b_0 is the value of Y when all of the independent variables (X_1 through X_p) are equal to zero, and b_1 through b_p are the regression coefficients. Each regression coefficient represents the change in Y relative to a one-unit change in the respective independent variable. In the multiple regression situation, b_1, for example, is the change in Y relative to a one-unit change in X_1, holding all other independent variables constant (i.e., when the remaining independent variables are held at the same value or are fixed). Statistical hypothesis testing can be performed to assess whether each regression coefficient is significantly different from zero and hence the significance of the variable as a predictor. Onagh et al. (2012) used Multiple Linear Regression Analysis to model landslide susceptibility zonation mapping in Narmab Basin Iran. The success rate of the model was 79.7% which shows high prediction accuracy and its application in an environmental setting. Chao et al. (2008) used MLR analysis in quantifying the relative importance of predictors in public health studies showing its multidisciplinary application. In the case of this study, the gully factors identified earlier in this section are used as independent variables to investigate their relationship with gully area and yearly gully change in metre squared per square metre (dependent variable) details in section **4.9.1**

4.10.4 Nonlinear Regression Analysis

Nonlinear regression modeling is similar to linear regression modeling in that both seek to graphically track a particular response from a set of variables. Nonlinear models are more complicated than linear models to develop because the function is created through a series of approximations. Nonlinear regression analysis is a regression analysis where observational data are modeled by a function which is a nonlinear combination of the model parameters and depends on one or more independent variables. The data are fitted by a method of successive approximations. The reason that these models are called nonlinear regression is because the relationships between the dependent and independent variables are not linear. Several research work in environmental sciences have used nonlinear regression analysis in their analysis of data. For example Hanumara and Hoenig (1987) and Matis et al. (2005) Nonlinear stochastic modeling of aphid population growth. The result was The approximations, which are simple for ecologists to calculate and give accurate predictions of the two endpoints of applied interest, namely (1) the peak aphid count and (2) the final cumulative aphid count. The application of nonlinear regression analysis in this study was based on the fact that some of the variables are not linearly represented and will seek to know the response of each independent variable to the dependent variable.

5 Presentation of the Results

In this chapter the results of the data analysis are presented. The data were collected and processed to specifically address the aims and objectives of this research work. Three fundamental goals drove the collection of the data and the subsequent data analysis. Those goals were i) to identify factors triggering gully development in South East Nigeria and increase the predictive capability of spatially locating these featires, ii) to develop a low cost, technology based, gully monitoring method to obtain data from inaccessible areas of the study area and iii) to ultimately find ways to avoid the need for field based gully measurements which represent a hazard of high risk due to frequent gully wall cave in. Some of the gullies are so large and deep that a researcher requires up to 2 to 4 months to measure in detail (the area, length and width etc of the gullies) and communities/government often restrict access to gully sites. The level to which these aims and objectives have been accomplished and the associated findings are presented in this chapter which demonstrates a clear potential for Remote sensing and GIS technology to provide a low cost and accessible way to circumvent the need for less than ideal *in-situ* data collection. At the same time increasing the ability for local communities to take responsibility to monitor, and uncover the causes and drivers of gully erosion to date and to be able to postulate the future.

5.1 Regional Topographical Analysis

Topography of an area determines the nature of the landscape which helps to influence gully erosion development Poesen et al. (2003), Marquisee (2010), Boardman (2006), Bochet (2004) and Igbokwe (2008) and as pointed out by Ofomata (2008), topography of southeast Nigeria is the main source of gully erosion. In South-East Nigeria, Ofomata (2001), found that there is a positive relationship between topography and gully erosion leading to more pronounced gully erosion in areas with valley topography than areas with flat land. Ofomata goes ahead to mention areas such as Agulu-Nanka, Njaba, Nekede-Owerri, Iyioku, Okigwe, Afikpo, Ohafia, Umuahia, the gullies can be traced to the natural slope of the topography. Some of the areas mentioned are part of this study.

This section will be analysing the relationship between gully erosion and slope, elevation, gully stream order and local soil of southeast Nigeria. This was why this section will answer one of the objectives as set out in this study "Rendering Digital Elevation Models (DEM) to detect changes and calculate gully dimensions of focused gully sites (to observe how slope, nature of slope, aspect and gully stream order influence gully development)". The adoption of Digital Elevation Model for this analysis is a new method that can easily reveal the nature of the landscape. Land surface topography has been reported to significantly affect the processes of runoff and erosion (Zevenbergen and Thorne 1987). The presentation of the regional topographic analysis in this study looks into the natural causes of gully development in the study area although known to be caused by both the contributions of topographic and anthropogenic disturbances (Arash et al. 2011; Igbokwe 2008). In this chapter, the analysis of Elevation, slope, curvature of slope, gradient of slope, slope Aspect, stream order generation, contour generation and cross profile of gully sites are presented with a subsection provided to cover the influence of each variable.

5.1.1 Elevation

In line with answering the objective 3 above, this study will look at how elevation as part of topography influences gully development. The study of Bromley (1995) observed that as elevation increased, there were considerable changes in soil horizon composition, including dramatic differences in soil texture, horizon depth and temperature which can affect gully development.

The digital elevation map of the study area is produced from the SRTM data at 30m (1 Arc-second) resolution. The elevation map of the study area presented has a minimum elevation value of -11 metres and a maximum of 516 metres ASL. When gully points were overlaid, as can be seen in **Figure 49**, it reveals that gullies are found on areas that are higher in elevation compared with the surrounding areas. All the 14 surveyed gullies are located on areas with elevation points above 10m.

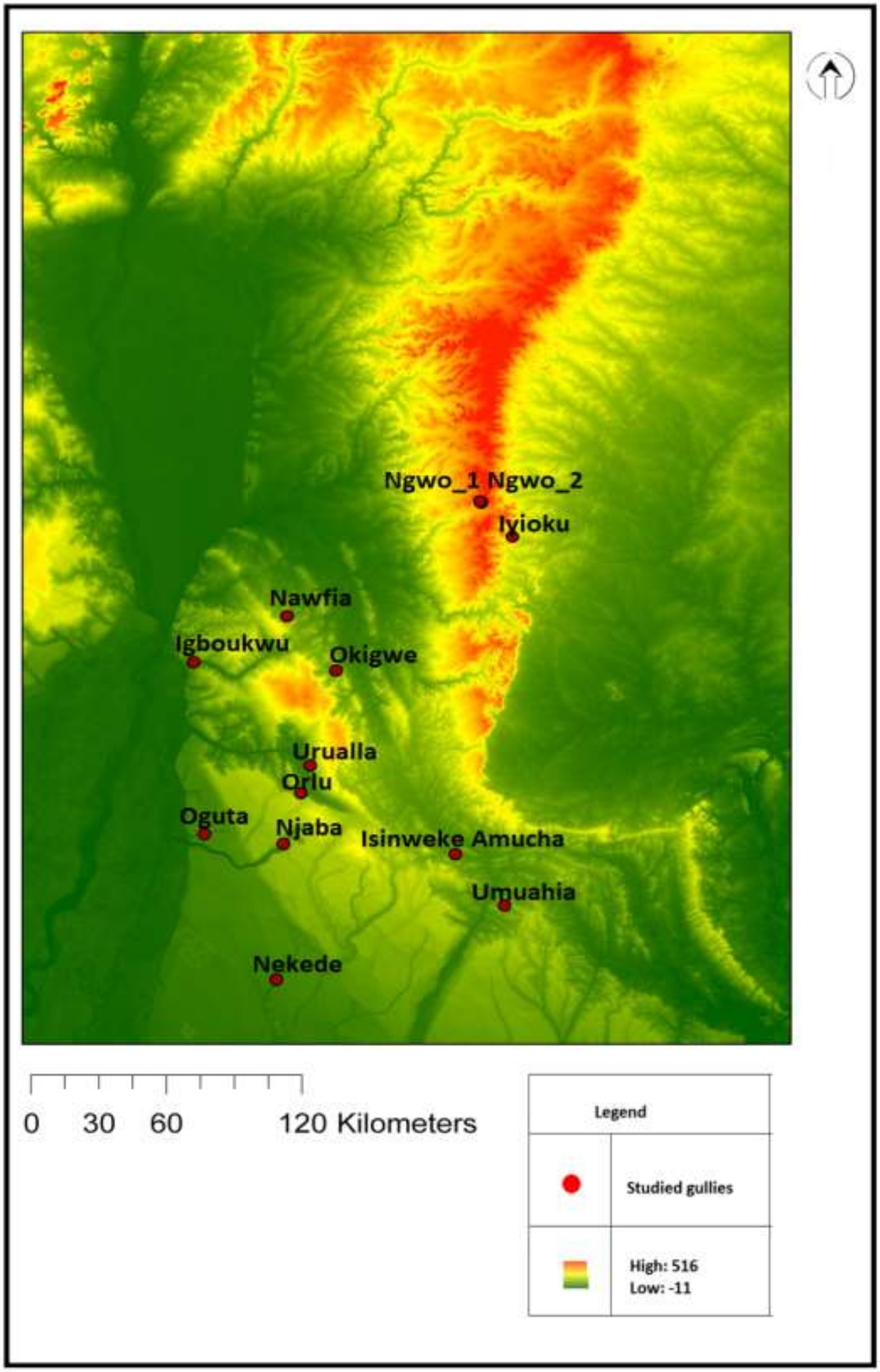


Figure 49: An SRTM DEM image of the 57,758.034km2 study area, cropped to Area of Interest green colour represents low elevation.

5.1.2 Slope

This section is part of the answer to objective 3 above, the slope gradient is one of the most important factors affecting gully erosion (Qing-quan et al. 2001). Ofomata 2001 also emphasises the importance of slope by showing that the studied gullies are located at the base of slopes or hills. Igbokwe (2008) observed that in the simplest terms, land located on steep inclines is more vulnerable to water erosion than flat land. Therefore, this section will analyse DEM of the study area to reveal how slope affects the development of gullies.

The highest elevations in the region are detected at elevations of 516m. In terms of degrees **Figure 50** shows that areas with 0 - 10^0 are mostly found in low lying areas which are mainly found on top of plateaux, flood plains, flat areas and areas liable to flooding. Areas with 10^0 – 20^0 - 30^0 and above accommodate the majority of gullies revealing that these areas are where gullies are most commonly developing. The analysis of slope and overlay of gully points have revealed that gullies mainly develop in areas with 10^0 and above. Of all the 14 surveyed gullies, 8 gullies (57%) are found at 10^0 - 20^0, and 6 gullies (43%) at 20^0 and above. **Figure 51** provides a graphic showing slope and elevation.

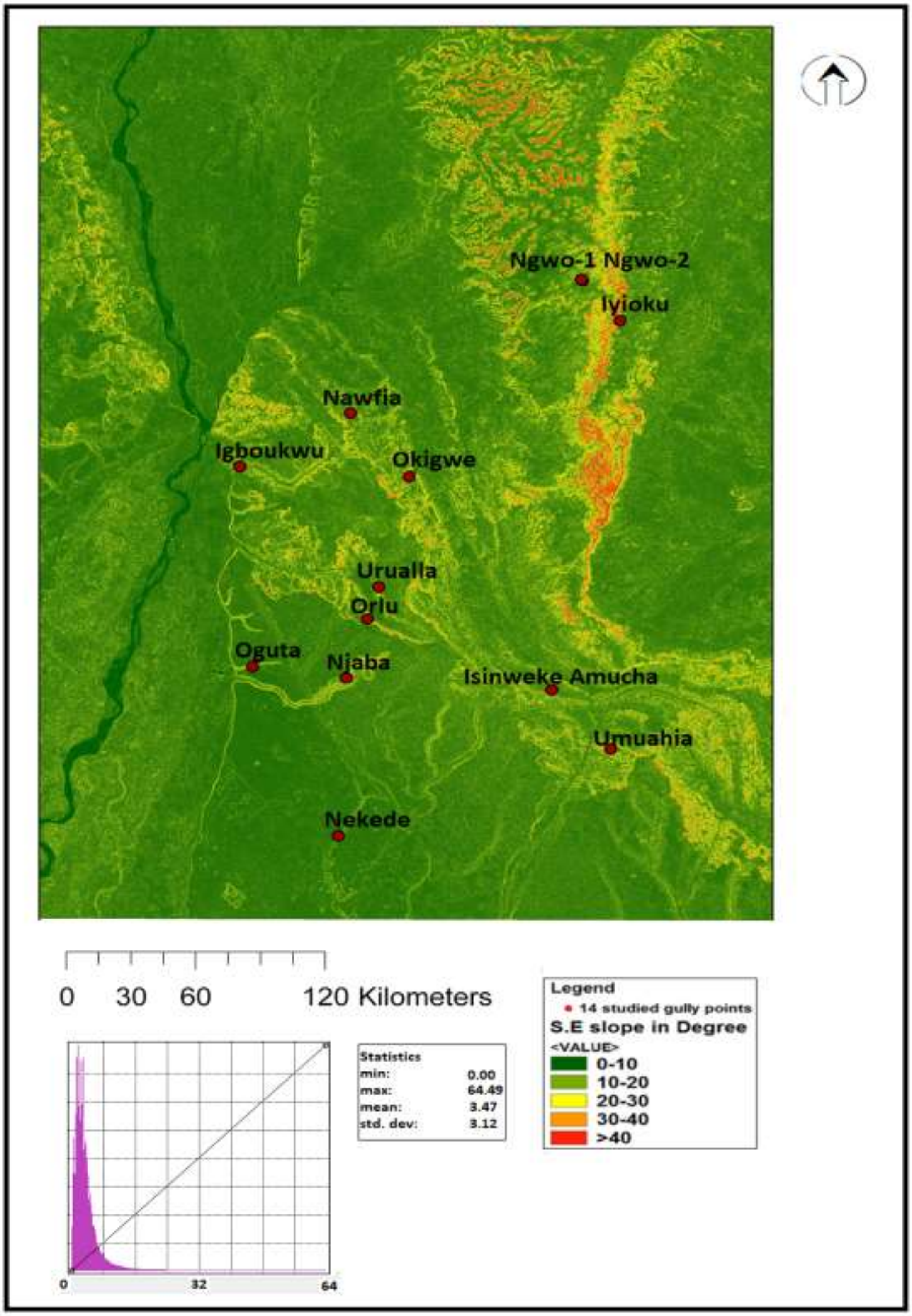


Figure 50: Maximum slope map of the study area shown as a degree gradient (flat areas have 0 – 10, 10 - 20^0 gentle slope and 20^0 and greater are higher).

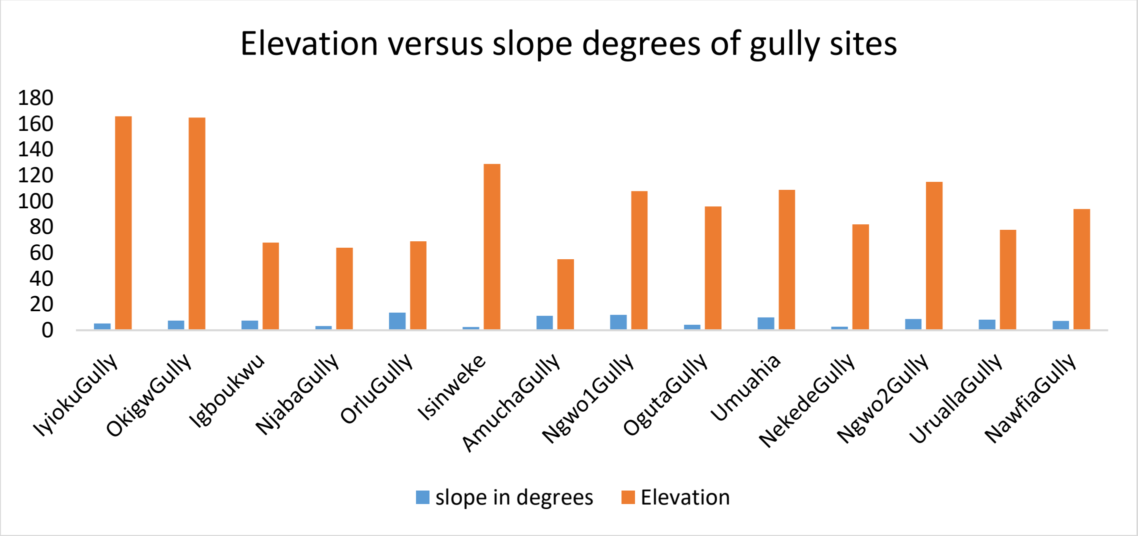


Figure 51: Slope versus elevation of the studied14 gully sites

5.1.3 Slope Aspect

Further analysis of topography was conducted via analysis of gully locations in respect to the slope aspect, which forms part of objective 3 above. Beullens et al. 2014, Marque and Mora 1992, maintained that slope orientation affects gully development which depends on the side that is receiving rainfall more which determines the amount of runoff. The aspect map of the study area, **Figure 52**, was classified into ten classes, defined as: flat, N, NE, E, SE, S, SW, W, NW. On this basis, the aspect classes of southeast Nigeria highlight a fairly homogeneous distribution. Slopes facing from North to North-west slightly predominate when compared with South, South-east and south-west while the value of -1 is used to identify flat surfaces such as flood plains, fluvial terraces, river courses and hill plains. None of the gullies were located on areas with value of -1 which represent a flat area.

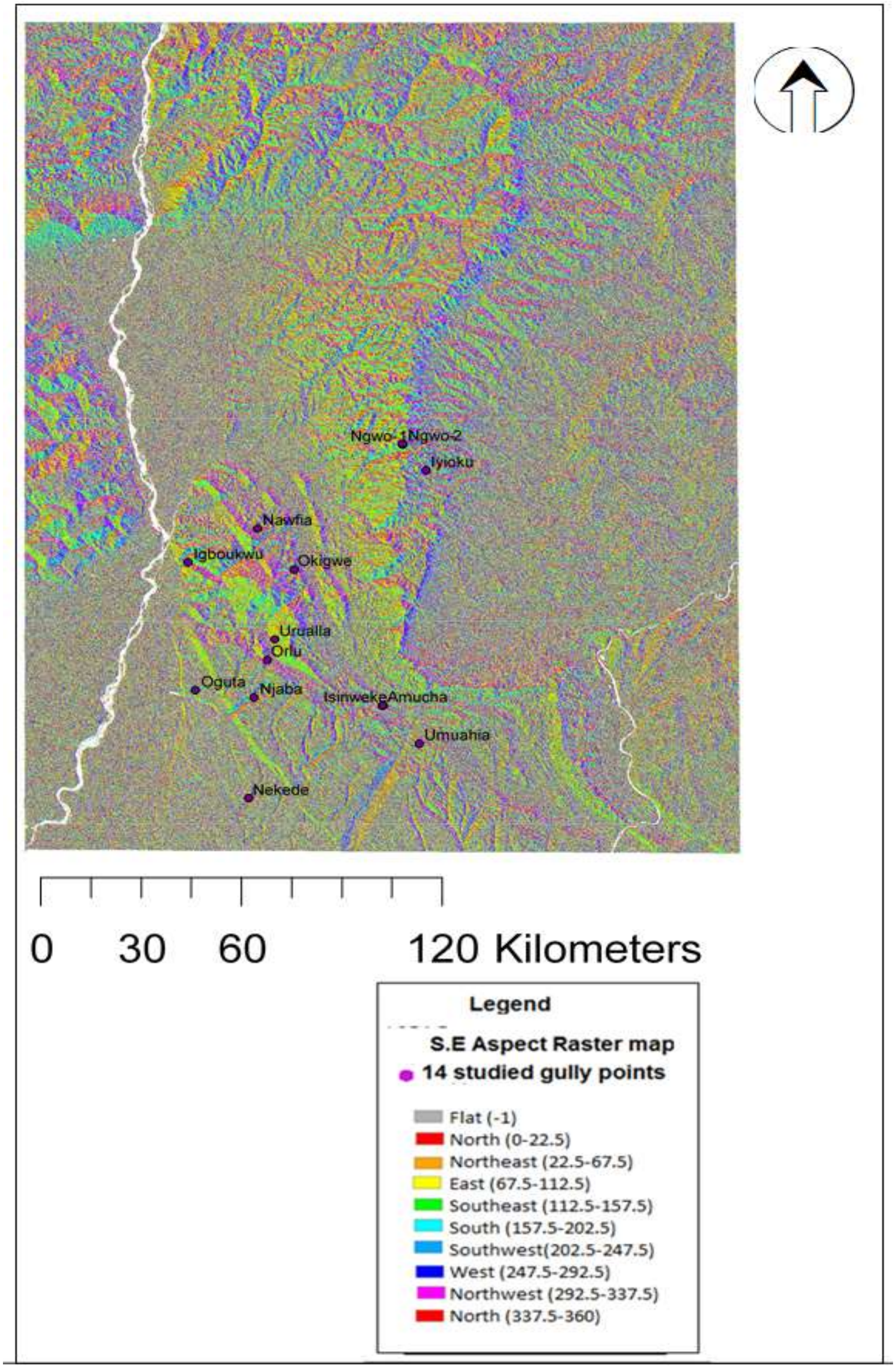


Figure 52: Aspect map overlayed by the gully points observed gully shapefiles and gully points. Flat, N(0 -22.5), NE (22.5 – 67.5), E (67.5 – 112.5), SE (112.5 – 157.5), S (157.5 – 202.5), SW (202.5 – 247.5), W (247.5 – 292.5), NW (292.5 – 337.5 and N (337.5 - 360)

5.1.4 Slope Plan Curvature

This section also looks at slope plan curvature as part of topography that influences gully development in the study area and answers part of objective 3 above. The slope geometry of hill sides whether convex or concave often contribute significantly to soil loss and gully development. Poesen et al. (2003), in working on gully erosion and environmental change in Leuven, Belgium, recorded that uplands act as a link through which run-off transports sediments down the hill, contributing to the development of gullies. Zapp and Nearing agreed that Slope shape has a significant impact on rill patterns and gully developemt. The curvature is very important in understanding how run-off flows in the study area, which influences gully erosion and deposition. The low values of -5 (x10^6) of plan curvatures define convexity; while high values of 6 (x10^6) plan curvatures characterize concavity of slope curvature. Values of plan curvatures around zero indicate that the surface is flat. The curvature data from across the study region is shown in **Figure 53.**

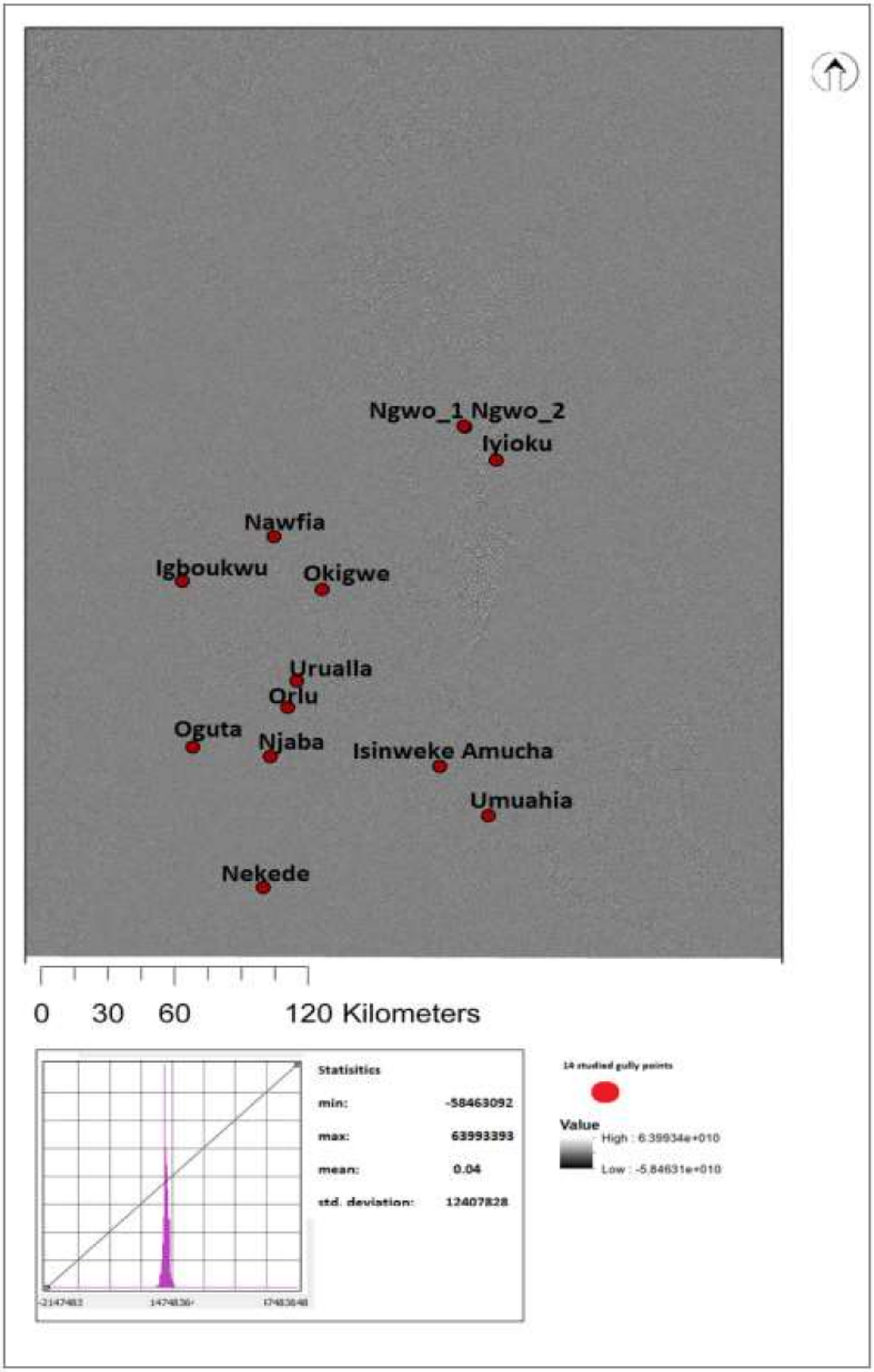


Figure 53: Curvature of the slope of the study area; The low values of -5 (x10^6) of plan curvatures define convexity; while high values of 6 (x10^6) plan curvatures characterize concavity of slope curvature, overlayed with gully points from the field.

5.1.5 Gradient of the Slope

This section as well looks at slope gradient as part of topography that influences gully development in the study area. Also, this section fulfils part of objective 3 above. The slope gradient is one of the most important factors affecting gully erosion. Under the same rainfall runoff, gully erosion could be drastically different on different slope gradient (Qing- quan (2001). Igwe (2012) maintained that as surface water continues to flow, it starts to remove the cementing materials of the soil through the fissures, which develop into gullies depending on the nature and gradient of the slope. In the analysis of geographical gradient of the slope of the 14 test gully sites, the data reveals that they have different gradient values. The Iyioku, Okigwe, Igboukwu, Njaba, Orlu, Amucha, Ngwo1, Ngwo2, Oguta, Umuahia, Isinweke, Nekede, Urualla, and Nawfia gully sites are shown in **Table 10.** The contours at the head of the 14 gully sites were higher than those at the lower end of the gully sites. The average gradient of the 14 studied gullies is 1 in 28.6m.

Table 10: Calculated gradient of gullies for the 14 specific gullies and Soil types are shown

	Gully Name	Maximum Elevation	Minimum Elevation	Horizontal Difference	Distance	Gradient (m)	Soil Type found
1	Iyioku	250m	150m	100m	6618m	1 in 66	Gleysols and Fluvisols
2	Okigwe	150m	75m	75m	7405m	1 in 99	Ferralic-Arenosols soils
3	Njaba	250m	175m	75m	945m	1 in 13	Feralsols and Nitosols
4	Igboukwu	250m	175m	75m	905m	1 in 12	Ferralic-Arenosols soils
5	Orlu	100m	75m	25m	107m	1 in 4	Feralsols and Nitosols
6	Amucha	175m	100m	75m	356m	1 in 5	Ferralic-Arenosols soils
7	Ngwo-1	175m	100m	75m	250m	1 in 3	Ferralic-Arenosols soils
8	Oguta	100m	50m	50m	2280m	1 in 46	Gleysols and Fluvisols
9	Umuahia	125m	50m	75m	115m	1 in 2	Feralsols and Nitosols
10	Isinweke	100m	50m	50m	2120m	1 in 42	Ferralic-Arenosols soils
11	Nekede	100m	25m	75m	2031m	1 in 27	Ferralic-Arenosols soils
12	Ngwo-2	150m	50m	100m	175m	1 in 2	Gleysols and Fluvisols
13	Urualla	250m	50m	200m	8039m	1 in 40	Ferralic-Arenosols soils
14	Nawfia	150m	75m	75m	2999	1 in 40	Ferralic-Arenosols soils

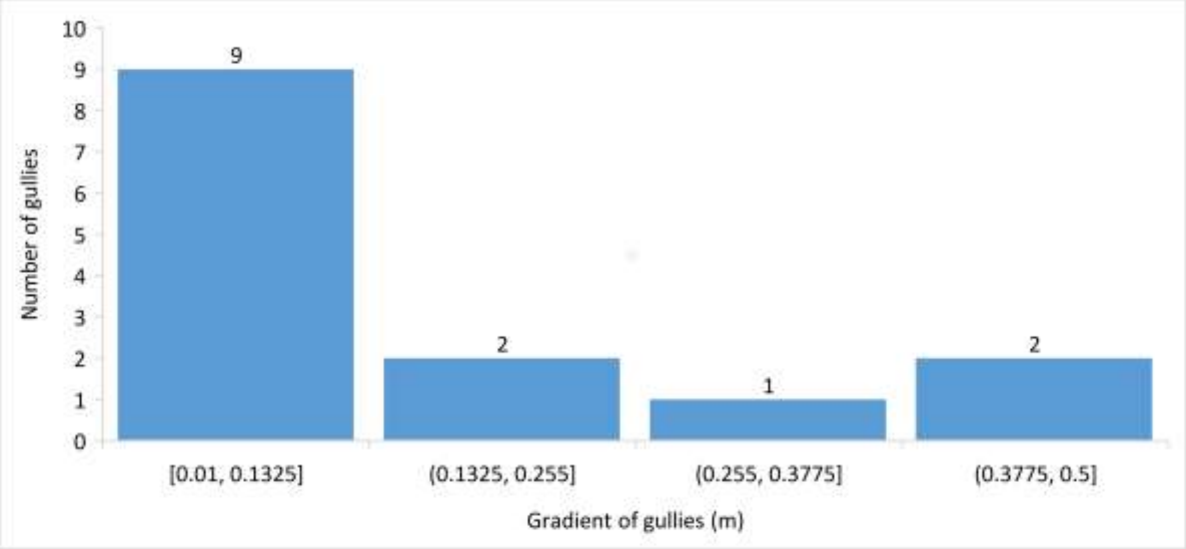


Figure 54: Histogram using the gradient data of the 14 gullies above

An observation from **Figure 54** above, the histogram of the gradient shows that there are 9 gully sites with the lowest gradient between 0.01 – 0.1325 which include Iyioku, Okigwe, Njaba, Igboukwu, Oguta, Isinweke, Nekede, Urualla and Nawfia gullies. Gullies with gradient from 0.1235 – 0.255 are Orlu and Amucha gullies, while with gradient between 0.255 – 0.3775 is only Ngwo1 and the gullies with the highest gradient between 0.3775 – 0.5 are Umuahia and Ngwo2. This is represented on the gradient chart **Figure 55** showing individual gullies.

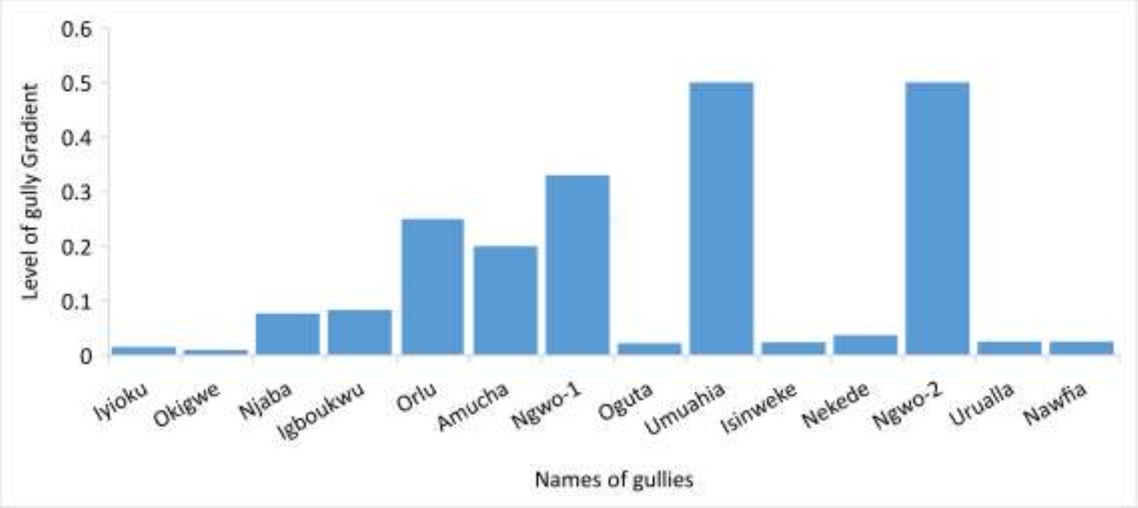


Figure 55: Chart using the gradient data of the 14 gullies by category

5.1.6 Local Soil

This section fulfils part of the objectives 6 “Employing the use of soil and geology maps of the study area to determine the prevalent types of soil and sediment, and identify relationships with those sites yielding more rapid gully erosion and associated meteorological data”. Some environmental Scientists have attributed soil as the main influence on gully development, (Lash et al. 1996; Wisner et al. 2004). Arash et al. (2011), attribute gully erosion to physical factors, but suggest that its severity is greatly influenced by the structure and texture of the prevalent soil. Ofomata 2008; Onwumerobi 2002; Igwe 2012 recomemmended soil as a strong factor in gully erosion development of southeast Nigeria.

Taking a look on the analysis from **Table 10** above, it reveals that even though the soils appear to have similar characteristics, the gradient of the gullies tends to be lower in areas where there are Ferralic-Arenosol soils (mean gradient = 1 in 37.7); rather than Gleysols and Fluvisols (mean gradient = 1 in 24). Ferralic-Arenosols soils; Gleysols and Fluvisols have deeper weathering and also unconsolidated sandy sediments (Akanwa 2017). Gleysols and Fluvisols have loose sandy sediments and have similar characteristics with Red Ferralsols and Hydromorphic soils but their weathered soil is not as deep as Ferralic-Arenosols and Feralsols and Nitosols soils (Akanwa 2017). All these physical factors are highly influenced by anthropogenic factors (Igwe 2012). In the location of the 14 gullies 8 gullies are located on (Ferralic and Arenosols), 3 gullies are located on (Feralsols and Nitosols) and 3 gullies are located on (Gleysols and Fluvisols). Which is represented by 57%, 21% and 21% of the number of gullies respectively.

5.1.7 Gully Strahler Stream Order

This section looks at gully stream order which forms part of objective 3 above. Ofomata 2002; Onwumerobi (2002); Igwe (2012); Igbozurike (2000); Egboka (1993) seperately attributed gully stream order as one of the gully factors that contribute in gully genaration and development. The studied gullies are found at the segment of the drainage which has mostly the hierarchy of tributary number 1, 2, 3 and 4, **Figure 38 section 4.7.1.** Showing that 1 and 2 contribute to 3 while 1, 2 and 3 contribute to 4 which produce high runoff. The hierarchy of 1, 2, 3 and 4 show that the gully sites are located at slope areas with high runoff. The cells that have 5, and above are surface water. The 14 gullies are located thus; hierarchy 1 (6 gullies), hierachy 2 (5 gullies), hierachy 3 (1 gully) and 4 (3 gullies). The 14 gullies are represented by 1, 2, 3 and 4 hierachy as 43%, 36%, 7% and 14% respectively. This is represented in **Figure 56** below.

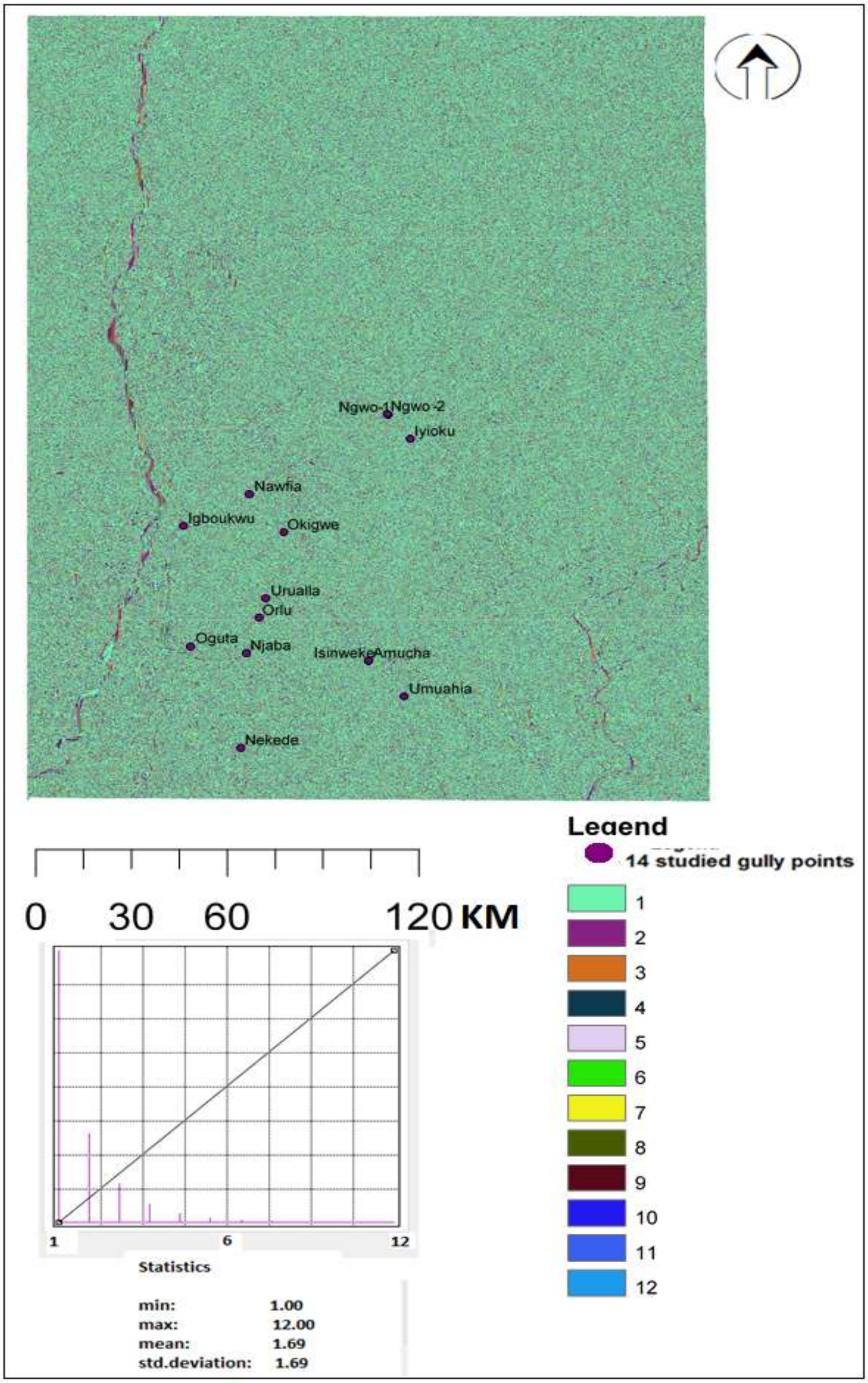


Figure 56: The Strahler stream order Drainage pattern of the study area overlaid by the gully points. From 1 to 12 are stream sizes based on a hierarchy of tributaries in the study area. The cell value shows that stream 1 are more in number than others

5.2 Landcover Change Analysis with SAR Backscatter Analysis of Forests Degradation

This section fulfils objective 3, Map dynamics of deforestation and forest degradation in southeast forests using radar satellite data and identify, if any, links between gully erosion rate and vegetation removal". Some researchers such as Rahman and Sumantyo 2007; Joshi et al. 2015 have applied this method in monitoring forest degradation as one of the causes of gully development.

To analyse the impact of freely available L Band SAR data on efforts to monitor the degradation of forests in proximity to gullies, ALOS PALSAR data was used. Although not released as open source data the data is available free of charge upon request through various data streams but is limited by regional location. The use of the L-Band data in this scenario acts as a precursor to the potential use of future data sources such as the NASA NI-SAR L-Band mission (Yu and Saatchi, 2016). This mission, due for launch in 2020, will operate an open data policy similar to that currently employed by the Landsat mission. Such availability will make the SAR data an integral part of any low budget landcover analysis methodology, particularly regarding the condition and extent of forest canopies. The strengths of the SAR data lie in the existence of relationships between the backscatter levels and the forest biomass, as well as in the ability to detect and infer structural variations. Refering to the work of Brolly et al. (2016), in this study the ALOS PALSAR data is employed to determine the degradation of forests via a change detection analysis to complement the theories exposed regarding the loss of vegetation and the emergence of gullies, and confirmed by the Landsat land cover analysis in **section 4.3.**

The investigation is conducted at the regional scale and as expected, given the land cover analysis, has revealed frequently disturbed forest areas within a continuum of surrounding disturbed land. To enable accurate detection of these areas, the advantage of multi-temporal and spatially continuous SAR images was exploited. Although the data availability is very limited in terms of temporal resolution, due in part to the acquisition priorities of the system and its relatively short lifespan, time-series analysis is conducted using four temporal points. These points are taken from the years 2007, 2008, 2009, and 2010. The available timespan is limited but will offer insight into the regional changes during this time but most importantly indicate the potential of future data streams for this purpose over similarly continuous timescales but over longer periods. The method for change detection using SAR data is outlined in the methodology section. The use of 4 temporally separated scenes allows the same pixel to be observed multiple times, assigning more confidence in determining its status as being disturbed or undisturbed land during the examined time period. To minimise detecting backscatter variations in forest degradation unrelated to anthropogenic disturbances, a local 3X3 moving-window filtering procedure that assumes that disturbances are more likely to be real if they neighbour other disturbances was used. The designed algorithm uses multi-temporal data as intermediate information to verify disturbance locations, and identify deforestation areas on the Radar image. This is indicated by differences evident between the images 2010 and 2007

Due to forest structure, in particular the random alignment of canopy constituents, forests tend to depolarize the radar signal (Woodhouse 2006). The result of this is that relatively high σ^0 HV backscatter values are received (Joshi et al. 2015). This is in relative comparison to HH and VV data that do not display the same sensitivities to forest canopies and therefore biomass (Ryan et al. 2013). When forest cover is reduced, resulting in a reduction in biomass and alteration to the canopy structure, a correlated reduction in HV backscatter is expected. This methodology uses the annual loss in σ^0 HV as a precursor to identify disturbed forest. To identify a disturbed pixel, the algorithm uses a threshold backscatter level (T -1.5db) to detect disturbance. The loss of -1.5 dB in any pixel between any two temporally separated datasets then indicates disturbance. The bigger the loss in backscatter the more severe the disturbance indicated. Normally deforestation causes differences in backscatter that exceed the -1.5 level (Joshi et al. 2015). The threshold level for this study was monitored through analysis of the changes exhibited in the time periods 2010-2007, 2009-2007 and 2008-2007 (this threshold provided a base to trace and track the level of changes in comparison with other subsequent years which allows the same pixel to be observed from the base year 2007, again if something changed in 2007 to 2008, also the change was seen in 2007 to 2009 and 2007 to 2010, then one can be more confident that it is real change). Using the -1.5dB threshold level the deforestation map is produced for each year. Example is presented in **Figure 57** and others can be found in **Figures 175 and 176** in **Appendix IV.** Three backscatter change maps using the four temporally separated images are created in order to confirm the existence of changes using three time differences. These can be presented as an example in **Figure 57** revealing the captured disturbances over these time periods.

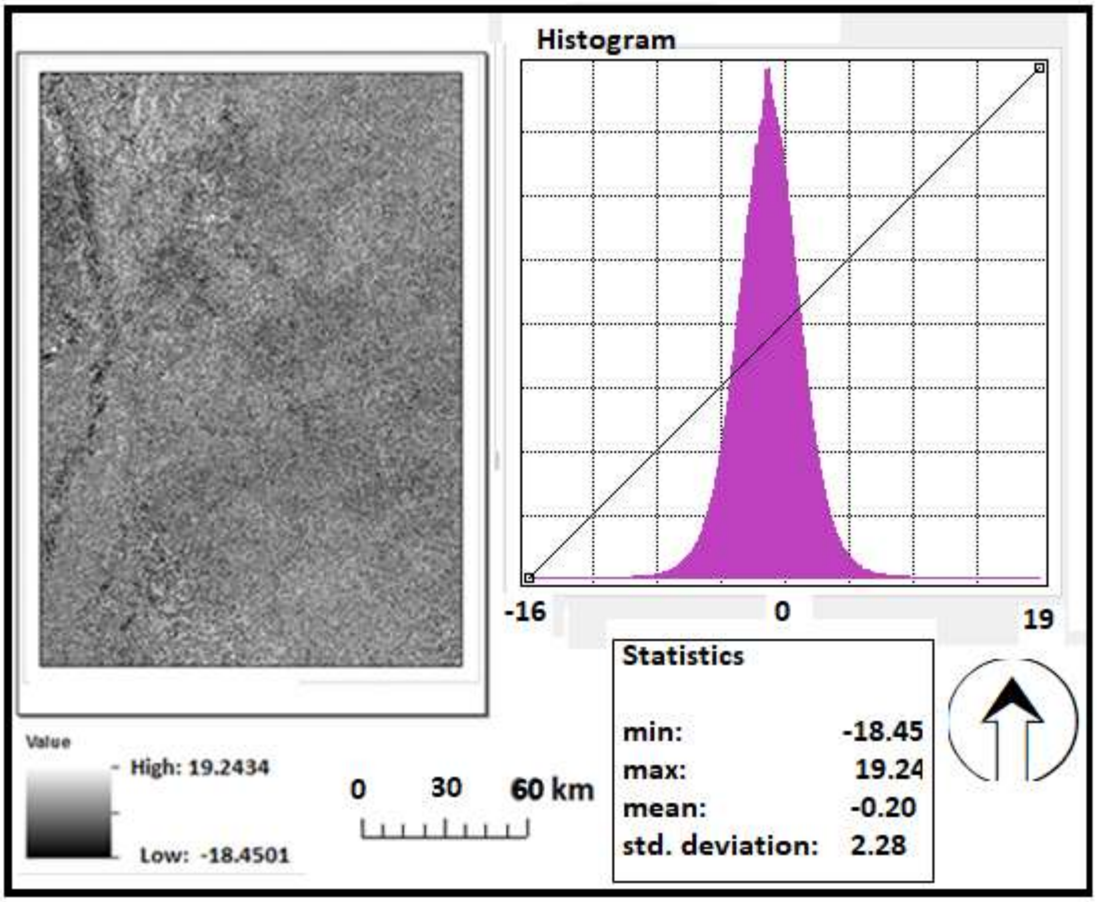


Figure 57: The Change detection of year 2010-2007 negative dB represents forest disturbance. 0dB represents no change with the mean of the distribution being close to this value at -0.2dB. As the data is normally distributed we can confidently state that 68% of the data values are found in the range -2.48dB to -2.08dB change between images represented by one standard deviation with 32% experiencing greater change.

Typically, deforestation has been reported to cause differences of -1.5 to -7 dB between HV images (Joshi et al. 2015). The selected differences have been used to get the deforestation threshold as can be found in **Figure 58 and in Figures 177 and 178 of Appendix IV**.

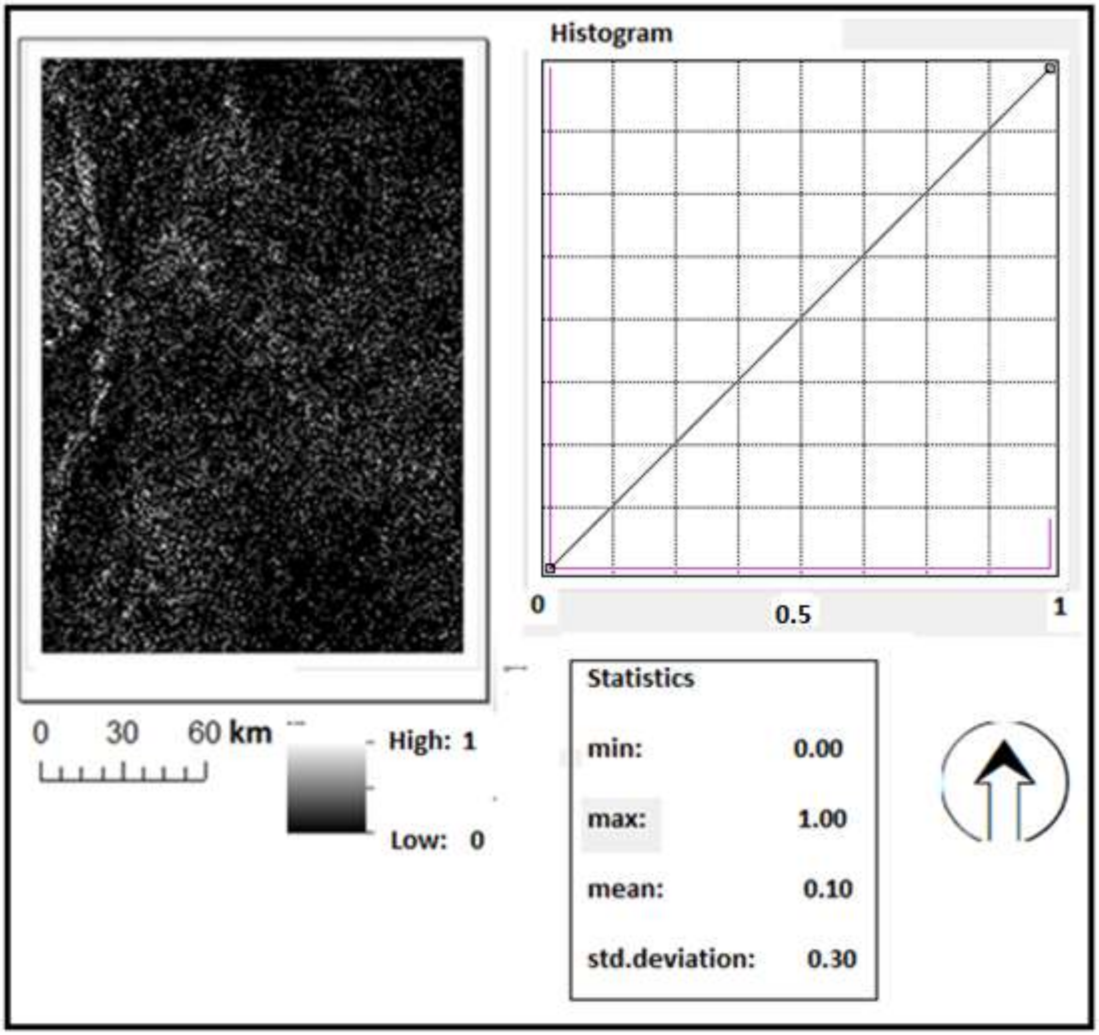


Figure 58: The Threshold map of 2010-2007; 1 represent deforestation, 0 represent forest and other land-cover (The purple line in the histogram shows the frequency of occurrence)

Forest degradation and deforestation have been one of the negative activities taking place in southeast Nigeria. These changes could be associated with logging, agricultural activities, urban drift and exploitation of raw materials by industries.

Table 11: : Reclass Total forest and deforestation coverage. Pixel size is 225m^2

	Total pixel count for undisturbed land	Actual area (m^2)	% undisturbed land	% Deforestation
2010-2007	86415772	19443548700m^2	90%	10%
2009-2007	86875281	19546938225m^2	91%	9%
2008-2007	88279633	19862917425m^2	92%	8%

Quantification of the forest degradation around the study area is presented in **Table 11** above, when compared with 2010-2007 image, it shows that it has 1% difference from 2009-2007 change image and 1% difference from 2008-2007 image representing a loss of 1% of area relative to 2007 levels per year. Again areas recognised where forest is being degraded during the field work, have been shown consistently on the 3 Radar images as areas where deforestation is going on. This methodology has been used to corroborate the landuse/landcover classification on forest removal on the study area. Areas where forest degradation is going on are mostly where gully erosion is taking place when gully points were overlaid.

5.3 Regional Land Cover Classification

This section answers objectives 1 “Use remote sensing data (Landsat and ALOS PALSAR) to determine change in land-cover through Pixel based and Object Based Image Analysis (OBIA) classification over a maximum 30-year period (1986 – 2015) in SE Nigeria”. The classification methods for this purpose will be compared and contrasted”. Many researchers have attributed landcover removal as the main source of gully development. In South East Nigeria, Igwe (2005); Onyekwere (2001); Ijeoma and Okey (2005) have separately agreed that gullies mostly develop on soil on which vegetal growth has been disturbed due to infrastructural developments, for example roads and housing developments. Land cover classification is one of the modern methods of ascertaining the level of landcover removal by human interference.

Pixel and Object Based Image Analysis (OBIA) land cover classification is conducted for the study region. Data is provided for each individual year within the defined study period. The regional study area measures approximately 57,758.034km^2. According to the two different classification methodologies, the results reveal that the vegetated land surface, at the beginning of the study in the year 1986, comprises 90% and 83% of the study area for Pixel and Object Based classification methods respectively. These values highlight the original dense canopy coverage of the region. By 2015, over a period of almost 30 years, this classified vegetated proportion of the total land surface has reduced to 35% according to Pixel based approaches and 41% for OBIA classification. According to both independent methodologies this highlights a significant loss in vegetated land surface. Losses of vegetated area are estimated at 55% and 41% of the total studied area, for Pixel and OBIA classification respectively, between 1986-2015. With respect to the regional land cover classification presented in **Table 12 and 13** for each of the available study years, the significant loss in vegetation is predominantly attributable to increases in Urban-land and Agriculture. As well as appearing to contribute to a loss in vegetation these increases in urban and agricultural areas appear to have influenced the existence and development of Gully/Open-land formation in the study area. While a 55% reduction in vegetated land has been detected over the study period, other land use classes exhibit increases. The increases exhibited for the other classifications are 38% (Urban), 13% (Gully) 0.4% (Water), and 3.6% (Agriculture) according to pixel based classification, see **Table 12**. For the 41% reduction in vegetated land evident using OBIA classification over the study period, these classes account for increases of 31% (Urban), 10% (Gully), 0% (Water), 0% (Agriculture) **Table 13**. Both classification methods evidence the significant correlated increases of urban land cover and gully size.

Table 12: Pixel based Classification Result as Percentage of total area classified. Total area size =. 57,758.034km^2

	Classes	‘86	‘87	‘88	‘89	‘90	‘91	‘92	‘93	‘00	‘01	‘02	‘03
		%	%	%	%	%	%	%	%	%	%	%	%
1	Water	0.6	0.8	2	0.9	0.9	1	1	2.5	1	1	0.8	1
2	Vegetation	90	90	76	75	72	70	64	62	59	59	57	52
3	Agriculture	5.4	5.2	11	11	12	14	13	12.5	12	11	11.2	13
4	Urban-Lands	2	2	8	9	10.1	10	15	16	17	18	20	22
5	Gully/openland	2	2	3	4	5	5	7	7	11	11	11	12
		‘04	‘05	‘06	‘07	‘08	‘09	‘10	‘11	‘12	‘13	‘14	‘15
		%	%	%	%	%	%	%	%	%	%	%	%
1	Water	1	3	1	1	3	2	3	3	3	1	1	1
2	Vegetation	52	51	49	44	44	43	42	43	41	38	37	35
3	Agriculture	13	10	14	14	10	10	10	9	9	9	9	9
4	Urban-Lands	23	24	25	30	32	33	34	33	35	38	39	40
5	Gully/openland	11	12	11	11	11	12	11	12	12	14	14	15

Table 13: OBIA classification Result as percentage of total area classified. Total area size =57,758.034km^2

	Classes	‘86	‘87	‘88	‘89	‘90	‘91	‘92	‘93	’00	‘01	‘02	‘03
		%	%	%	%	%	%	%	%	%	%	%	%
1	Water	1	1	1	1	1	1	2	1	1	2	2	2
2	Vegetation	83	80	76	75	73	71	71	68	61	59	57	56
3	Agriculture	7	8	8	8	8	9	6	7	10	10	10	10
4	Urban-lands	5	6	9	10	11	12	14	16	19	21	23	24
5	Gully/openland	4	5	6	6	6	7	7	8	9	8	8	8
		‘04	‘05	‘06	‘07	‘08	‘09	‘10	‘11	‘12	‘13	‘14	‘15
		%	%	%	%	%	%	%	%	%	%	%	%
1	Water	2	2	2	2	2	2	2	2	2	2	1	1
2	Vegetation	54	50	50	48	48	47	46	46	46	44	44	42
3	Agriculture	9	9	9	9	8	8	8	8	7	7	7	7
4	Urban-lands	26	29	29	30	32	33	33	32	33	34	35	36
5	Gully/openland	9	10	10	11	10	10	11	12	12	13	13	14

5.3.1 Land-Cover Classification using ALOS PALSAR L-Band.

This section answers part of objective 1 above, tries to compare the classification results of Landsat image and ALOSPALSAR L-Band. In comparing the results of Landsat and ALOS PALSAR images of 2008 and 2009, they present similar trends with the exception of water class which increased when compared with Landsat images, **Table 14**. Also, showing that SAR differentiated water from other classes better than Landsat, may be because of the resolution which is higher than Landsat but more likely through the spectacular scattering resulting in zero backscatter to the SAR sensor. As stated in the methodology section, ALOSPALSAR data in the study area has an image resolution of 15m which is better than Landsat of 30m but was only available from 2007 while Landsat was available from 1986 for the study area. The ALOS PALSAR measurements of

2008 and 2009 where used to validate the Landsat measurements which leant more confidence to the classification approach. Differences between SAR and Landsat classifications at no point exceeded 5% which was recorded for the difference in vegetation classifications in the 2008 and 2009 data following the pixel approach. The OBIA method produced much more synergistic results. In the validation and laying more credence to this process, Accuracy Assessment Matrix for Landsat and ALOS 2008 Pixel Classification were carried out with 2008 Google Earth image, which gave 88% and 89% respectively **Table 15**. Also, Accuracy Assessment Matrix for Landsat and ALOS 2008 OBIA Classification gave 91% and 91% respectively **Table 16**. Again, t-Test for SAR and Landsat results show no statistical significant of the two values **Appendix IX, Table 97 and 100**.

Table 14: Comparison of Pixel and OBIA land cover classification of ALOS PALSAR and Landsat Images from 2008 and 2009 in terms of % of regional study area (57,758.034km2 total area) covered. Difference column shows difference % values. t-test is conducted with no significant differences detected, as expected given the use of % values.

		Pixel (%) (SAR)		Pixel (%) (Landsat)		Difference (%)	
	Classes	2008	2009	2008	2009	2008	2009
1	Water	4.5	5.0	3	2.5	1.5	2.5
2	Vegetation	48	48	44	43	4	5
3	Agriculture	5	6.0	10	10	-5	4
4	Urban-Lands	33	34	32	33	1	1
5	Gully/openland	9.5	8.5	11	11.5	-1.5	3
	P value					1	0.87
		OBIA (%) (SAR)		OBIA (%) (Landsat)		Difference (%)	
	Classes	2008	2009	2008	2009	2008	2009
1	Water	3	2	2	2	1	0
2	Vegetation	49	46	48	47	1	1
3	Agriculture	6	8	8	8	2	0
4	Urban-Lands	34	32	32	33	2	1
5	Gully/openland	8	12	10	10	2	2
	P value					1	1

Table 15: Accuracy Assessment Matrix for Landsat and ALOS 2008 Pixel Classification using 2008 imagery

2008 Google Earth Image						
2008 Landsat Pixel Class	Water	Vegetation	Agric	Urbanland	Gully/openland	Raw Total
Water	5	0	0	0	1	6
Vegetation	0	41	2	1	0	45
Agric	0	4	21	0	0	23
Urbanland	1	1	0	13	0	16
Gully/openland	0	0	1	1	8	10
Column Total	6	46	24	15	9	100
Overall Accuracy = 88/100 =88%						
2008 Google Earth Image						
2008 ALOS Pixel Class	Water	Vegetation	Agric	Urbanland	Gully/openland	Raw Total
Water	5	0	0	0	1	6
Vegetation	0	42	2	0	0	49
Agric	0	3	20	0	0	20
Urbanland	0	2	0	14	0	15
Gully/openland	1	0	1	1	8	10
Column Total	6	47	23	15	9	100
Overall Accuracy = 89/100 = 89%						

Table 16: : Accuracy Assessment Matrix for Landsat and ALOS 2008 OBIA Classification

2008 Google Earth Image						
2008 Landsat OBIA Class	Water	Vegetation	Agric	Urbanland	Gully/openland	Raw Total
Water	5	0	0	1	1	6
Vegetation	0	45	2	1	0	46
Agric	0	0	21	0	0	22
Urbanland	0	2	0	13	0	15
Gully/openland	0	0	1	1	7	10
Column Total	5	47	24	16	8	100
Overall Accuracy = 91/100 = 91%						
2008 Google Earth Image						
2008 ALOS OBIA Class	Water	Vegetation	Agric	Urbanland	Gully/openland	Raw Total
Water	5	0	0	0	1	6
Vegetation	0	45	1	1	0	49
Agric	0	2	19	0	0	20
Urbanland	0	2	0	14	0	15
Gully/openland	0	0	1	1	8	10
Column Total	5	49	21	16	9	100
Overall Accuracy = 91/100 =91%						

5.3.2 Gully/Open-land Classification

This section also fulfils part of objective 1 above, and looks at gully/open land as one of the classes in landcover classification. It is evident from the percentage changes that converse to the vegetation loss the Gully/open-land classification has followed a significant and steady increase in area covered over the same time period. According to pixel based classification (**Table 17 a**), the Gully/open-land class has increased from a proportionate land cover of 2% in 1986, to 15% in 2015 for Pixel, and 4% in 1986 to 14% in 2015 for OBIA classification. This represents an increase in area size of gully/open-lands of 13% and 10% for Pixel and OBIA classifications respectively over 30 years, see **Figure 59** (a) and (b). A mean increase of 11.5%.

The absolute values of area covered by the Gully/Openland class are shown in **Table 17** a) and b) for Pixel and OBIA classification respectively. According to the

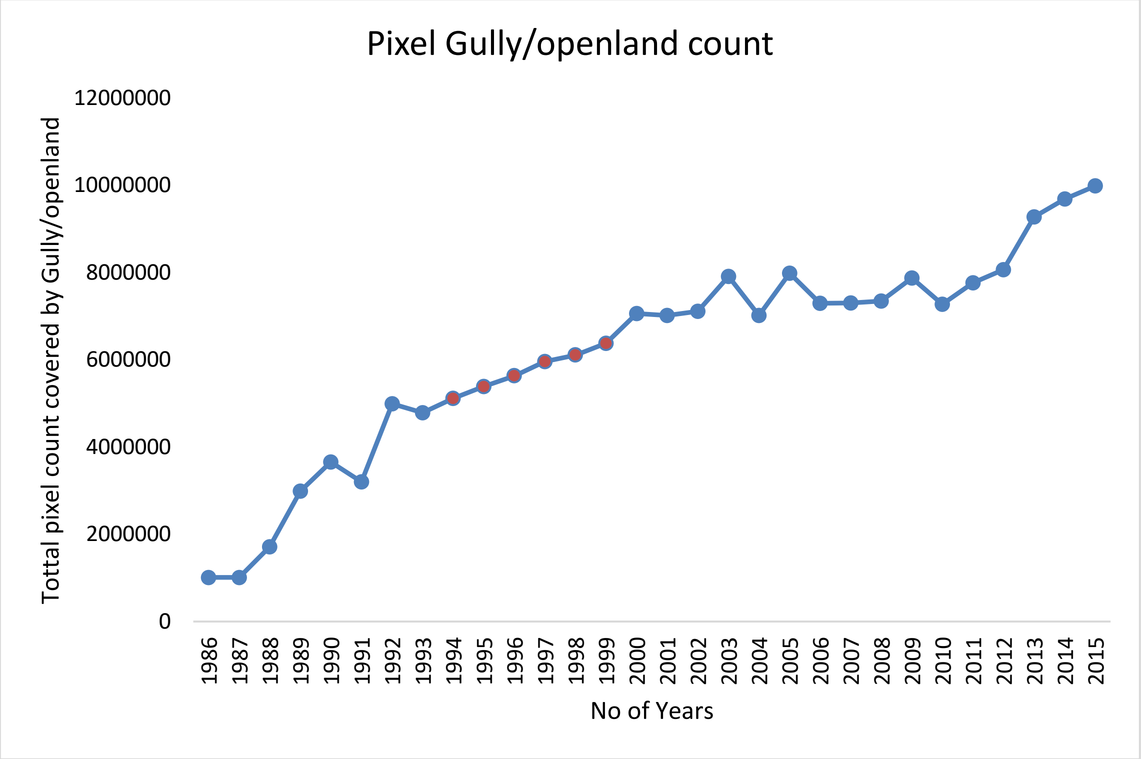
Pixel classification an increase of 8974257 pixel count is exhibited during the study period. This equates to a mean annual increase of 299141.9 per year across the region. For the OBIA classification the value is 214043.1 per year. Performing a simple two sample t test of difference between the two groups of data show that there is no significant difference between the two classification methods and their accounts of the gully/openland class ($p=<.05$).

Table 17: (a): Calculated Pixel classification based Area (pixel count) and % covered by Gully/Openland class from 1986-2015 (red = interpolated). (red = interpolated). Single pixel is equal to 900m^2 (57,758.034km^2 total area).

Years	Gully/openland pixel count	% of Area covered		Years	Gully/openland pixel count	% of Area covered
1986	1012176	2		2001	5616757	11
1987	1012176	2		2002	5417067	11
1988	1715029	3		2003	5741335	12
1989	2210168	4		2004	5017688	11
1990	2804669	5		2005	6389870	12
1991	3200445	5		2006	7296029	11
1992	3993673	7		2007	7423424	11
1993	4790330	7		2008	6301827	11
1994	4857860	7		2009	8024697	12
1995	4966274	7		2010	7999151	11
1996	5030673	8		2011	7367368	12
1997	5132196	8		2012	8064697	12
1998	5115838	8		2013	9276909	14
1999	5297842	8		2014	9686547	14
2000	5263041	11		2015	9986433	15

(b): Calculated OBIA classification based Area (pixel count) and % covered by Gully/Openland class from 1986-2015 (red = interpolated). Single pixel is equal to 900m^2 (57,758.034km^2 total area).

Years	Gully/openland pixel count	% of Area covered		Years	Gully/openland pixel count	% of Area covered
1986	2653360	4		2001	5344361	8
1987	3679894	5		2002	5567043	8
1988	3849040	6		2003	5938179	8
1989	4124799	6		2004	6012407	9
1990	4308708	6		2005	6680451	10
1991	4676316	7		2006	6682816	10
1992	4676526	7		2007	7348497	11
1993	5344361	8		2008	5344361	10
1994	5439796	8		2009	5344388	11
1995	5426162	8		2010	7279418	11
1996	5446288	8		2011	8016542	12
1997	5516558	8		2012	8016752	12
1998	5587394	8		2013	8684587	13
1999	5743545	9		2014	8999346	13
2000	6012406	9		2015	9074653	14



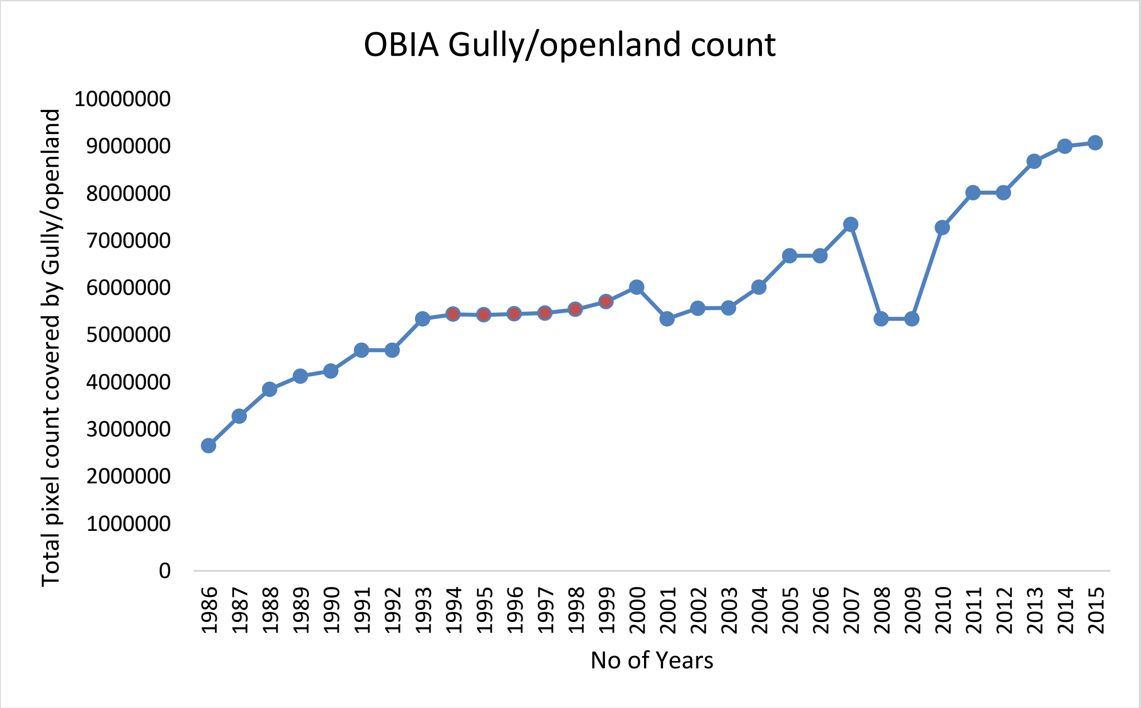


Figure 59: (Top) Pixel based (pixel count) change over time of Gully/open-land showing from 1986 to 2015 (observed images are in blue circle points while interpolated points are in red circle points). (b): (Bottom) OBIA Area changes over time of Gully/open-land. Pixel size is equivalent to 300m^2.

5.3.3 Correlation of Regional Land- Covers

This section is part of objective 1 above that looks at the correlation of regional land covers of the study area. The correlation between the pixel and OBIA count of vegetation, pixel and OBIA count of Gully/open-land development and Pixel and OBIA count of Urbanland is shown in **Table 18,** and therefore area of land-cover change is examined using Pearson's Correlation. The resulting coefficients for Vegetation against Gully/Openland are, Pixel based classification r= -0.971 ($p<0.01$) and OBIA classification r= -0.920 ($p<0.01$) indicating a very strong negative correlation, emphasising the reducing vegetation levels and the increase in Gully/open-land development. Pixel and OBIA vegetation versus pixel and OBIA urbanland classification are -0.976 ($p<0.01$) and -0.963 ($p<0.01$) respectively, equally showing very strong negative correlation. Pixel and OBIA gully/openland versus pixel and OBIA urbanland show 0.962 ($p<0.01$) and 0.887 ($p<0.01$) respectively showing very strong positive correlations, over the study period 1986-2015. This is a very simple test but signifies that according to the chosen classification process vegetation land cover reduction, predominantly through anthropological activities, correlates with increases in open lands and gully development. It is good to point out here that some of these open land could not revegetate because the land gets used by activities like mining, mineral exploration and exploitation, and sand excavation activities. These deteriorate the land and allow gullies to set-in (Chigbu et al. 2011; Aigbedion, and Iyay 2007).

Table 18: Correlation results when correlating pixel vegetation count, OBIA vegetation count, Pixel Gully/openland count, OBIA Gully/openland count, Pixel Urbanland count, OBIA Urbanland count for each year of study period

Correlations

		Pixel_Vegetation	OBIA_Vegetation	Pixel_Gullyopenland	OBIA_Gullyopenland	Pixel_Urbanland	OBIA_Urbanland
Pixel_Vegetation	Pearson Correlation	1	.981**	-.971**	-.892**	-.976**	-.996**
	Sig. (2-tailed)		.000	.000	.000	.000	.000
	N	30	30	30	30	30	30
OBIA_Vegetation	Pearson Correlation	.981**	1	-.965**	-.920**	-.973**	-.963**
	Sig. (2-tailed)	.000		.000	.000	.000	.000
	N	30	30	30	30	30	30
Pixel_Gullyopenland	Pearson Correlation	-.971**	-.965**	1	.897**	.962**	.962**
	Sig. (2-tailed)	.000	.000		.000	.000	.000
	N	30	30	30	30	30	30
OBIA_Gullyopenland	Pearson Correlation	-.892**	-.920**	.897**	1	.887**	.887**
	Sig. (2-tailed)	.000	.000	.000		.000	.000
	N	30	30	30	30	30	30
Pixel_Urbanland	Pearson Correlation	-.996**	-.973**	.962**	.887**	1	1.000**
	Sig. (2-tailed)	.000	.000	.000	.000		.000
	N	30	30	30	30	30	30
OBIA_Urbanland	Pearson Correlation	-.976**	-.973**	.962**	.887**	1.000**	1
	Sig. (2-tailed)	.000	.000	.000	.000	.000	
	N	30	30	30	30	30	30

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

Similar correlation analyses with the other 2 classes showed that the resulting correlation between Vegetation and Urban-land were r= -0.9 and r= -0.9 for Pixel and OBIA classification respectively. Values of r= -0.9 and r= -0.2 for pixel and OBIA classification respectively show a very strong negative correlation and a weak negative correlation respectively between Agriculture land increase and vegetation loss. The difference between the two values could be the different ways OBIA and pixel do classification, it could be that some of the vegetation area that were classified as Agric land in pixel, while OBIA separated it and placed it under agric land. This could be through pixel grouping and homogeneity of a region (Blaschke 2014).

5.3.4 Local Correlation Analyses

This section is also part of objective 1 above which looks at the correlation of local land covers of the study area. In order to determine the correlation between gully expansion and land-cover changes over time, further correlation was performed with respect to each of the studied gullies. Correlation was conducted in terms of the landcover changes regionally and then locally with respect to the increasing gully size. The validity of the use of the Pearson correlation test is examined using the Shapiro-Wilk normality test with results presented in **Table 19**. As evidenced, a significant amount of the data is considered non normal at the 90% confidence level. **Table 20** presents the results of correlation testing using the nonparametric Spearman's Rank test (Ornstein and Lyhagen 2016). Each specific gully is correlated in terms of the surface area of the gully (m^2) in each year against the increasing or decreasing levels of vegetated or urban landcovers across the study region. Results are determined for both classification methods. **Table 21** then presents an analysis of the correlations seen within a 10km x 10km local vicinity to each gully. This is done to be specific about the contribution of local vegetation loss and urban land increases on the local scale and to see how far the local trends depart from the regional findings.

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Table 19: Shapiro-Wilk test was used to test for normality for each variable and gully associated area across the study period (p>0.05 indicates normality).

	Data	Shapiro-Wilk test result	Normality
1.	Pixel-Vegetation	.023	Non-normal
2	OBIA-Vege	.094	Normal
3	GullyOpenland	.041	Non-normal
4	PixelUrban	.332	Normal
5	OBIAUrban	.174	Normal
6	Rainfall Data	.002	Non-Normal
7	Iyioku	.056	Normal
8	Okigwe	.061	Normal
9	Njaba	.192	Normal
10	Igboukwu	.371	Normal
11	Orlu	.824	Normal
12	Isinweke	.788	Normal
13	Amucha	.992	Normal
14	Nekede	.660	Normal
15	Ngwo1	.608	Normal
16	Ngwo2	.088	Normal
17	Oguta	.029	Non-normal
18	Umuahia	.497	Normal
19	Urualla	.402	Normal
20	Nawfia	.190	Normal

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Table 20: Correlation results when correlating gully area with regional values of vegetation and urban areas for both Pixel and OBIA classifications. All statistics are Pearson correlation unless Spearman is indicated.

		PiXel_Vege	OBIA_Vege	Pixel Urban	OBIA_Urban	Rainfall Data
1.	IyiokuGully	Spearman				Spearman
	Correlation	-.720**	-.785**	.848**	.814**	.455*
	Sig. (2-tailed)	.000	.000	.000	.000	.012
	N	30	30	30	30	30
2.	OkigweGully	Spearman				Spearman
	Correlation	-.938**	-.988**	.983**	.992**	.475**
	Sig. (2-tailed)	.000	.000	.000	.000	.008
	N	30	30	30	30	30
3.	NjabaGully	Spearman				Spearman
	Correlation	-.960**	-.971**	.987**	.978**	.466**
	Sig. (2-tailed)	.000	.000	.000	.000	.009
	N	30	30	30	30	30
4.	IgboukwuGully	Spearman				Spearman
	Correlation	-.962**	-.968**	.988**	.976**	.468**
	Sig. (2-tailed)	.000	.000	.000	.000	.009
	N	30	30	30	30	30
5.	OrluGully	Spearman				Spearman
	Correlation	-.728*	-.741*	.925**	.937**	.770**
	Sig. (2-tailed)	.017	.014	.000	.000	.009
	N	10	10	10	10	10
6.	IsinwekeGully	Spearman				Spearman
	Correlation	-.974**	-.974**	.959**	.973**	.799**
	Sig. (2-tailed)	.000	.000	.000	.000	.006
	N	10	10	10	10	10
7.	Amucha2Gully	Spearman's				Spearman
	Correation	-.960**	-.975**	.823**	.919**	.741*
	Sig. (2-tailed)	.000	.000	.003	.000	.014
	N	10	10	10	10	10
8.	NekedeGully	Spearman				Spearman
	Correlation	-.960**	-.964**	.969**	.957**	.792**
	Sig. (2-tailed)	.000	.000	.000	.000	.006
	N	10	10	10	10	10

9	Ngwo1Gully	Spearman				Spearman
	Correlation	-.988**	-.894**	.836**	.945**	.830**
	Sig. (2-tailed)	.000	.000	.003	.000	.003
	N	10	10	10	10	10
10	Ngwo2Gully	Spearman				
	Correlation	-.917**	-.939**	.919**	-.103	.762*
	Sig. (2-tailed)	.000	.000	.000	.777	.010
	N	10	10	10	10	10
11	OgutaGully	Spearman				
	Correlation	.717*	-.705*	-.681*	-.697*	.509
	Sig. (2-tailed)	.020	.023	.030	.025	.133
	N	10	10	10	10	10
12	Umuahia2Gully	Spearman				Spearman
	Correlation	-.968**	-.977**	.954**	.968**	.758*
	Sig. (2-tailed)	.000	.000	.000	.000	.011
	N	10	10	10	10	10
13	Urualla Gully	Spearman				
	Correlation	-.949**	-.948**	.948**	.964**	.707*
	Sig. (2-tailed)	.000	.000	.000	.000	.022
	N	10	10	10	10	10
14	Nawfia Gully	Spearman				
	Correlation	-.937**	-.781**	.733*	.856**	.750*
	Sig. (2-tailed)	.000	.008	.016	.002	.013
	N	10	10	10	10	10

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

Table 21: Correlations between Pixel Vegetation and OBIA vegetation seen within a 10km x 10km local vicinity to each gully

		10km × 10km Pixel Vege	10km × 10km OBIA Vege
1	Iyioku Gully		
	Pearson Correlation	-.760**	-.840**
	Sig. (2-tailed)	.000	.000
	N	30	30
2	Okigwe Gully		
	Pearson Correlation	-.984**	-.994**
	Sig. (2-tailed)	.000	.000
	N	30	30
3	Njaba Gully		
	Pearson Correlation	-.988**	-.971**
	Sig. (2-tailed)	.000	.000
	N	30	30
4	Igboukwu Gully		
	Pearson Correlation	-.991**	-.980**
	Sig. (2-tailed)	.000	.000
	N	30	30
5	OrluGully		
	Pearson Correlation	-.990**	-.918**
	Sig. (2-tailed)	.000	.000
	N	10	10
6	Isinweke		
	Pearson Correlation	-.978**	-.924**
	Sig. (2-tailed)	.000	.000
	N	10	10
7	Amucha2		
	Pearson Correlation	-.698*	-.781**
	Sig. (2-tailed)	.025	.008
	N	10	10
8	Nekede		
	Pearson Correlation	-.855**	-.875**
	Sig. (2-tailed)	.002	.002
	N	10	10
9	Ngwo1		
	Pearson Correlation	-.989**	-.980**
	Sig. (2-tailed)	.000	.000
	N	10	10

10	Ngwo2		
	Pearson Correlation	-.911**	-.933**
	Sig. (2-tailed)	.000	.000
	N	10	10
11	Oguta		
	Pearson Correlation	.798**	.808**
	Sig. (2-tailed)	.006	.005
	N	10	10
12	Umuahia		
	Pearson Correlation	-.986**	-.985**
	Sig. (2-tailed)	.000	.000
	N	10	10
13	Urualla		
	Pearson Correlation	-.726*	-.789**
	Sig. (2-tailed)	.017	.007
	N	10	10
14	Nawfia		
	Pearson Correlation	-.839**	-.791**
	Sig. (2-tailed)	.002	.006
	N	10	10

Figure 60 presents the correlation coefficients between the areas of each of the numbered gully sites over the course of the study period and the areas covered by the 4 classifications Pixel Veg, OBIA Veg, Pixel Urban, and OBIA Urban on the regional scale. Data is also shown to exhibit the correlation with the rainfall data. **Figure 61** shows the local data; 10km x 10km area surrounding the gully.

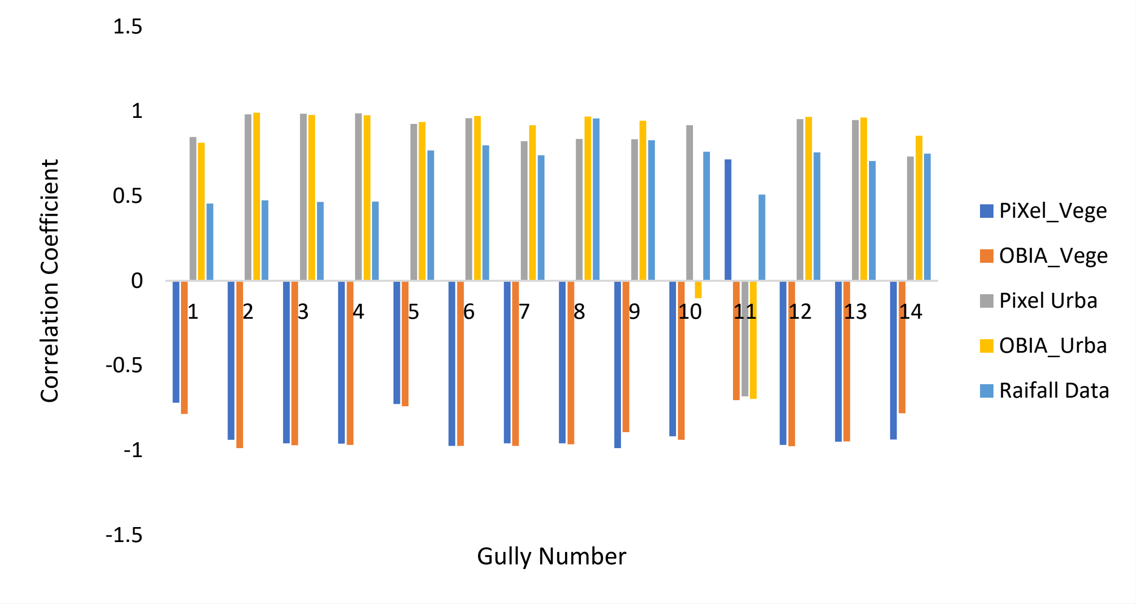


Figure 60: Correlation coefficients of independent variables on the regional scale against individual gully sizes (m2) during the period 1986-2015 with the regional classified areas of vegetation and urban using Pixel and Object based classification methods. Refer to Table 20 for specific gully names associated with the presented numbers, and detailed values. Rainfall correlations also shown as regional collection. Data includes gully interpolated values for the years 1994 to 1999.

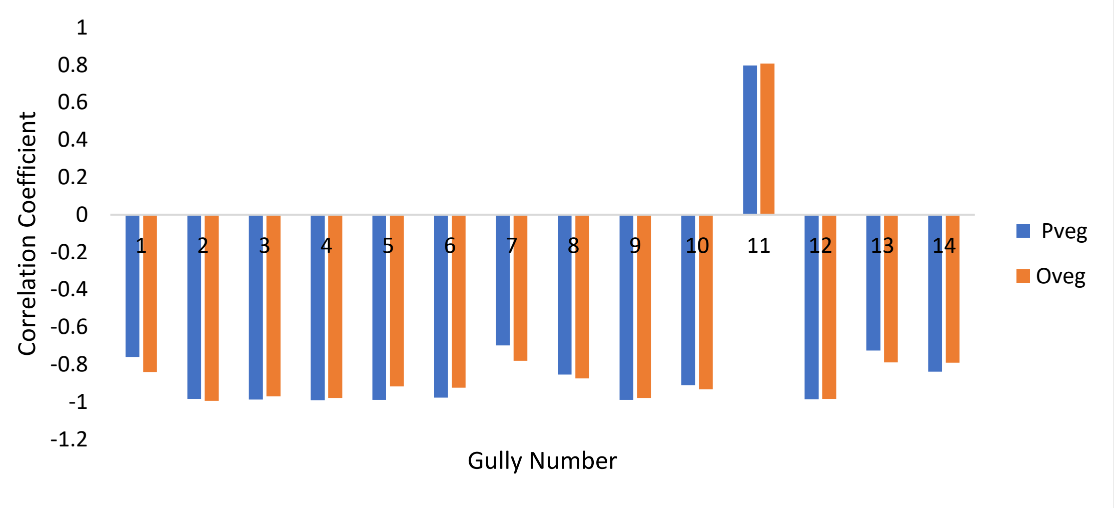


Figure 61: Correlation coefficients between independent variables of pixel and object based vegetation areas against gully sizes (m2) during the period 1986-2015 using the local (10km x 10km) classified areas of vegetation area. Refer to **Table 21** for specific gully names associated with the presented numbers, and detailed values. Data includes linearly interpolated values for the years 1994 – 1999.

Correlation was used to test the relationship between the gully test site's development in terms of area in m^2 with vegetation and urban classification pixel count values in m^2. Consulting the regional correlation coefficients for pixel based classification, shown in **Figure 60**, almost all gullies report a very strong negative correlation between vegetation area and gully area. Values are shown in the range r= (-.717) to (-0.984) except gullies11 (Oguta) for pixel vegetation.

The OBIA based classification equally shows that the majority of gullies exhibit a strong negative correlation between gully area and vegetation area, exhibiting a range of r = (-0.705) to (-0.994). The majority of the studied gullies have a strong positive correlation with urban land area with negative correlations exhibited at Oguta (Gully 11) with -0.68 and -0.69 for pixel urban and OBIA urban respectively and also at gullies 10 (Ngwo2). These gullies and their exhibited anomalies will be discussed further in the Discussion, **Section 6**. The range of positive correlations between gully area and OBIA classified urban lands ranges from r=0.71 to 0.1 indicating very strong and significant correlations. Although much weaker correlations are exhibited, each gully, aside from Gully 11 (Oguta), offers a positive correlation between gully size and level of rainfall. Although not identifying causation there is a clear correlatory relationship with the regional measurement of the environmental variable. Although a positive correlation is shown in all the gully sizes and rainfall data, it is not a significant correlation at the 95% confidence level and must be viewed with caution.

Table 21 and Figure 61 show the analysis of correlation between the area of land-cover locally (10km x 10km vicinity) and the specific gully area. Again both measured in m^2. The range of negative correlations between gully area, r= -0.698 to -0.991 again except gully 11 (Oguta). This highlights that the correlations and general trends exhibited on a regional level are common at the local scale.

For the OBIA correlation analysis, at the local scale, results reveal that again the majority report strong and significant negative correlations of between r= -0.781and -0.985 except gully 11 (Oguta). **All the 14 gullies exhibited** a positive correlation coefficient with rainfall data over the 30 years' period.

5.4 Focussed Analysis of 14 Gullies; Area and % Change

This section answers objective 2 “Vectorise and quantify gully extent and rates of change of gully sites over identified life spans. Gullies chosen using remote sensing data according to associated severity and level of management”. This section tries to assess the 14 gully areas and their % change from 1986 – 2015 for older gullies and 2006 – 2015 for younger gullies respectively. The gully areas and % change graphs show how the gullies have been changing over the years. The older gullies Iyioku, Okigwe, Njaba and Igboukwu are shown in **Figures 62, 63, 64, and 65** respectively. They show that their development precedes 1986 but also, aside from Iyioku, that along the way gully % rate of change has been reducing. In gullies like Iyioku where in 2014 the % change is high, it could be attributed to meteorological changes. This is discussed thoroughly in **Section 6.6.** Linearly interpolated values are used throughout to account for the years 1994 – 1999, representing years of non-availability of Landsat imagery.

The more recently formed gullies of Orlu, Isinweke, Amucha, Nekede, Ngwo1, Urualla, Nawfia, Ngwo2, Oguta and Umuahia are shown in **Figures 66 - 75**. All of the displayed gullies are showing positive relationships between time and gully size although the proportional change each year is changeable. This is later discussed in **section 6.6** Each figure below is featured with the linear regression of area against years displayed. All show a positive trend between these variables with the lowest R^2 value being 0.404. In general the R^2 values exceed 0.7. The trend of the proportional change is much less predictable with both positive and negative trends common but with no gully exceeding an R^2 value of 0.30 **Table 22**. What is then apparent is that gullies are growing in general every year but the proportional change year on year is highly variable.

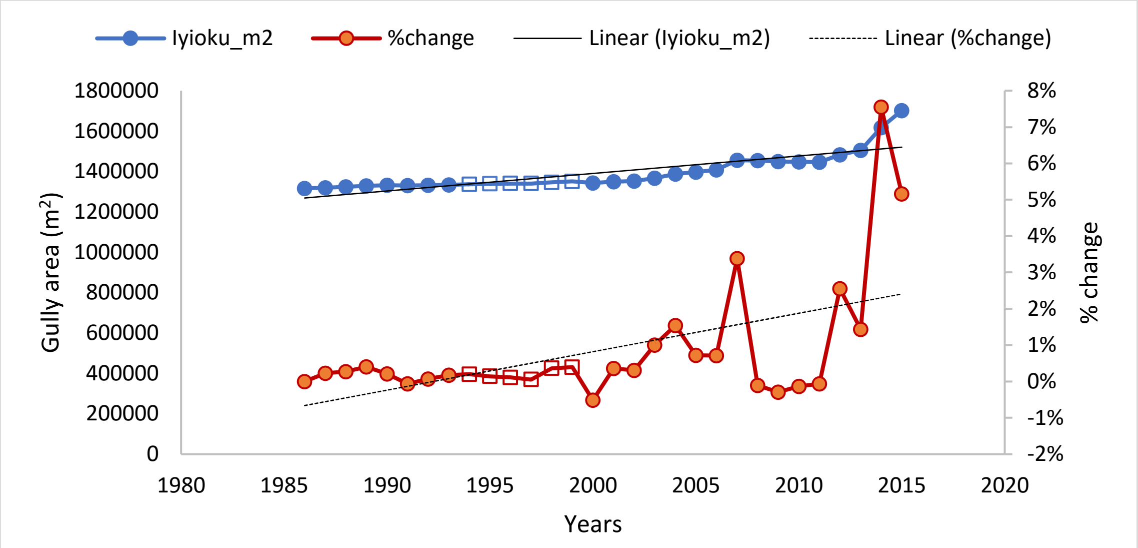


Figure 62: Iyioku Gully area and % change graph showing from 1986 – 2015 including interpolated values in white point. (Observed gully are in circle points while interpolated gully is in square points).

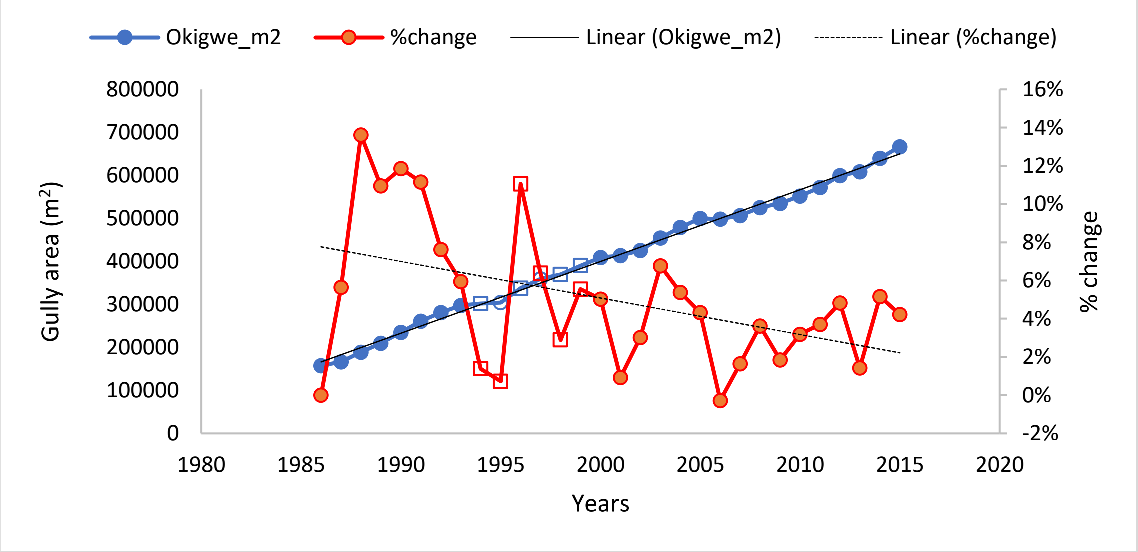


Figure 63: Okigwe Gully area and % change graph showing from 1986 – 2015 including interpolated values in square point. (Observed gully are in circle points while interpolated gully is in square points).

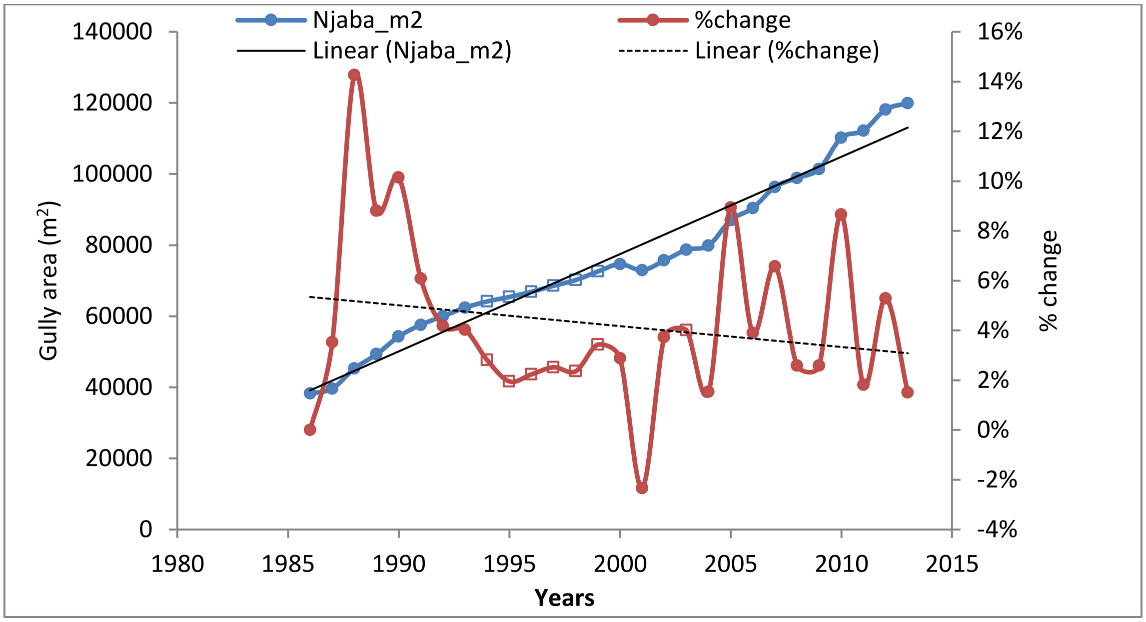


Figure 64: Njaba Gully area and % change graph showing from 1986 – 2015. Observed gully are in circle points while interpolated gully is in square points.

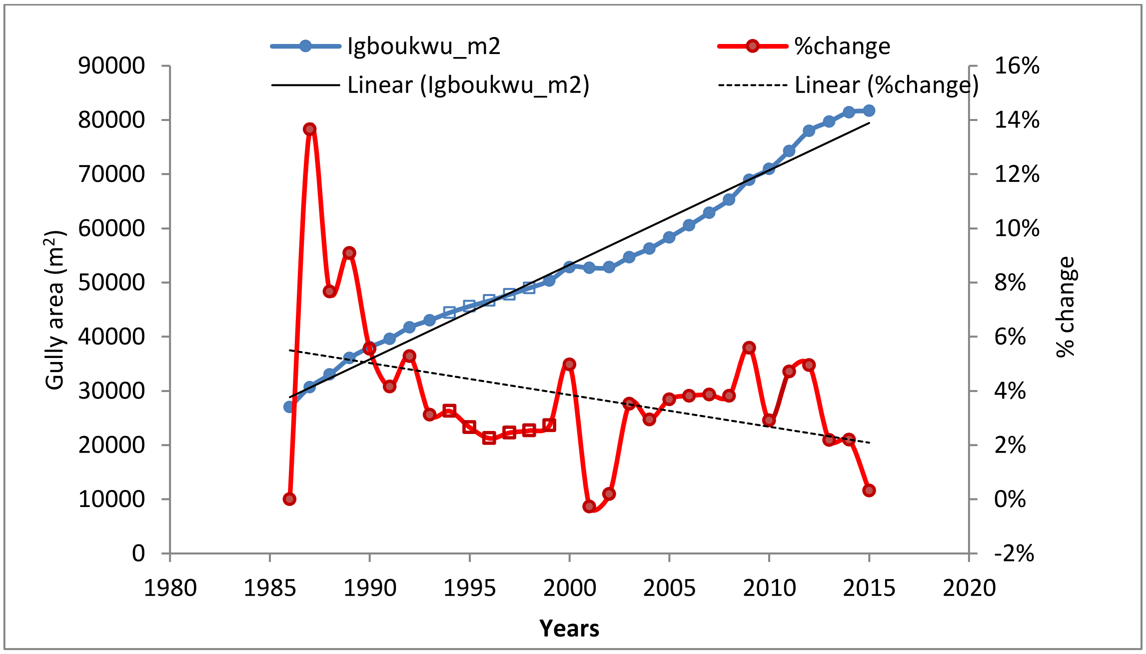


Figure 65: Igboukwu Gully area and % change graph showing from 1986 – 2015. Observed gully are in circle points while interpolated gully is in square points.

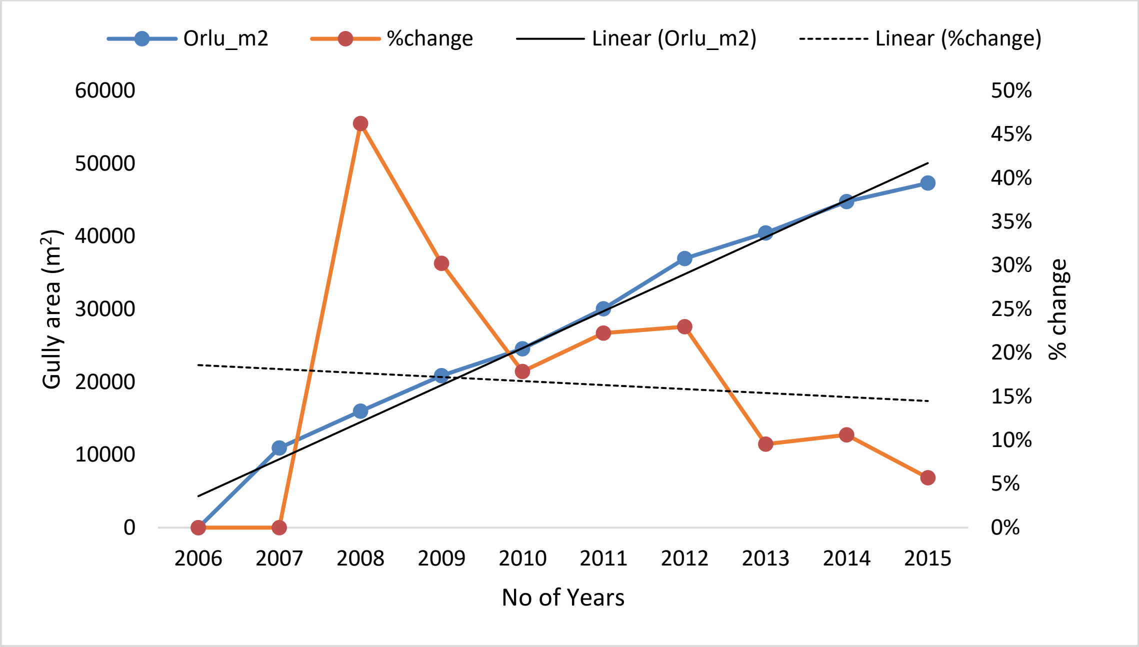


Figure 66: Orlu Gully area and % change graph showing from 2006 – 2015

Figure 67: Isinweke Gully area and % change graph showing from 2006 – 2015

Figure 68: Amucha Gully area and % change graph showing from 2006 – 2015

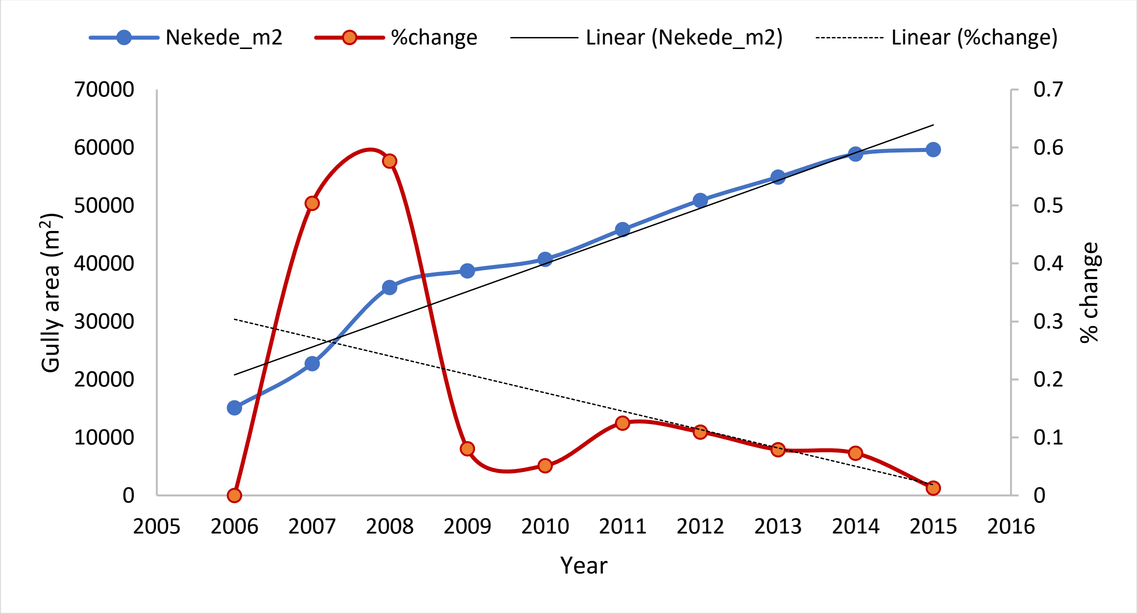


Figure 69: Nekede Gully area and % change graph showing from 2006 – 2015

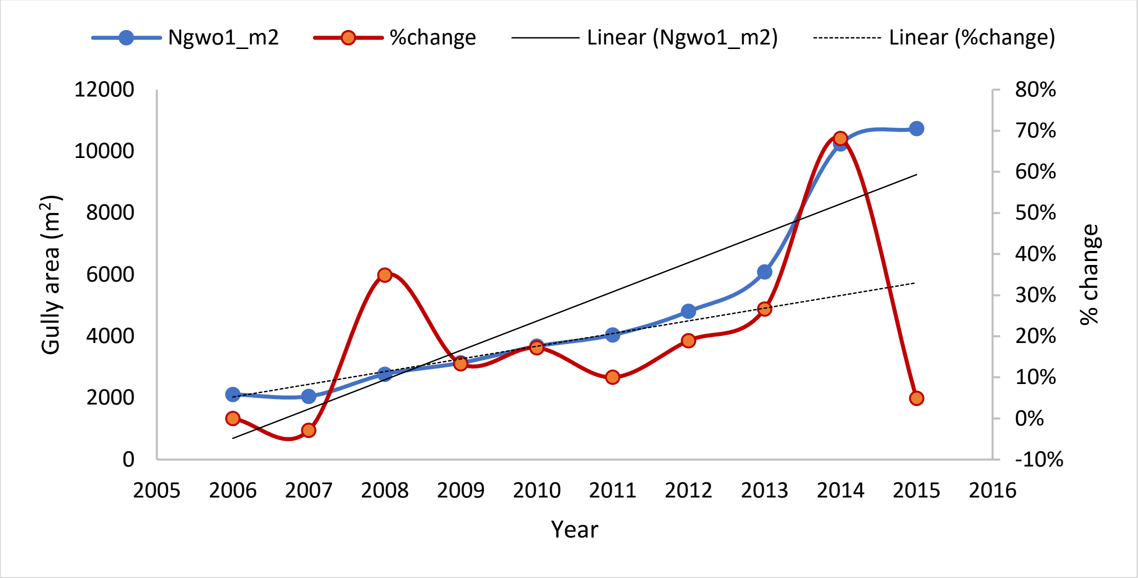


Figure 70: Ngwo1 Gully area and % change graph showing from 2006 – 2015

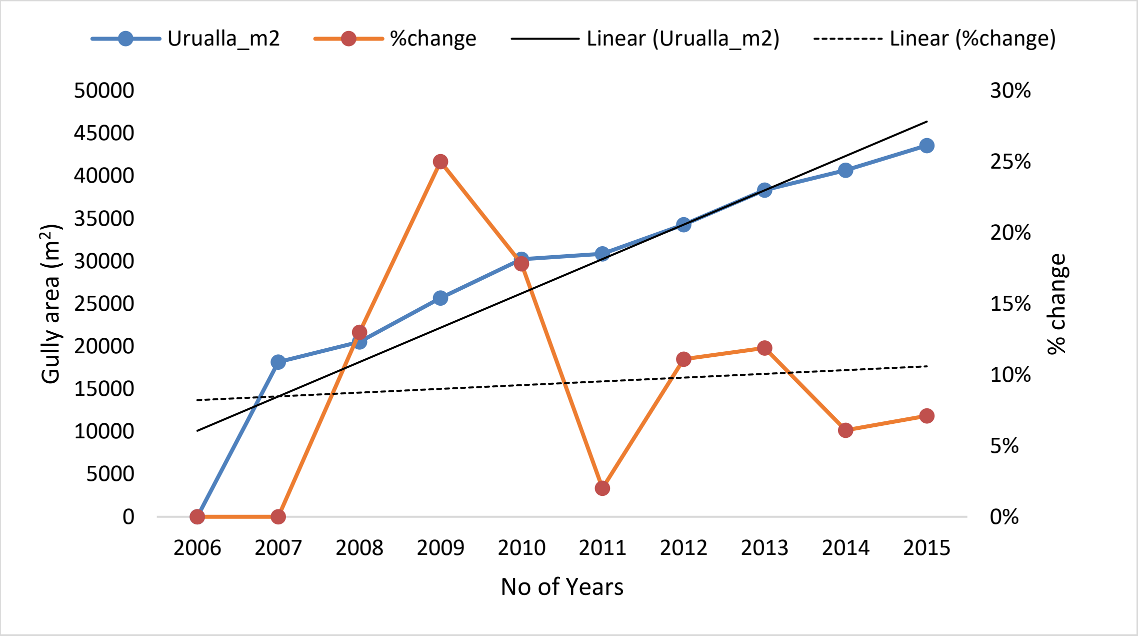


Figure 71: Urualla Gully area and % change graph showing from 2006 – 2015

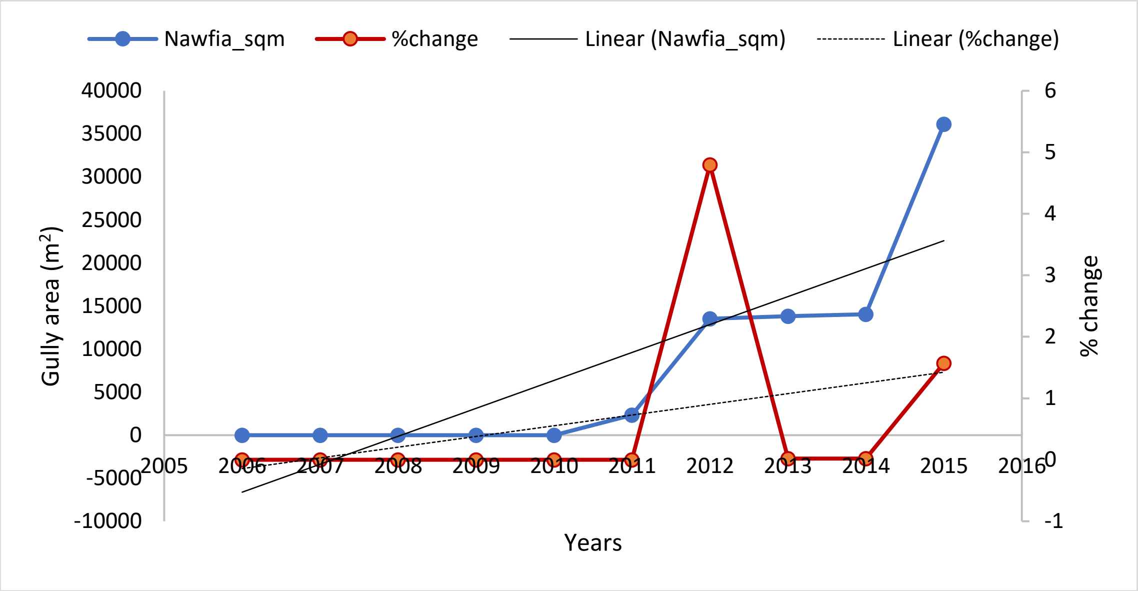


Figure 72: : Nawfia Gully area and % change graph showing from 2006 – 2015

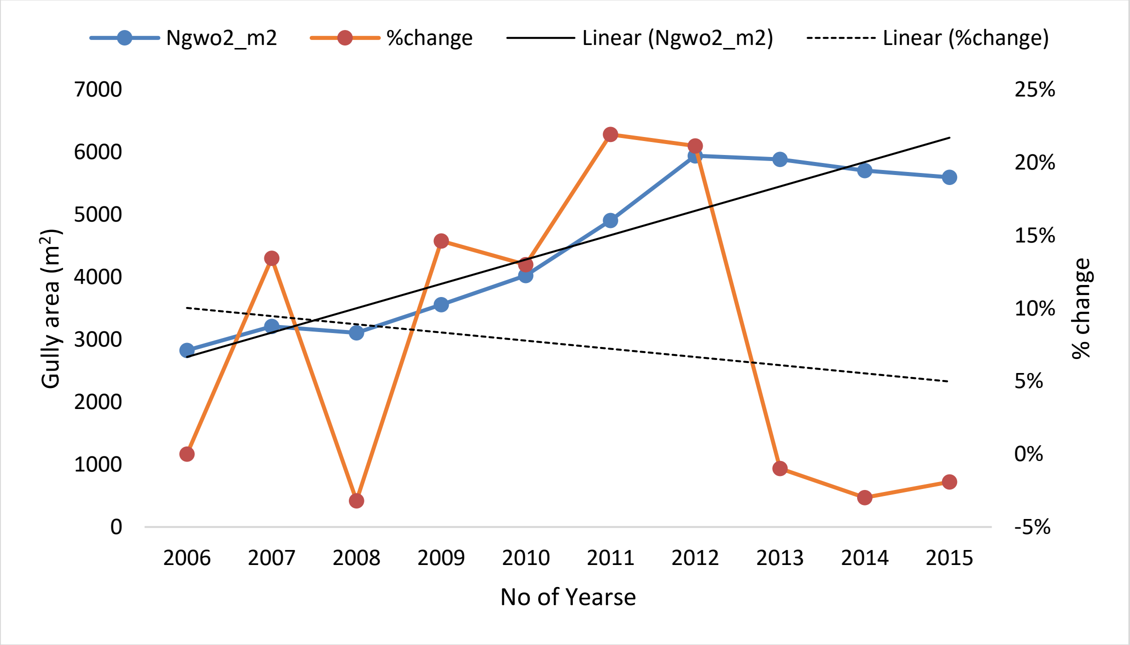


Figure 73: Ngwo2 Gully area and % change graph showing from 2006 – 2015

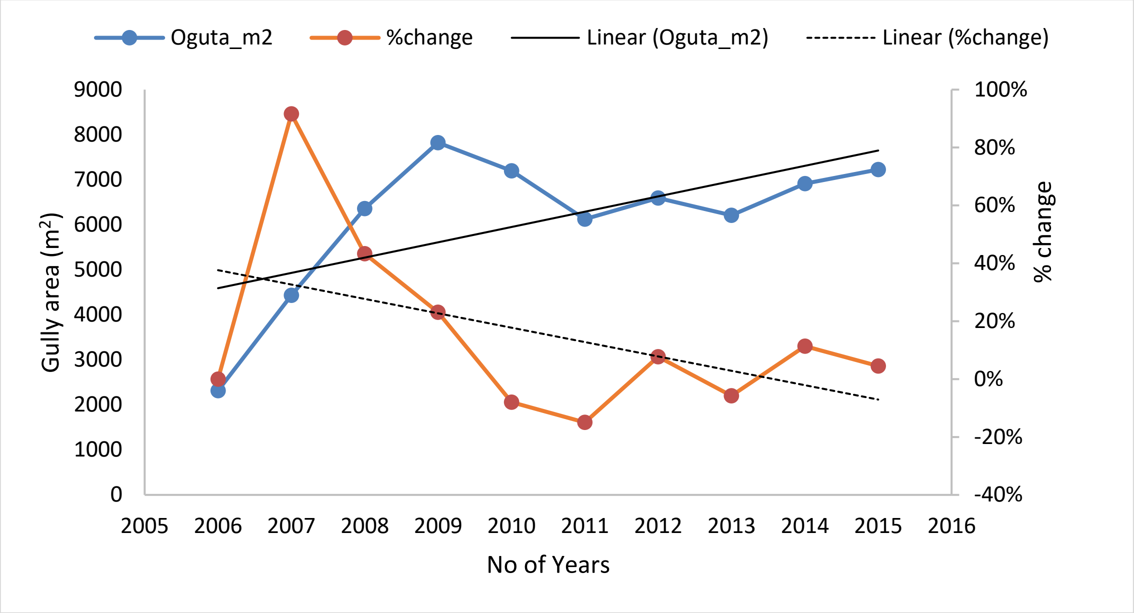


Figure 74: Oguta Gully area and % change graph showing from 2006 – 2015

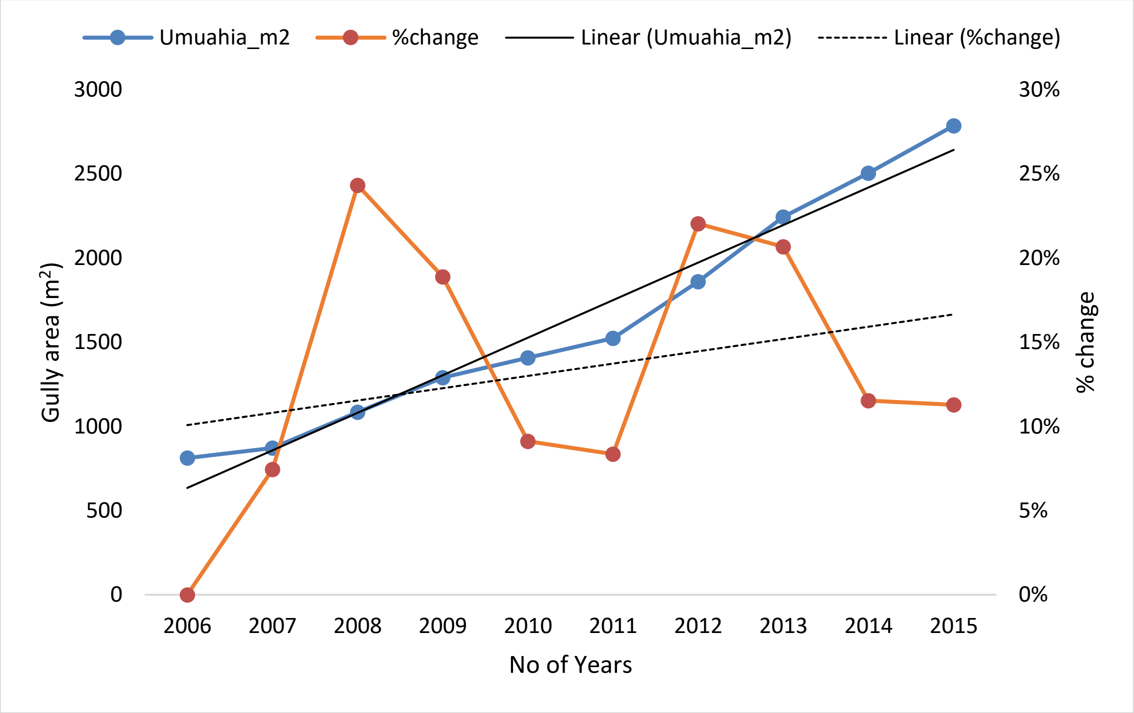


Figure 75: Umuahia Gully area and % change graph showing from 2006 – 2015

Table 22: R square values and Trend line values for gully areas and % change

	Gully Name	Trend line and R square equation (Gully area)	Trend line and R square equation (% change of the gully)
1	Iyioku	$y = 8676x - 2E+07$ $R^2 = 0.7023$	$y = 0.0011x - 2.1086$ $R^2 = 0.2907$
2	Okigwe	$y = 16682x - 3E+07$ $R^2 = 0.995$	$y = -0.0019x + 3.8743$ $R^2 = 0.2073$
3	Njaba	$y = 2737.5x - 5E+06$ $R^2 = 0.9627$	$y = -0.0008x + 1.7162$ $R^2 = 0.0405$
4	Igboukwu	$y = 1745.1x - 3E+06$ $R^2 = 0.9759$	$y = -0.0012x + 2.3903$ $R^2 = 0.1387$
5	Orlu	$y = 5080.6x - 760.58$ $R^2 = 0.9827$	$y = -0.0046x + 0.1905$ $R^2 = 0.0091$
6	Isinweke	$y = 690.76x + 2878.1$ $R^2 = 0.9853$	$y = 0.0036x + 0.0842$ $R^2 = 0.033$
7	Amucha	$y = 874.05x + 138.16$ $R^2 = 0.9714$	$y = 0.0091x + 0.0853$ $R^2 = 0.0993$
8	Nekede	$y = 4788.9x - 1E+07$ $R^2 = 0.9472$	$y = -0.0317x + 63.877$ $R^2 = 0.2209$
9	Ngwo1	$y = 950.71x - 2E+06$ $R^2 = 0.8317$	$y = 0.0309x - 61.88$ $R^2 = 0.2027$
10	Urualla	$y = 4031.2x + 6058.4$ $R^2 = 0.8915$	$y = 0.0026x + 0.0795$ $R^2 = 0.0099$
11	Nawfia	$y = 3245.4x - 7E+06$ $R^2 = 0.6986$	$y = 0.1742x - 349.53$ $R^2 = 0.1171$
12	Ngwo2	$y = 390.02x + 2331.9$ $R^2 = 0.8752$	$y = -0.0056x + 0.1059$ $R^2 = 0.0273$
13	Oguta	$y = 339.75x - 676939$ $R^2 = 0.4048$	$y = -0.0497x + 99.997$ $R^2 = 0.2263$
14	Umuahia	$y = 223.02x + 411.35$ $R^2 = 0.967$	$y = 0.0073x + 0.0934$ $R^2 = 0.081$

5.4.1 The Graph of Gully Area % Change and Rainfall Pattern in mm

This is one of the sections that answers part of objective 2 above, it tries to find out if there are changes in individual gullies with rainfall pattern of the study area. Igwe (2005), identified the influence of climate as one of the contributing factors. Obi (1995);. Greenland (1998); Eze (2000) and Udoh (2002) also identified rainfall as the major environmental cause of gully erosion, in southeast Nigeria.

The gully % change and rainfall data graphs (**Figures 75 - 88**) show the influence of rainfall in gully % change. The older gullies Iyioku, Okigwe, Njaba and Igboukwu were graphed and compared with rainfall data from 1986 to 2015 **Figures 76, 77, 78 and 79** respectively. The relationship is discussed in discussion **section 6.8.1.** The gullies of Orlu, Isinweke, Amucha, Nekede, Ngwo1, Urualla, Nawfia, Ngwo2, Oguta and Umuahia, **Figures 80– 89** were compared with rainfall data from 2006 to 2015; also discussed in **section 6.8.1**. The rainfall level is collected on a regional scale and is not specific to the individual gullies. This is a consequence of a limited weather station network in the study region. From **figure 76**, as an example, it can be seen that a weak positive trend is evident with a correlation of ~0.5 between the rainfall and years which indicates the increasing level of rainfall with subsequent years. For the Iyioku gully a very similar correlation is seen for both the gully % change and the rainfall against time. Although an interesting trend, this behavior is not replicated for the other studied gullies, particularly where the % change is decreasing year on year.

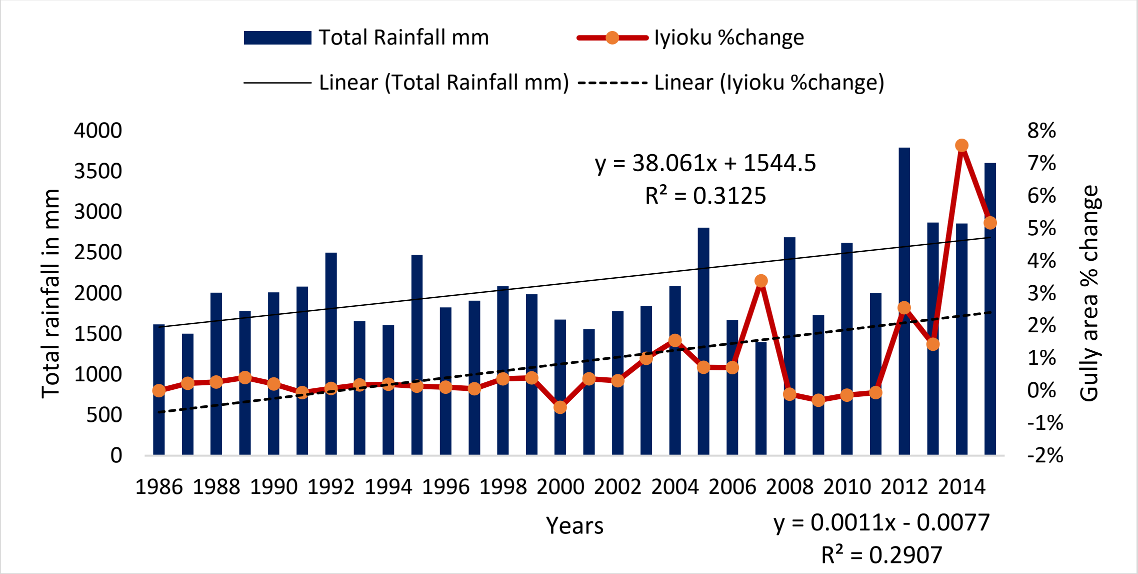


Figure 76: The Graph of Iyioku gully area % change and Total Rainfall pattern in mm from 1986 - 2015

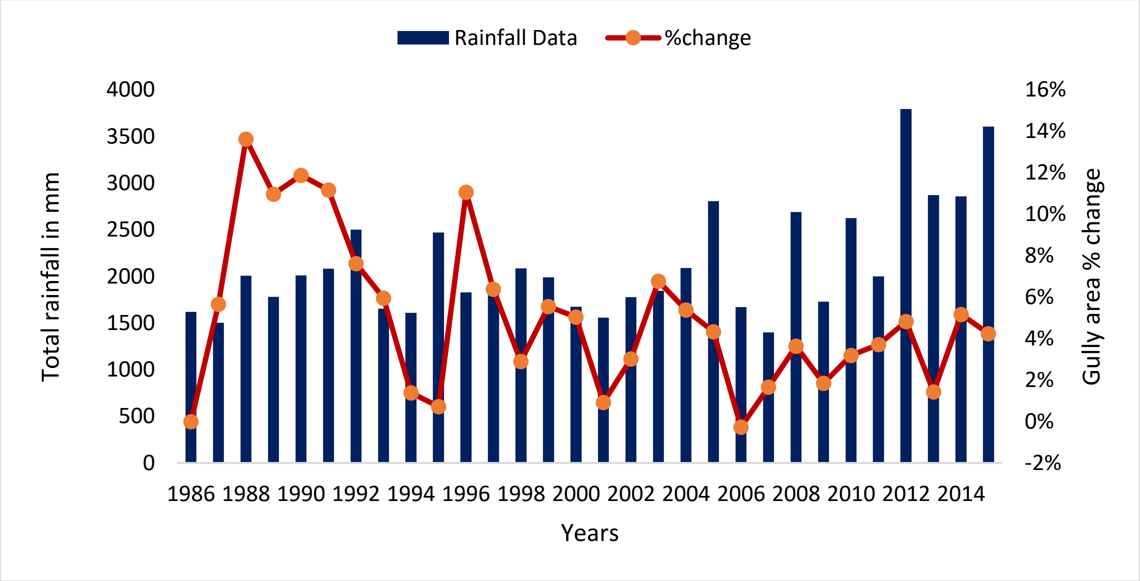


Figure 77: The Graph of Okigwe gully area % change and total Rainfall pattern in mm from 1986 – 2015

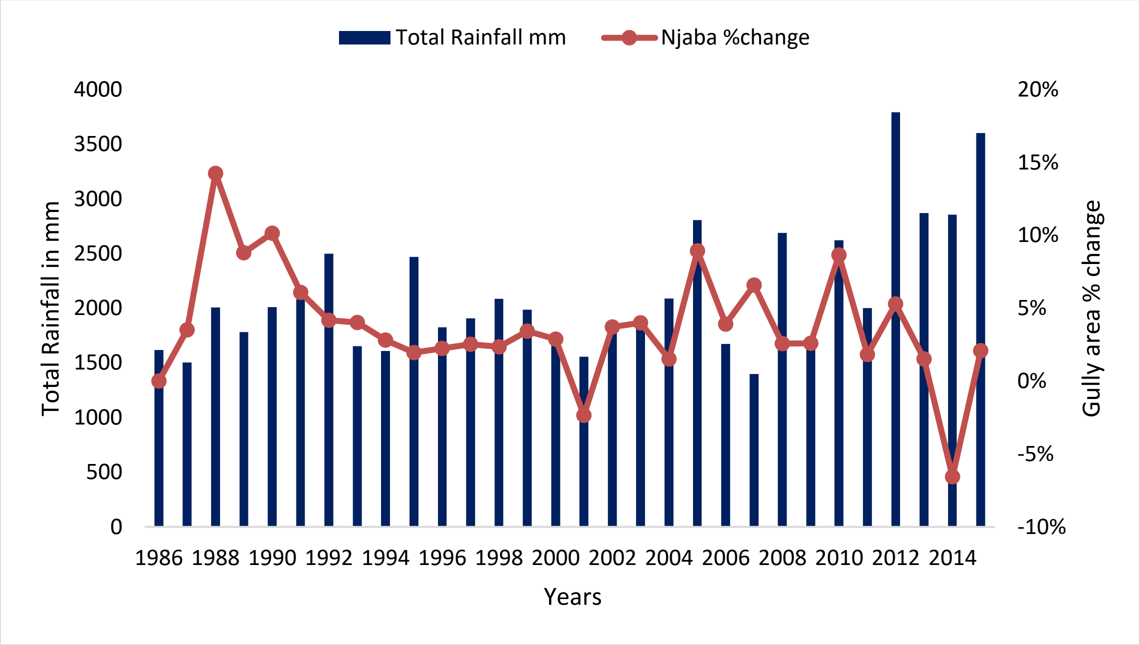


Figure 78: The Graph of Njaba gully area % change and total Rainfall pattern in mm from 1986 - 2015

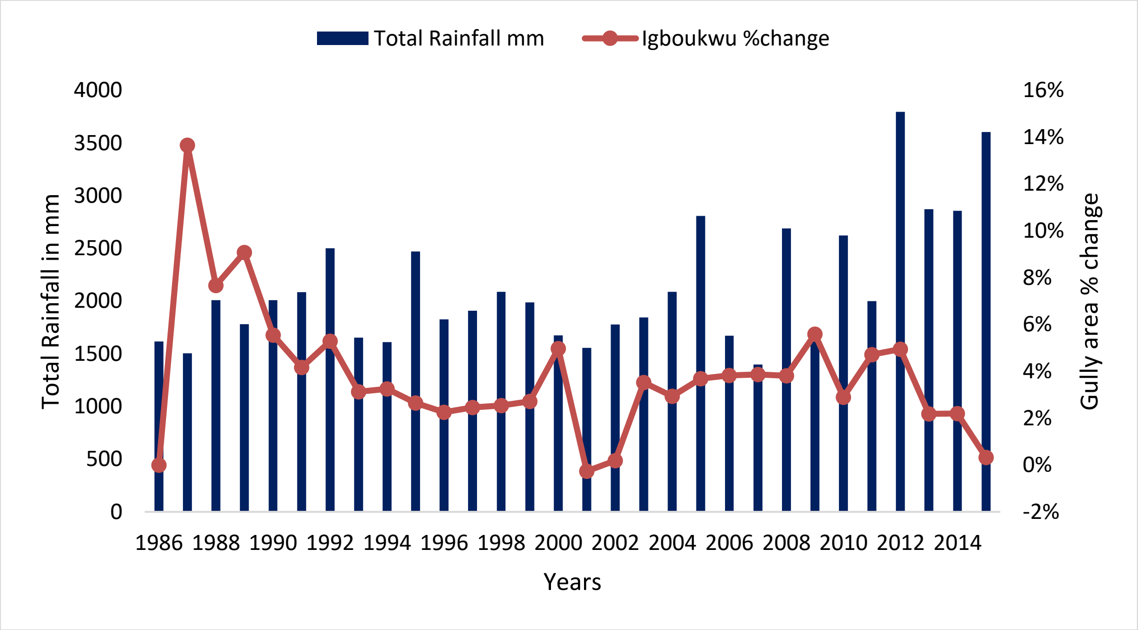


Figure 79: The Graph of Igboukwu gully area % change and Rainfall pattern in mm from 1986 – 2015

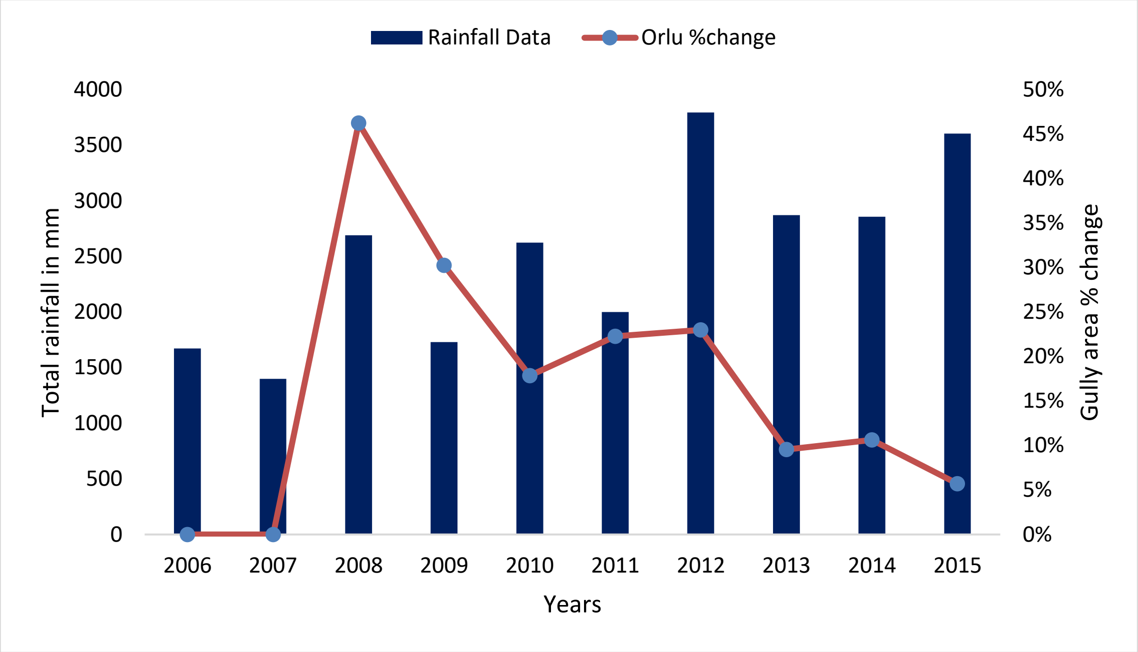


Figure 80: The Graph of Orlu gully area % change and Rainfall pattern in mm from 2006 – 2015

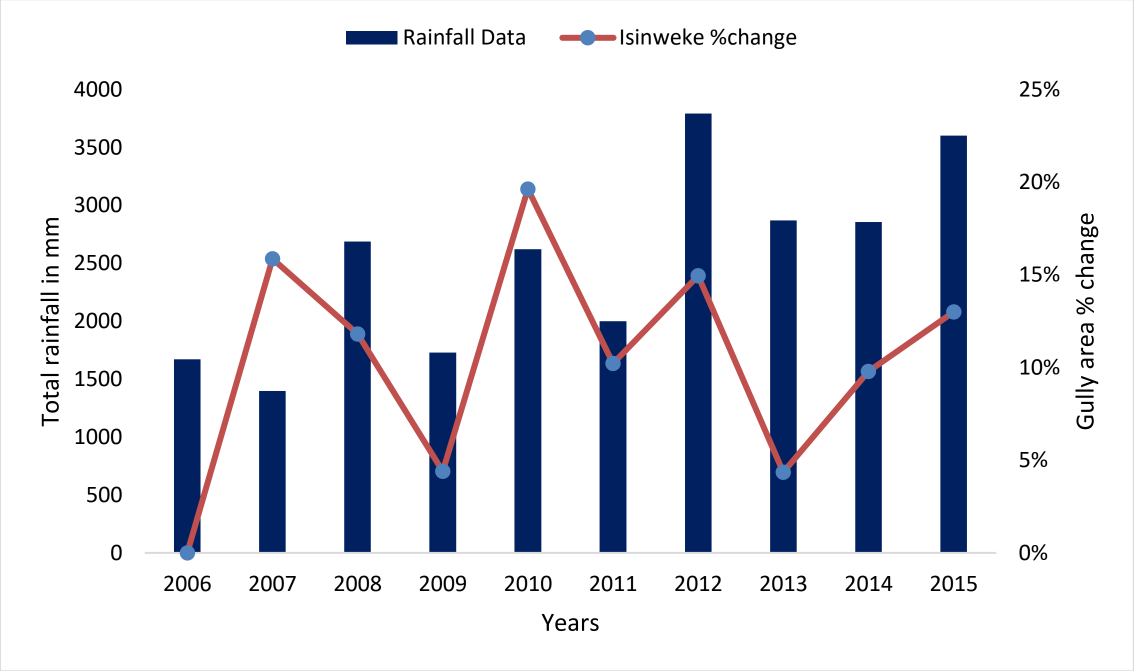


Figure 81: The Graph of Isinweke gully area % change and Rainfall pattern in mm from 2006 – 2015

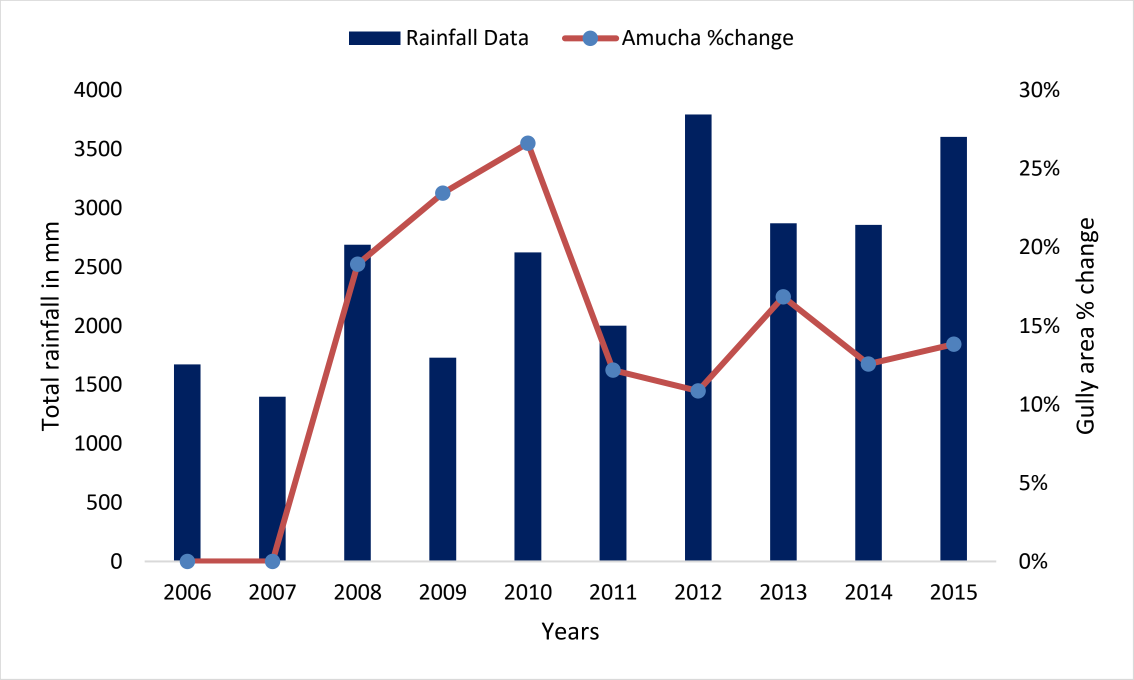


Figure 82: : The Graph of Amucha gully area % change and Rainfall pattern in mm from 2006 – 2015

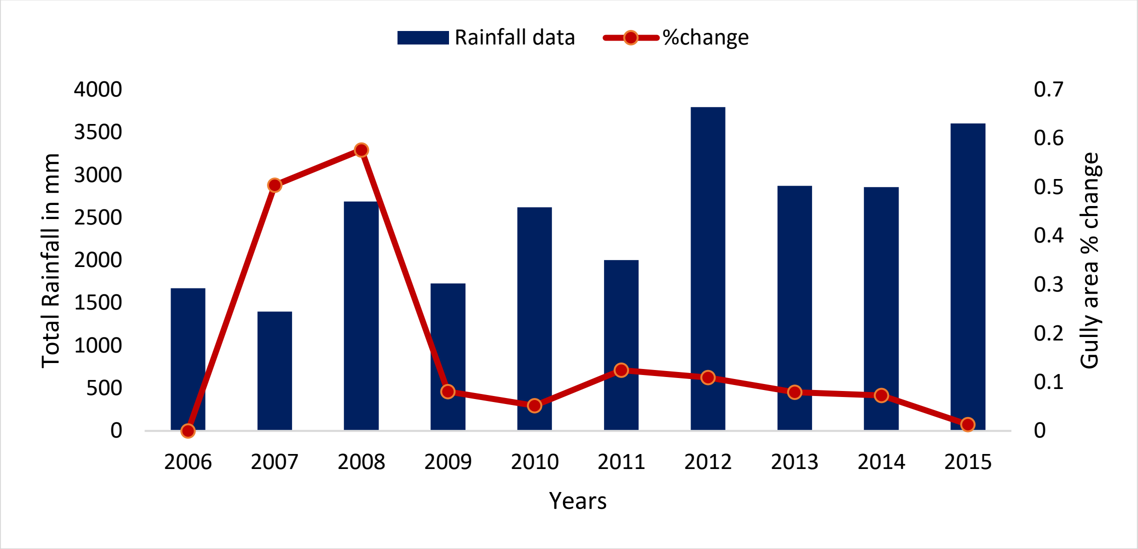


Figure 83: The Graph of Nekede gully area % change and Rainfall pattern in mm from 2006 – 2015

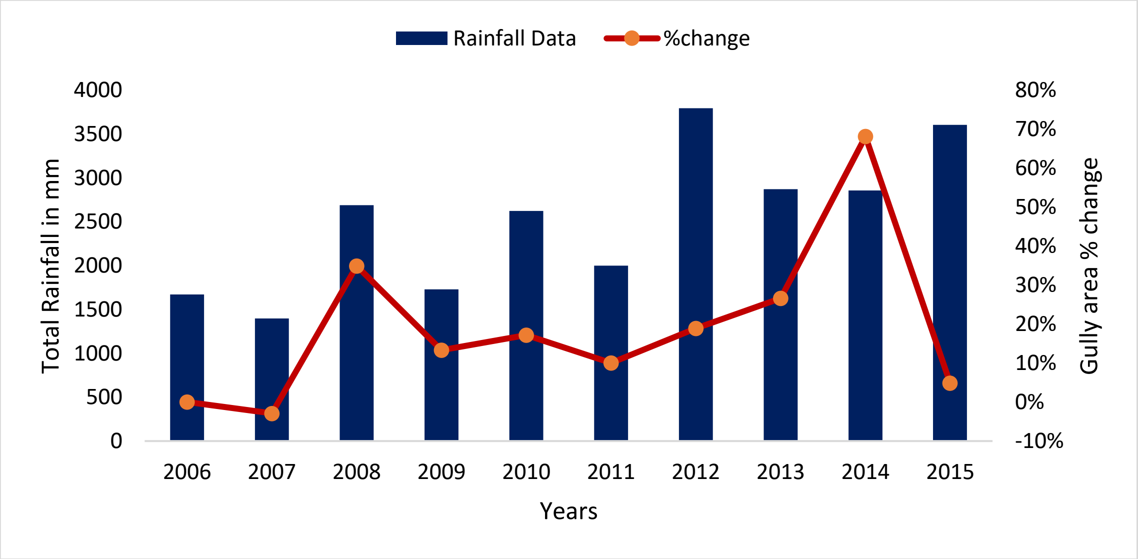


Figure 84:The Graph of Ngwo1 gully area % change and Rainfall pattern in mm from 2006 – 2015

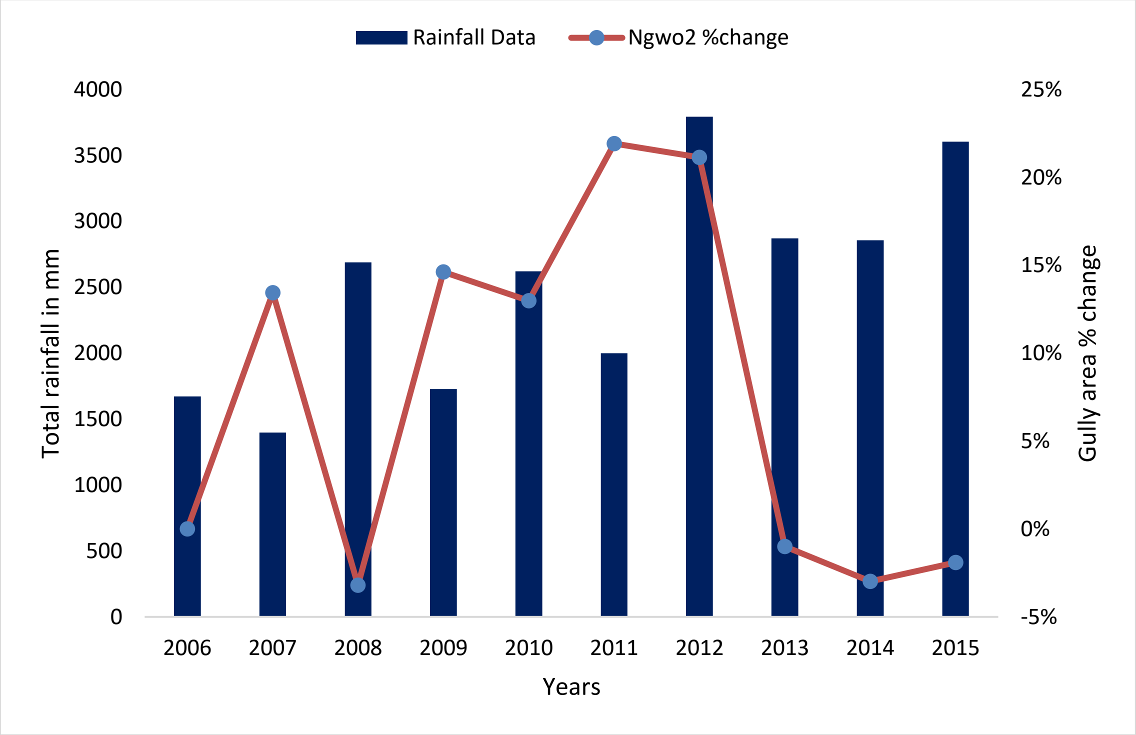


Figure 85: The Graph of Ngwo2 gully area % change and Rainfall pattern in mm from 2006 – 2015

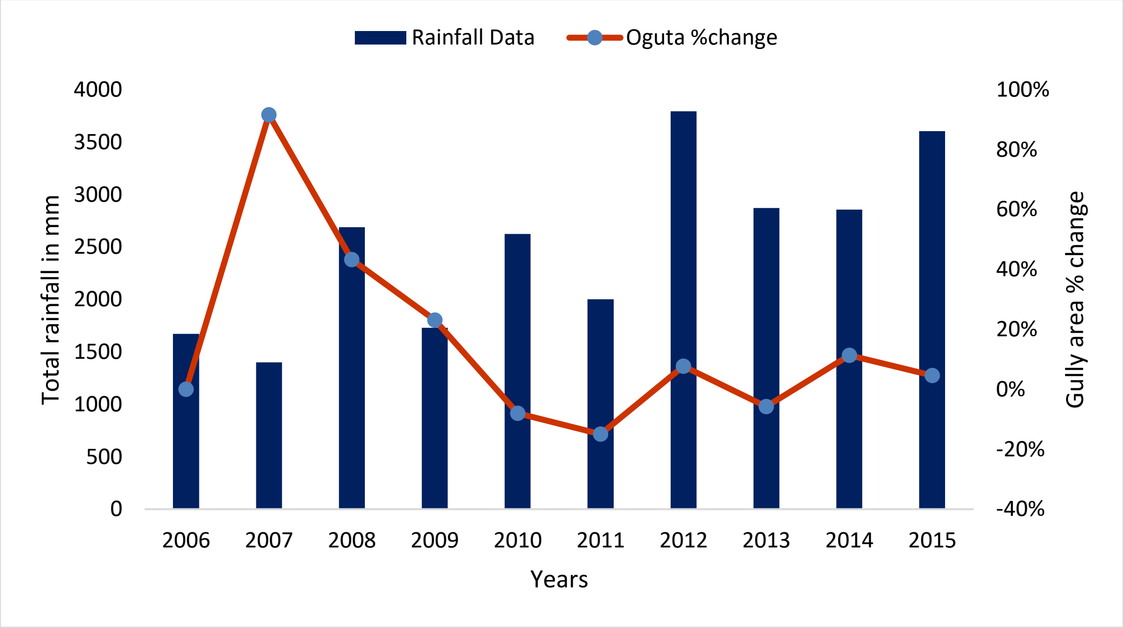


Figure 86: The Graph of Oguta gully area % change and Rainfall pattern in mm from 2006 – 2015

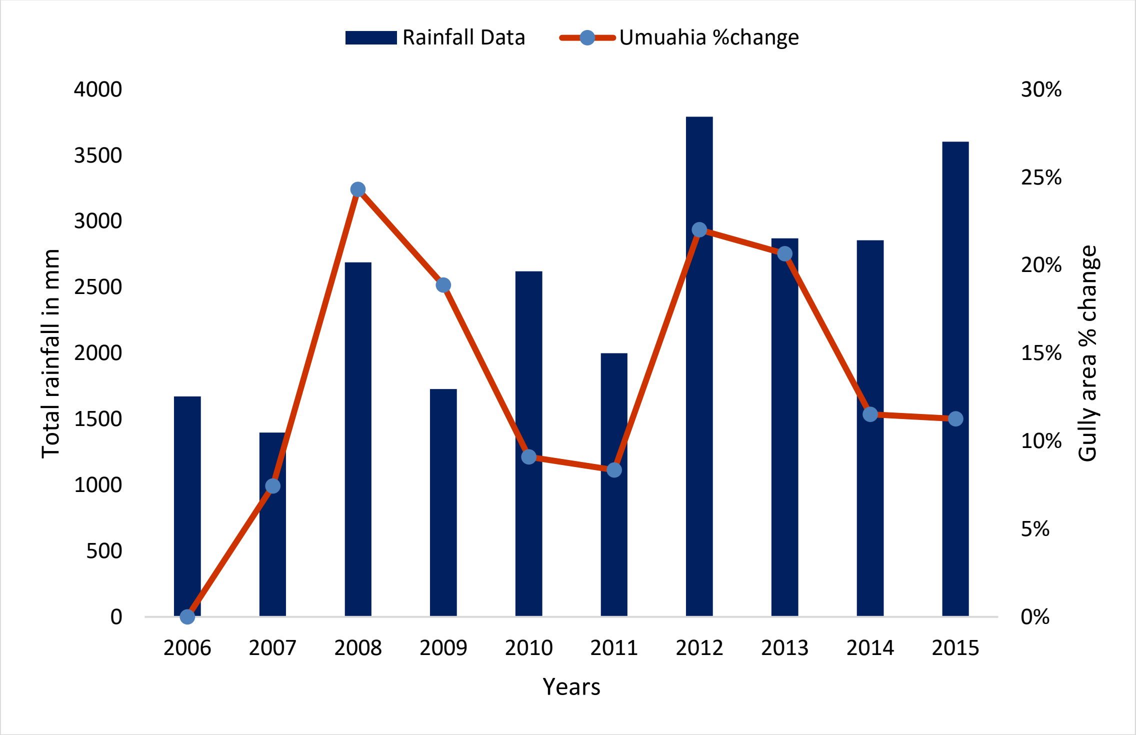


Figure 87: The Graph of Umuahia gully area % change and Rainfall pattern in mm from 2006 – 2015

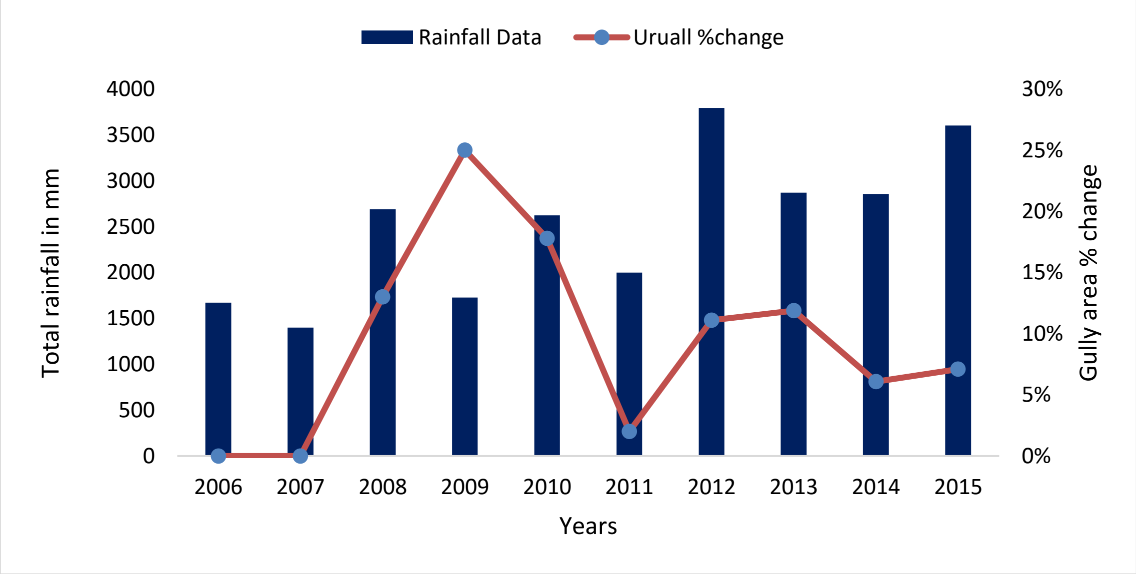


Figure 88: The Graph of Urualla gully area % change and Rainfall pattern in mm from 2006 – 2015

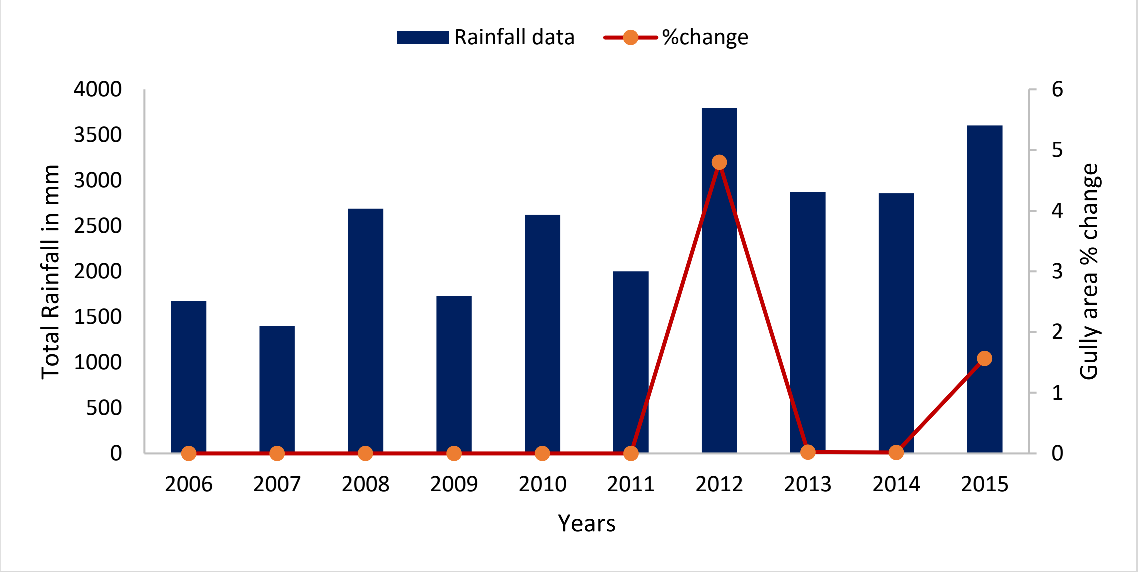


Figure 89: The Graph of Nawfia gully area % change and Rainfall pattern in mm from 2006 – 2015

5.5 Regional Scale Multivariate Analysis

In this section multivariate analysis of the study region will be presented using seven key variables which have all been introduced earlier in the thesis. The most key variables considered are that of Gully areas over the duration of 1986-2015, the 4 older gullies, and over the duration of 2006 – 2015, for the 10 younger gullies examined, and crucially their rates of change. The aim therefore is to determine the effect, similarity, relationships, and influence on gully area exhibited by looking at the variables - vegetation loss, slope, soil, elevation, gully area, yearly gully change in metre squared per square metre (proportional change) and gully stream order. These variables have been chosen because they a have been identified as potential erosion drivers by various gully erosion studies (Abdulfata et al. 2014; Parnwell 2011; Arash et al. 2011; Poesen et al. 2003; Anejionu et al. 2013). The results of the 2014/2015 statistical analysis were compared with the results from years 2009/2010 and 2006/2007. These years were chosen due to data availability and also as the majority of gullies have developed by 2006/2007. Again, 2009/10 was used to check the results between 2006/2007 and 2014/15 the last year of the study. The temporal spacing allows observable changes to be detected more clearly. Bivariate analyses were initially conducted to identify if any obvious trends existed in the data across the years 2006/07, 2009/10 and 2014/15.

5.5.1 Cluster Analysis (The Reasons and Advantages for the Choice of Cluster Analysis in this Study have been Highlighted in Section 4.10.1

In this study, cluster analysis will be used to look at yearly gully change in metre squared per square metre. This represents a proportional change in the gully to allow comparison across all gully sizes. It is considered the Dependent variable and examined in relation to 6 independent variables (Vegetation loss, soil, slope, elevation, gully stream order and gully area) for all the studied 14 gullies. Investigations used variables from 2014/15, 2009/10, and 2006/07 to determine the relationship of other variables with yearly rate of change per unit area of gullyt. These years where chosen because most of the gullies have not developed prior to 2006. The years studied exhibit a collective mean yearly gully change in metre squared per square metre similar. For example, 2006/2007, 2009/2010 and 2014/2015 have mean yearly gully change in metre squared per square metre of gully ranging from -0.01 - 0.4. This cluster analysis will characterise and group similar variables to examine their behaviour in relation to the yearly gully change in metre squared per square metre.

Variables that remain constant for a gully over the duration of the study period (temporally constant), but differ amongst gullies (spatially variable), were included (slope, soil, elevation and gully stream order) alongside the temporally and spatially variable data from 2015, 2010 and 2007.

Variables that have spatial and temporal variation are used in the following way: Variables used for 2015 are 2014/15 yearly rate of gully change in metre squared per square metre, 2015 absolute Gully area and 2014/2015 vegetation loss.

Rainfall data was not used here because the data represents the entire study area not individual gully sites. As pointed out by some researchers in the area, for example Igbozurike (1989), southeast Nigeria is a rainforest zone with over 1000mm mean annual rainfall data reported every year. Igbozurike is of the opinion that since the area has high rainfall data, which is natural and almost the same every year, emphasis should be more on other gully factors which encourage runoff to devastate the area. The reason is that rainfall has been there all these years, until disturbances in the ecosystem set in. Earlier analysis of the relationship between area change and rainfall show to be inconclusive.

In a similar fashion, variables used for 2010 are 2009/2010 yearly gully change in metre squared per square metre, 2010 Gully area and 2009/2010 vegetation loss.

Variables used for 2007 are 2006/2007 yearly gully change in metre squared per square metre, 2007 Gully area and 2006/2007 vegetation loss

By identifying which variable(s) cluster closely with yearly gully change in metre squared per square metre, the data will answer the question of "Which variable behaves in the most similar manner to the rate of change?" Therefore providing some insight into the drivers of this annual change.

Given the variety of drivers reported in the literature review, the expectation is that there is no single variable acting as a driver but it will provide insight into how the gully variables relate to yearly gully change in metre squared per square metre of gully. This approach reflects that taken by Feng et al. (2016) as pointed out in **chapter 4 section 4.10.1.**

5.5.1.1 2014/2015 Cluster Analysis of Variables:i) 2014/2015-VegLoss

ii) 2015- Gully area
iii) SlopeDegrees
iv) Soil
v) Elevation
vi) Gully stream

vii) 2014/15 yearly gully change in metre squared per square metre

A simple bivariate analysis of variables is conducted and displayed in Figure 90. No clear linear relationships with the dependent variable of GullyChange are evident therefore suggesting the need to explore multivariate approaches

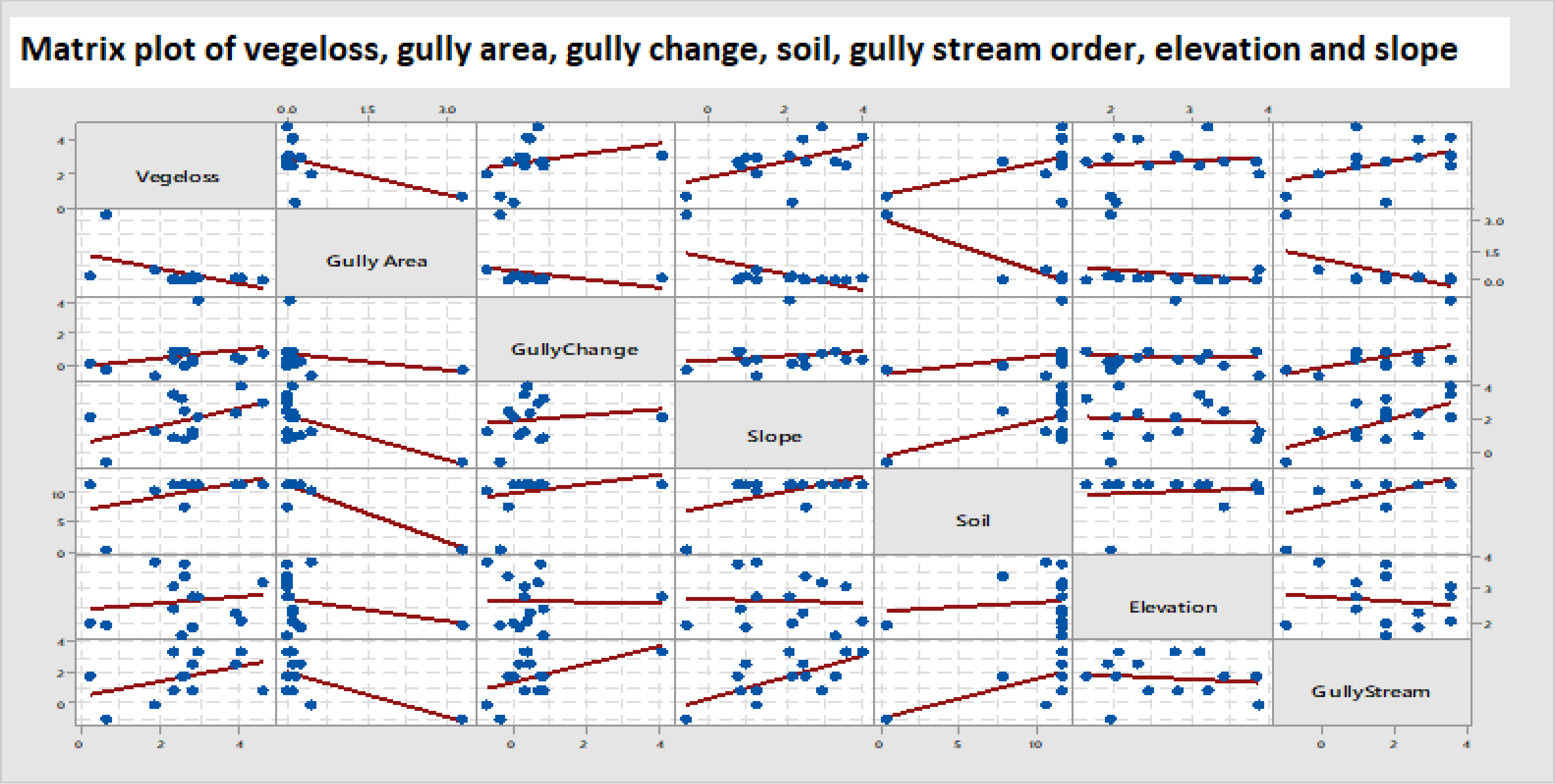


Figure 90: Matrix Plot of 2014/15-VegLoss, SlopeDegrees, Soil, Elevation, Gully stream order, 2015-Gully area, 2014/2015- yearly gully change in metre squared per square metre. (The solid lines represent linear regression). The x,y plots show little evidence of linear relationships between yearly gully change in metre squared per square metre and variables.

Amalgamation Steps are shown in **Table 23**.The Complete Linkage method groups clusters based upon single pair distances and is considered best suited for the variables of this study. This is because the analysis is looking for the natural clustering of variables to the yearly gully change in metre squared per square metre.

Table 23: Correlation Coefficient Distance, Complete Linkage

Step	Number of clusters	Similarity level	Distance Level	Clusters joined	New cluster	Number of obs. in new cluster
1	6	83.7766	0.32447	4 7	4	2
2	5	76.5325	0.46935	4 5	4	3
3	4	71.6695	0.56661	1 4	1	4
4	3	57.7517	0.84497	1 3	1	5
5	2	43.0426	1.13915	1 6	1	6
6	1	3.4204	1.93159	1 2	1	7

Table 24: Final Partition of the 3 clusters for 2014/15

Cluster 1 (Blue)	Vegeloss, GullyChange, Slope, Soil, GullyStream
Cluster 2 (Green)	Elevation
Cluster 3 (Red)	Gully Area (Max 3.4204 similarity with other clusters)

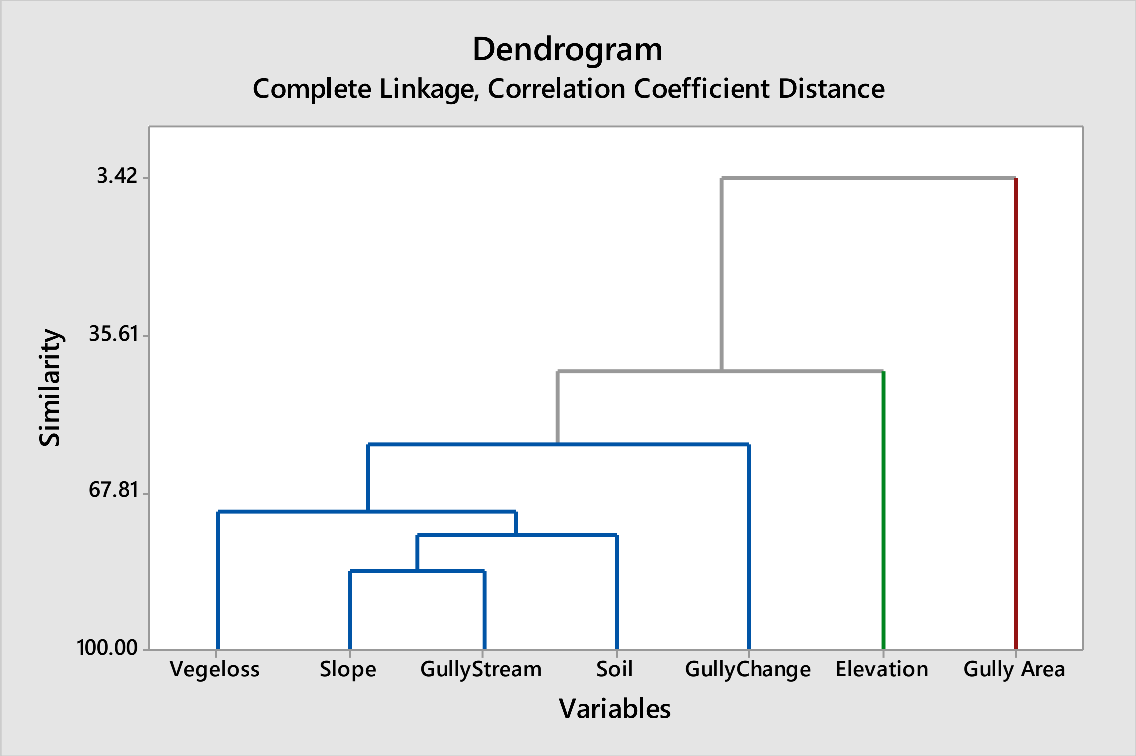


Figure 91: Dendrogram of the year 2015 with 7 gully variables represented using 3 cluster solution and 14 gullies

Closer look at **Table** 23 shows similarity levels between the clustered variables to construct the dendrogram of **Figure 91**. The analysis here is identifying the variables which are considered most similar to yearly gully change in metre squared per square metre, the proportional change. Initially each variable is considered an independent cluster, the clusters are then created by analysing which variables exhibit the highest similarity in accordance with the dictate of complete linkage. Slope is the first variable to be clustered, with the gully stream order variable, showing a similarity of 83.78%. The subsequent clustering of variables is then described in **Table 24**. This cluster is then joined to Soil (similarity 76.53%), VegLoss (similarity 71.67%), and yearly gully change in metre squared per square metre (similarity 57.75%) showing decreasing order of similarity. These variables are considered to form a single cluster in the dendrogram of Figure 91, shown in blue although the similarity level associated with the yearly gully change in metre squared per square metre is close to the 50% similarity mark. The second and third clusters shown on the right hand side (red and green) of **Figure 91** are joined with the first cluster (blue) with Elevation showing a similarity of 43% with cluster 1; highlighting the significant difference between the variables of cluster 1 and the other two. The Gully area cluster has a similarity with all other variables of no more than 3.42%. This shows openly that the current size of a gully has little bearing on the yearly gully change in metre squared per square metre. This is to be expected due to the vast range of gully sizes examined in this study. The table shows that vegetation loss, slope, soil and gully stream order are closer to yearly gully change when compared with other variables in terms of similarity level. 57.75% similarity is the best connection of the yearly gully change variable with the other variables in Cluster1. The yearly gully change has a very low similarity to Cluster3 3.420%. From the dendrogram it is clear that the clustering of VegLoss, slope, Soil and Gully stream show that they have similar behaviour and character and exhibit similar trends and behaviour to the key variable,. This will be discussed more in the **Discussion section.**

5.5.1.2 2009/10 Cluster Analysis of Variables:

i) 2009/10-VegLoss
ii) 2010- Gully area
iii) SlopeDegrees
iv) Soil
v) Elevation
vi) Gully stream
vii) 2009/10 yearly gully change in metre squared per square metre

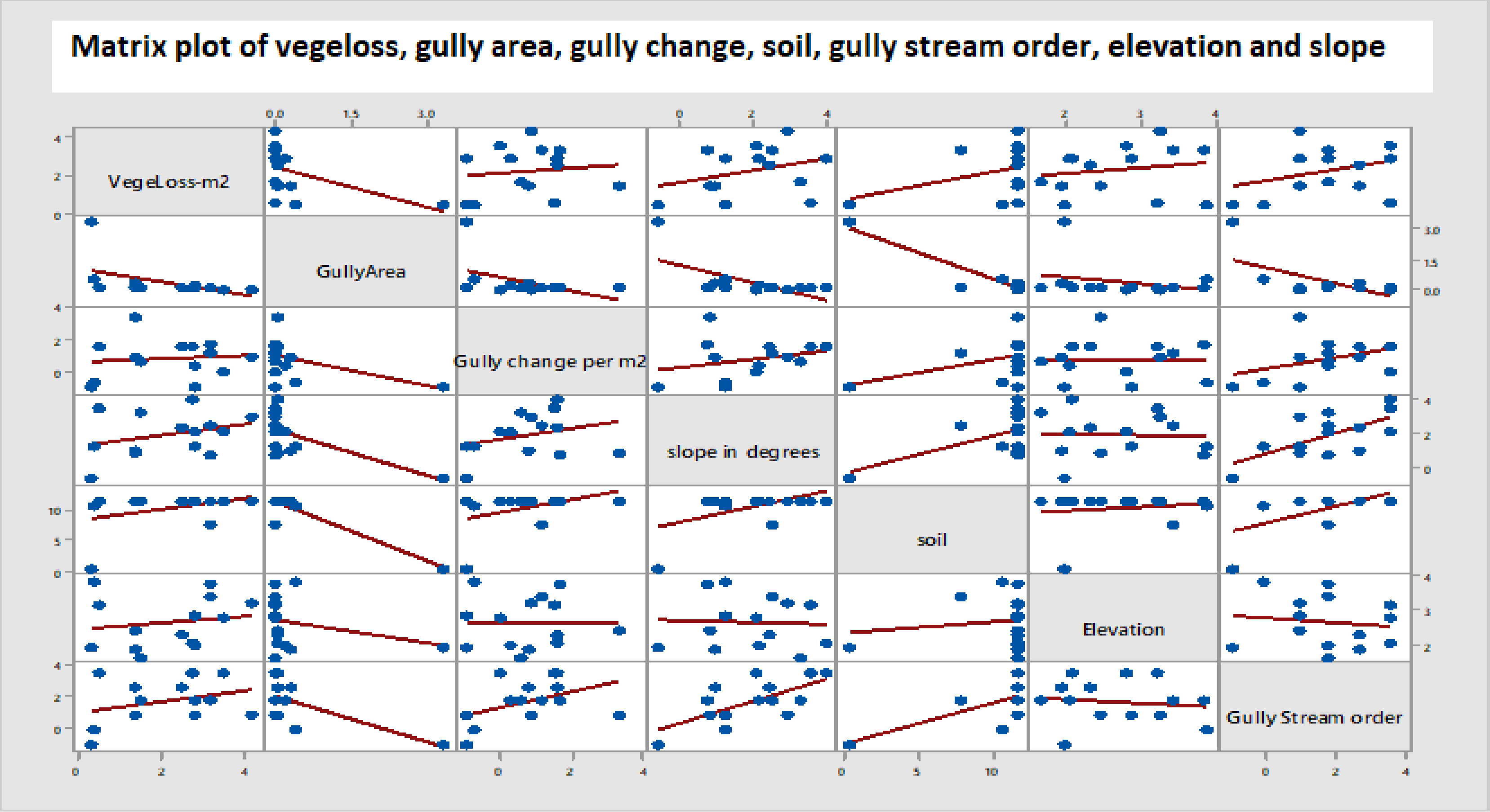


Figure 92: Matrix Plot of 2009/10-VegLoss, SlopeDegrees, Soil, Elevation, Gully stream order, 2010-Gully area, 2009/2010- yearly gully change in metre squared per square metre. (The solid lines represent linear regression).

Figure 92 highlights the bivariate nature of the variables being examined. Again the likelihood of multivariate relationships is examined. This analysis is similar to 2014/2015 analysis, a look at **Table 25** shows similarity levels between the clustered variables to construct the dendrogram of **Figure 93**. Due to the similarities in the non temporally varying variables there are very similar trends exhibited as in the previously studied year. Looking at the joining of clusters as described in Table 20, Slope is the first variable to be clustered, with the gully stream order variable, showing a similarity of 83.78%.. This cluster is then joined with Soil (similarity 76.53%), VegLoss (similarity 65.47%), and then yearly gully change in metre squared per square metre (similarity 56.41%) showing decreasing order of similarity. As for 2014/2015 the rate of change shows know no outstanding similarity with any other individual variable. These variables are considered to form a single cluster in the dendrogram as shown in **Figure 93**, in blue,. The second and third clusters shown on the right-hand side (red and green) of **Figure 93** are joined with the first cluster (blue) with Elevation showing a similarity of only 43.68% with cluster 1; highlighting the significant difference between the variables of cluster 1 and the other two; Area and Elevation having very little bearing on the rate of change. The Gully area cluster has a similarity with all other variables of no more than 3.35%. This shows openly that the current size of a gully has little bearing on the proportional yearly gully change. This is to be expected due to the vast range of gully sizes examined in this study. **Table 26** shows that vegetation loss, slope, soil and gully stream order are closer to yearly gully change in metre squared per square metre in terms of similarity level. 56.41% similarity is the best connection with the other variables in Cluster1. Again reinforcing the idea that no single variable is a dominant driver.

Table 25: Correlation Coefficient Distance, Complete Linkage (complete linkage methods group clusters based upon single pair distances and best suited for the variables of this study.

Step	Number of clusters	Similarity level	Distance Level	Clusters Joined	New cluster	of obs. in new cluster
1	6	83.7766	0.32447	4 7	4	2
2	5	76.5325	0.46935	4 5	4	3
3	4	65.4657	0.69069	1 4	1	4
4	3	56.4063	0.87187	1 3	1	5
5	2	43.6751	1.12650	1 6	1	6
6	1	3.3543	1.93291	1 2	1	7

Table 26: Final Partition of the 3 clusters for 2009/10

Cluster 1 (Blue)	VegeLoss, Gully change, slope, soil, Gully Stream order
Cluster 2 (Green)	Gully Area
Cluster 3 (Red)	Elevation

Looking at **Table 26 and Figure 93,** cluster 1 comprises of 2010-vege loss, Soil, Gully stream order, slope and 2010- yearly gully change in metre squared per square metre showing that they are closely related, Cluster 2 consists of only Gully area and Cluster 3 with Elevation.

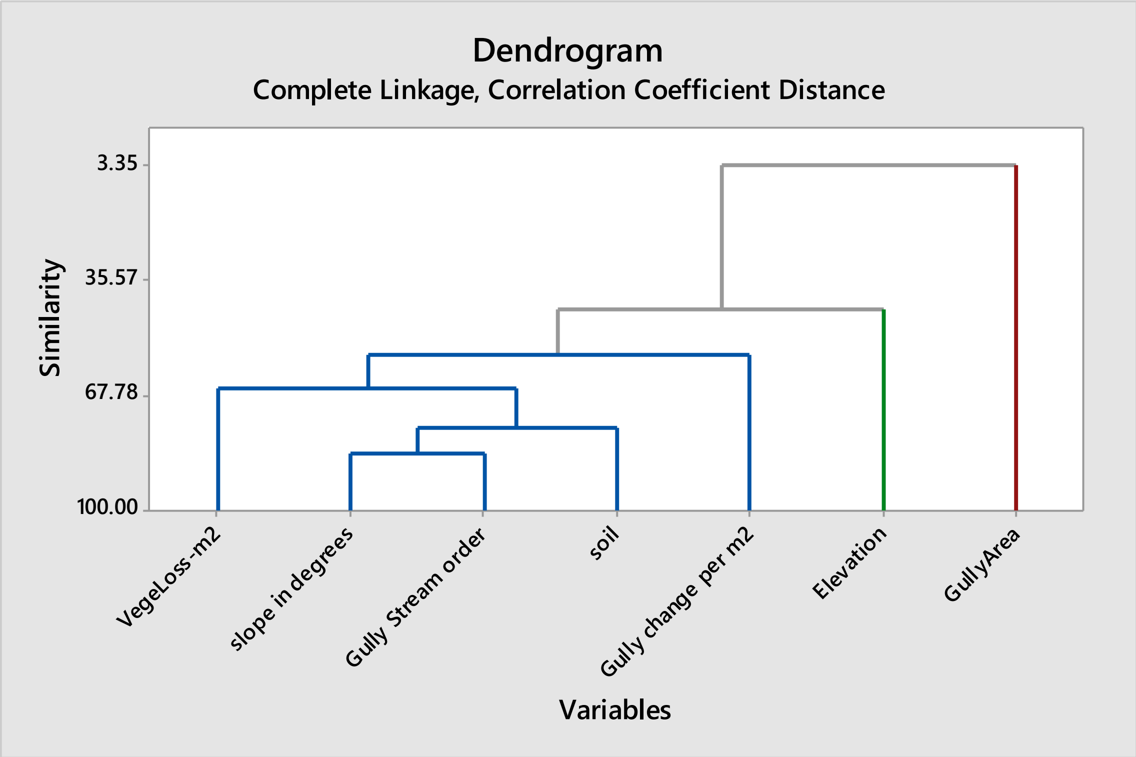


Figure 93: Dendrogram of the year 2009/10 with 7 gully variables represented in 3 cluster solutions. That linear relationship also exhibited in (**Figure 91)**

Visually the connections are shown in **Figure 93,** the dendrogram for the gully variables. There are clearly two very distinct groups, the left-hand group consists of 5 variables including yearly gully change in metre squared per square metre, Vegetation Loss, Soil, Slope and Gully stream order, while the right-hand group, representing two clusterseach of a single variable, consists of Elevation and Gully area. The dendrogram is clearly showing distinctively that yearly gully change in metre squared per square metre is most closely related to Soil, stream order and slope but vegetation loss aren't far behind. Relationships inherent in both the 2010 and 2015 data. By discounting the non temporally variant variables across the years that are contained within Cluster 1there is an evidentlink with the annually changing vegetation area, although not a conclusive link.

5.5.1.3 2006/07 Cluster Analysis of Variables:

i) 2006/7-VegLoss
ii) 2006- Gully area
iii) SlopeDegrees
iv) Soil
v) Elevation
vi) Gully stream
vii) yearly gully change in metre squared per square metre

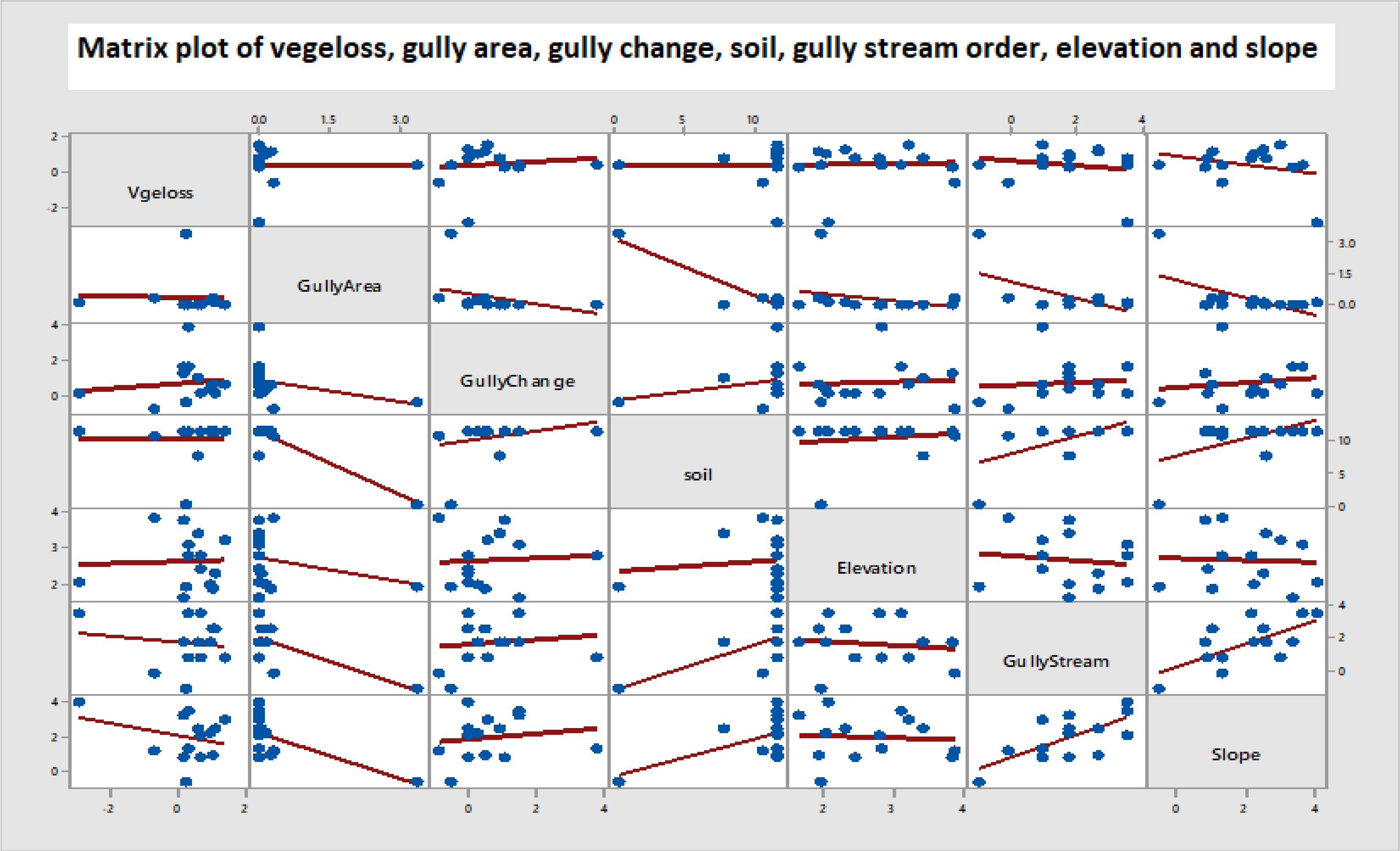


Figure 94: Matrix Plot of 2006/07-VegLoss, SlopeDegrees, Soil, Elevation, Gully stream order, 2007-Gully area, 2006/2007- yearly gully change in metre squared per square metre. (No linear relationships apparent with the yearly gully change in metre squared per square metre).

Table 27: Correlation Coefficient Distance, Complete Linkage Amalgamation Steps (complete linkage methods group clusters based upon single pair distances and best suited for the variables of this study.

Step	Number of clusters	Similarity level	Distance Level	Clusters Joined	New cluster	Number of obs. in new cluster
1	6	83.7766	0.32447	6 7	6	2
2	5	76.5325	0.46935	4 6	4	3
3	4	56.9878	0.86024	1 3	1	2
4	3	51.9754	0.96049	1 5	1	3
5	2	35.7369	1.28526	1 4	1	6
6	1	3.1732	1.93654	1 2	1	7

Table 28: Final Partition of the 3 clusters for 2006/07

Cluster 1 (Green)	Soil, GullyStream, Slope
Cluster 2 (Blue)	Vgeloss , GullyChange, Elevation
Cluster 3 (Red)	GullyArea

Table 27 and **Figure 95** again outline the similarity between the variables for the of 2006/07 data. The first cluster to develop consists of the Soil, Gully stream order, and Slope variables. Again these represent temporally constant variables. The first two variables join with 83.77% similarity with the cluster showing similarity between all included variables of at least 76.53%. In the second cluster, vegetation loss and yearly gully change in metre squared per square metre show similarity of 56.99% and connect to Elevation with 51.98%. The first two clusters show an inter cluster similarity of 35.74%. Vegetation loss and yearly gully change in metre squared per square metre are joined with similarity levels of 56.99% which shows the best connection with the key variable investigated. This again potentially outlines the importance of the vegetation loss variable in drving gully changes. Gully area is once again isolated from the other variables with only a 3.17% similarity on display.

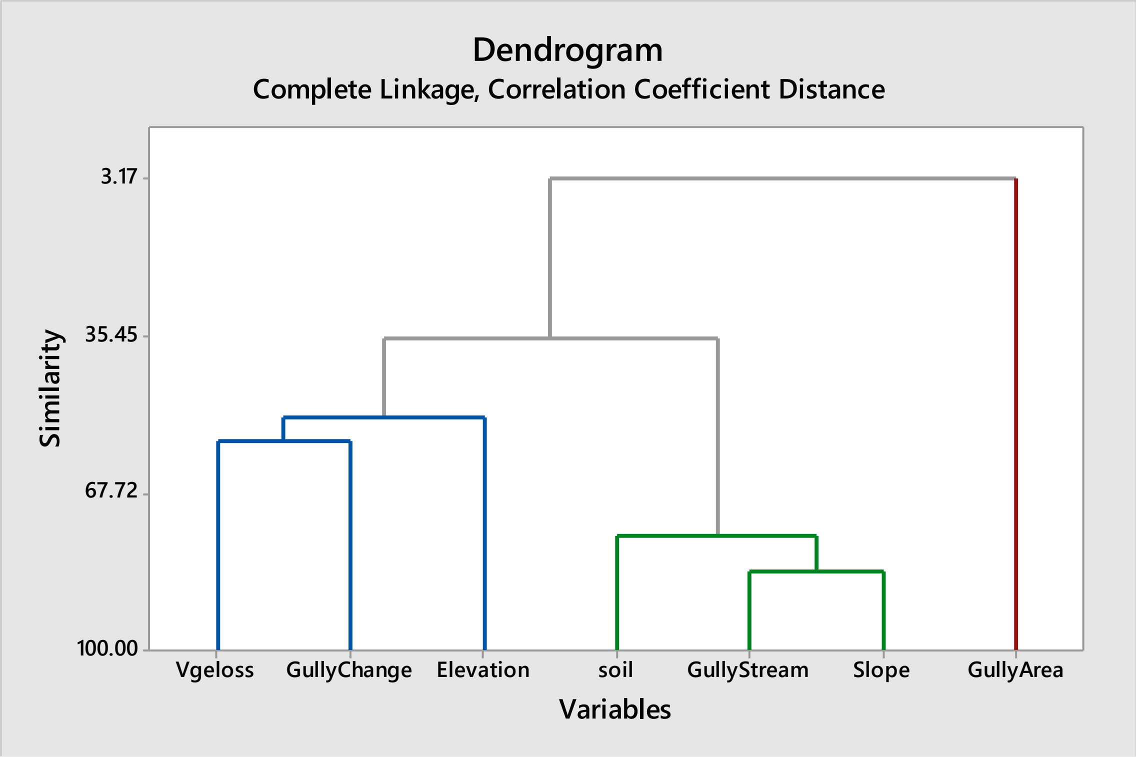


Figure 95 : Dendrogram of the year 2007 with 7 gully variables represented in 3 cluster solutions

In summary the veg loss, slope, gully stream order and soil type are consistently found on the correct side of the dendrogram in relation to the yearly gully change in metre squared per square metre. An indication of low distance and therefore similarity in behaviour exhibited by the variables.

Vegetation loss, elevation, soil, gully stream order and slope are consistently the key variables, fulfilling the expectation that there is no single variable that defines the rate of change. The analysis shows conclusively that gully size has little bearing on the yearly gully change in metre squared per square metre and suggests in each year the importance of the vegetation loss to gully development. This will be looked at more in the **Discussion** section and to develop the statistical testing.

5.5.1.4 Cluster Analysis of Variables Vegetation Loss, and Rainfall Data to Establish their Relationship with Yearly Gully Change in Metre Squared per Square Metre.

Cluster analysis will be further applied to look at the yearly gully change in metre squared per square metre in relation to the 30 year development of the four major gullies and the 10 year development for the other 10 gullies under review. The intention is to identify natural clustering of years which possess the same eroding rate of change. This will enable the study to look at two important temporal factors in relation to the erosion; annual rainfall pattern and the yearly pattern of vegetation loss for those years. With these variables being temporally and spatially variable the use of a localised vegetation loss parameter from the 10km x 10km region surrounding each individual gully is incorporated in to the analysis. High rainfall could produce high runoff which could make gullies erode faster. Wood, (2013) maintained that the intensity, duration and amount of rainfall in conjunction with other specific gully influences, contribute to determine how soil will be removed from areas via gullying. The magnitude of rainfall erosivity provides a useful insight into the causes of the catastrophic erosion problems in south-east Nigeria (Obi 1995; Greenland 1998). This, thus decreases or increases the gully rate of change depending on the rainfall intensity, amount and duration. Igwe, (2005) observed that in South East Nigeria, gullies mostly develop on soil on which vegetal growth has been disturbed. According to Igwe, (2005) and Onyekwere, (2001); they separately maintained that there would be no gully erosion without constant vegetation loss coupled with the type of rainfall southeast Nigeria regularly receives. They observed that the duration, intensity and amount of rainfall received in southeast Nigeria is high which can readily cause gully erosion when the soil has lost its vegetal cover and other gully drivers are in place. Other studies focussed on the region have warned that less emphasis should be put on rainfall as a driver since it has a typical mean of over 1000mm annually; enough to generate gullies on a yearly basis. Maintaining that more emphasis should be focused on other variables like vegetation loss, soil, slope etc. (Igbozurike 1989). The other variables are spatially variable but temporally constant across the study period which include slope (the slope is that of the larger geomorphological landscape), gully stream order, elevation and soil.

These factors remain invariable during the study period while rainfall can change in amount, intensity, and duration. Vegetation loss can change via the amount removed which is perceived to influence gully development and yearly gully change in metre squared per square metre.

In this analysis the variables used are yearly gully change in metre squared per square metre for the 14 gullies, looking at changes in individual years. 30 (29) and 10 (9) year time periods are examined for the two groups of gullies based on life term.

The tests here conducted are done so to identify years which have similar rates of change influenced by rainfall regime and vegetation loss. 3 variables are being tested i)the yearly rate of change per square metre for the 14 gullies, ii) annual rainfall data and iii) yearly vegetation loss of the 10km x 10km region surrounding each gully site. The underlying question to answer here is ; does yearly rainfall data and yearly vegetation loss affect the yearly gully change in metre squared per square metre regardless of gully similarities or dissimilarities? The expectation is that these two variables will strongly drive the yearly gully change in metre squared per square metre with the evidence of the prior cluster analysis supporting this investigation regarding vegetation loss and the earlier examination of trends with rainfall highlights this as a potential driver. This will investigate the theory that yearly gully change in metre squared per square metre for any given year is controlled by amount, intensity and duration of rainfall and loss of vegetation (Carey, 2006).

5.5.1.5 Cluster Analysis of Observations: Yearly Gully Change in Metre Squared per Square Metre for 4 Main Gullies, Yearly 10X10 Vegetation Loss for the 4 Main Gullies and Mean Annual Rainfall Data for 29 years (1986/87 – 2014/15)

Using the variables stated above, a look at **Table 29** and **Figure 96** shows the development of the clusters of years and final clusters resulting from the analysis.. Each observation is represented by a different cluster initially with the final clustering process depicted numerically and visually. The visual representation is shown in **Figure 96** showing 5 distinct clusters. The maximum intra cluster similarity is shown to be 39.93% with inter cluster similarity as high as 88.72%.. Some of the years exhibited high similarity with a neighbouring year that could suggest a level of autocorrelation in these results, for example 1992 – 1993 and 2002 – 2003. One significant difference is seen when observing the year 1987 which exhibits minimal similarity with any other given year. In a similar manner the years 2014 and 2015 stand out.

Table 29: Step by step breakdown of clustering of yearly data consisting of vegetation loss, rainfall, and rate of gully area change Euclidean Distance, Complete Linkage; Amalgamation Step (complete linkage methods group clusters based upon single pair distances).

Step	Number of clusters	Similarity level	Distance level	Clusters joined	New cluster	Number of obs. in new cluster
1	28	88.7221	1.02528	8 12	8	2
2	27	87.3289	1.15194	11 13	11	2
3	26	83.5409	1.49631	14 25	14	2
4	25	82.3541	1.60421	22 27	22	2
5	24	81.0747	1.72052	8 9	8	3
6	23	79.3775	1.87481	5 10	5	2
7	22	79.3630	1.87613	16 17	16	2
8	21	79.1901	1.89184	8 20	8	4
9	20	78.0418	1.99624	19 24	19	2
10	19	77.3387	2.06016	18 23	18	2
11	18	73.9516	2.36808	8 11	8	6
12	17	72.5199	2.49824	6 7	6	2
13	16	70.8866	2.64673	8 15	8	7
14	15	69.5908	2.76453	16 21	16	3
15	14	67.4949	2.95507	19 26	19	3
16	13	66.5923	3.03712	18 22	18	4
17	12	65.7838	3.11062	3 14	3	3
18	11	63.3257	3.33409	3 5	3	5
19	10	59.8876	3.64665	8 18	8	11
20	9	53.8774	4.19305	28 29	28	2
21	8	52.8389	4.28746	8 16	8	14
22	7	52.0064	4.36314	2 6	2	3
23	6	51.6956	4.39140	3 19	3	8
24	5	47.8678	4.73939	2 4	2	4
25	4	39.9308	5.46095	3 8	3	22
26	3	24.5153	6.86239	3 28	3	24
27	2	18.9841	7.36523	1 2	1	5
28	1	0.0000	9.09109	1 3	1	29

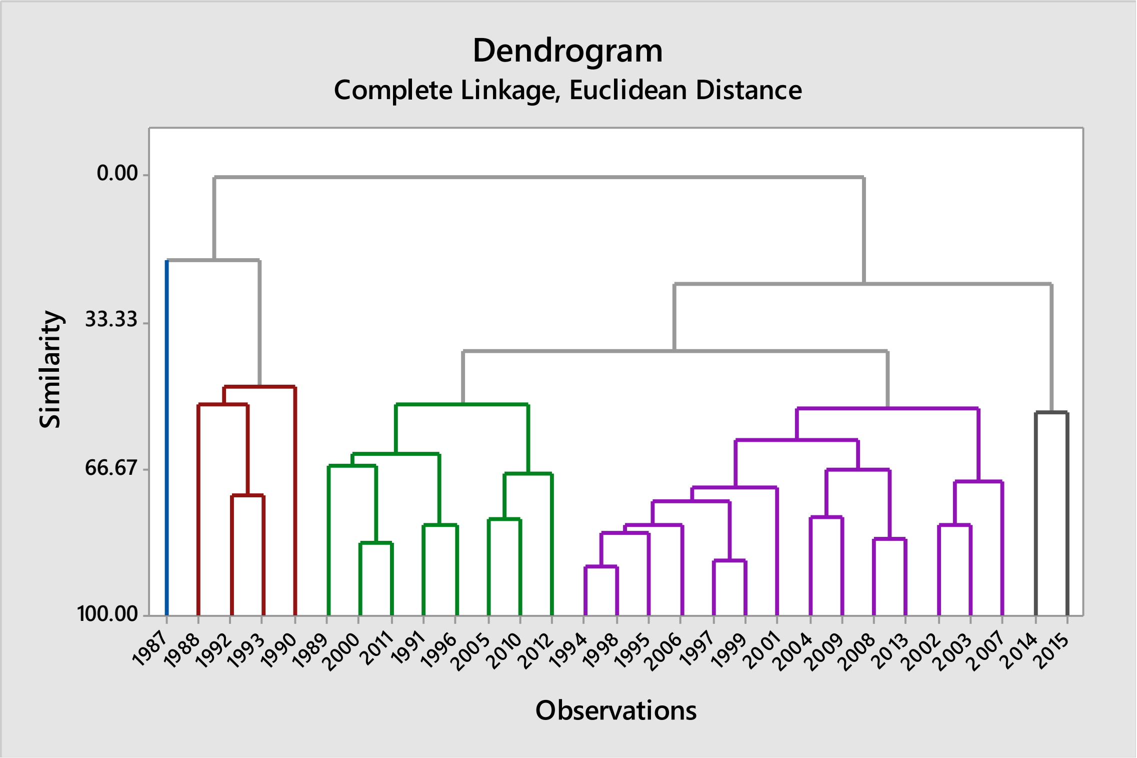


Figure 96: Dendrogram: Cluster Analysis of Observations: yearly gully change in metre squared per square metre for the 4 gullies for Years 1986/87 to 2014/15 with mean annual rainfall data and yearly 10km X 10km vegetation loss around each gully

Table 30: Distances of the 5 cluster solution

	Cluster1	Cluster2	Cluster3	Cluster4	Cluster5
Cluster1(Blue)	0.00000	6.53288	6.40945	6.83180	8.40073
Cluster2(Red)	6.53288	0.00000	3.22828	3.73491	5.87199
Cluster3(Green)	6.40945	3.22828	0.00000	1.70283	4.70321
Cluster4(Purple)	6.83180	3.73491	1.70283	0.00000	4.23464
Cluster5(Grey)	8.40073	5.87199	4.70321	4.23464	0.00000

Closer look at **Table 30** shows the distance between cluster centroids of the 5 identified clusters, shown in the dendrogram of **Figure 96**. Small distances indicate similarity between clusters while large distances indicate dissimilarity.

5.5.1.5.1 Characteristics of the 29 Cases (1986/1987- 2015)

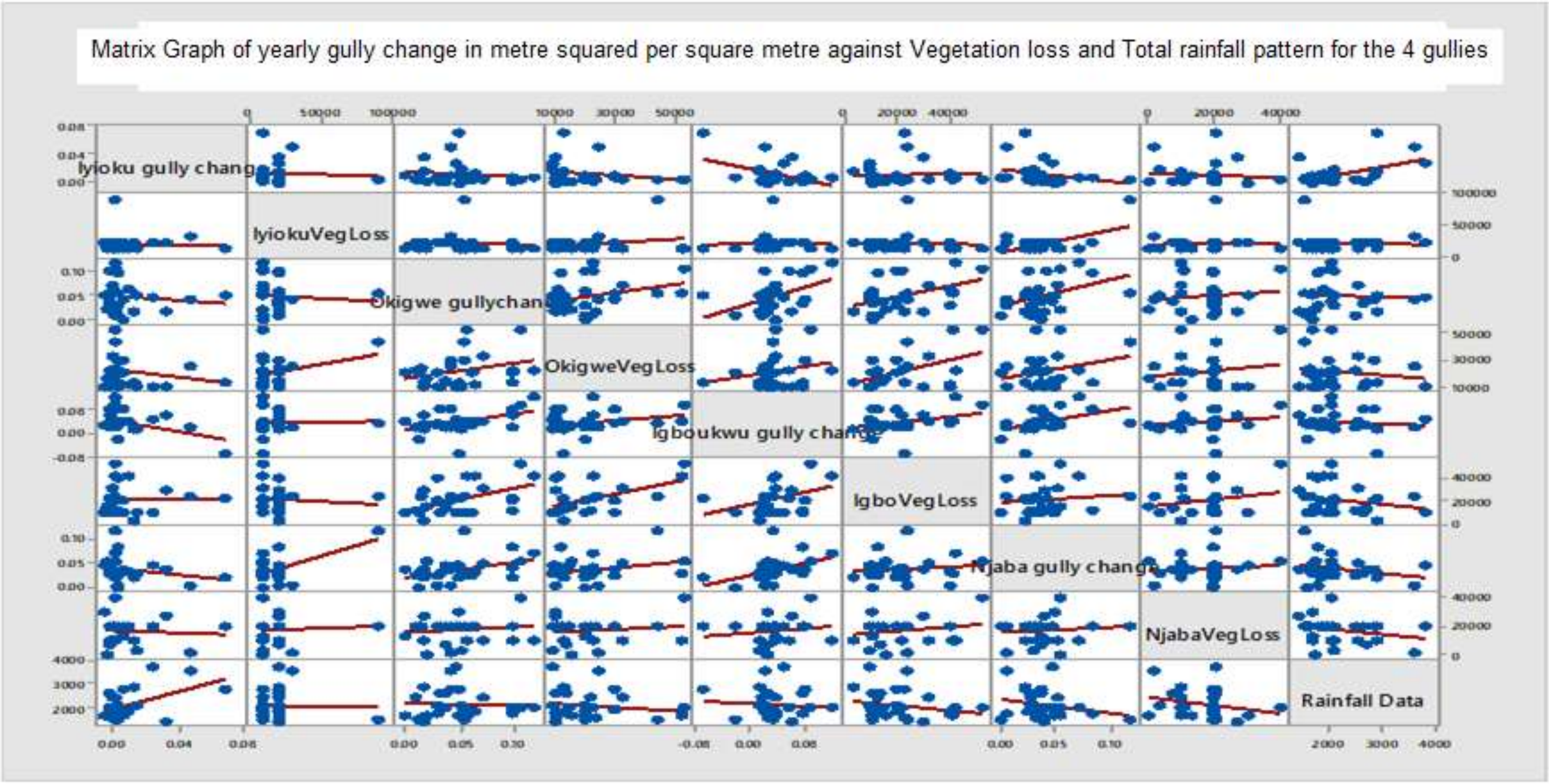


Figure 97: Matrix Graph of yearly gully change in metre squared per square metre against Vegetation loss and Total rainfall pattern for 1986 – 2015 for Iyioku, Okigwe, Njaba and Igboukwu gullies.

To properly understand these clusters, this Figure 96 will be discussed with yearly gully change in metre squared per square metre of each gully (representing the proportional change), yearly vegetation loss of each gully and with the mean annual rainfall data (**Table 9**) the 3 variables used to cluster the years. Cluster 1 (Blue) has only the single case of 1987, with a distinct characteristic in terms of rate of change per square metre, the value of which is 0.07 representing a 7% change. 1987 also has mean vegetation loss of 44556m^2 and the lowest mean annual rainfall of 1504mm out of all the study years. It was reported in Achebe (2011) that after the civil war between Nigeria and Biafra (southeast Nigeria), southeast Nigeria witnessed massive industrial and construction sites which resulted in the area losing about 15% of its rainforest area. The area started to recover its lost rainforest area by gradual introduction of a tree planting campaign by the governors of the area starting from 1987. As a mean value across all of the gullies this could be a possible reason for the yearly gully change in metre squared per square metre exhibited in 1987 and because of the inconsistency in the tree planting program this may have affected yearly gully change in metre squared per square metre trend in some years. Although some areas of recovery will be evident, some vegetation area is still being lost through logging and through urban development at this time (Njoku 2010).The rainfall pattern of 1987 was smaller when compared with other years but more than enough to initiate and support gully development when other gully factors are in place, for example vegetation loss as pointed out by Igbozurike (1989). The amount of rainfall in the year 1987 is likely the primary reason that the yearly gully change in metre squared per square metre was low when compared with some other years studied, analysis of the bivariate plot of mean yearly gully change in metre squared per square metre against rainfall presents some evidence of this.

Cluster 2 (Red) with 4 cases comprising 1988, 1990, 1992, 1993 shows how these years are being clustered loosely with regards to the yearly gully change in metre squared per square metre values of 0.08, 0.05, 0.05, and 0.04 respectively. Three of these values are lower than the 1987 value with 1988 following a very similar rate to the 1987 data. Across these years there is a consistently high vegetation loss, for example in 1993 with mean vegetation loss of 17540m^2 and high mean annual rainfall of more than 1600mm in . In Cluster 3 (Green) with 8 observations comprising of 1989, 2000, 2011, 1991, 1996, 2005, 2010 and 2012 these years reveal similarities in the tested variables but is likely most evident in the mean yearly gully change in metre squared per square metre with 0.07, 0.02, 0.01, 0.009, 0.03, 0.03, 0.03, 0.04 respectively. Consistently high rates of vegetation loss and rainfall data patterns are recorded in these years of more than 1600mm. Looking at Cluster 4(Purple) with 14 cases of years 1994, 1998, 1995, 2006, 1997, 1999, 2001, 2004, 2009, 2008, 2013, 2002, 2003, 2007, and mean yearly gully change in metre squared per square metre was 0.04, 0.03, 0.03, 0.02, 0.03, 0.03, 0.01, 0.02, 0.02, 0.02 0.02, 0.02, 0.03, 0.03 respectively. These years consistently record high rate of vegetation loss and high mean annual rainfall. For example, in 2013, it recorded high mean annual rainfall data of 2871mm across the study period, **Table 9**. The clustering is likely a result of the presence of high rainfall but also very low levels of erosion represented by the rate of area change. Also, Cluster 5 (Grey) with 2 cases of 2014 and 2015, reveals that these two years have similar characteristics in terms of the tested variables. Mean yearly gully change in metre squared per square metre were presented of 0.01 and 0.01 in addition to similar yearly rates of vegetation loss and high rainfall data patterns. For example, in 2015 with 3604mm and 2014 exhibiting the 3rd highest levels. Possible reasons for low recordings in rate of change per sq. metre exhibited in these years despite higher mean rainfall data and mean vegetation loss could be the result of gully erosion control measures adopted by some communities and agencies. For example, towards the end of the study period of 2015, there is slow rate of yearly gully change in metre squared per square metre of gullies like Njaba, Igboukwu, Orlu and Urualla due to communities, government and agency interventions, this was as well observed by Columbus (2012). More details are provided in the **Discussion section** of this study.

5.5.1.5.2 Cluster Analysis of Observations.The Variables Employed are: Yearly Gully Change in Metre Squared per Square Metre for 10 Gullies, Yearly 10x10 Vegetation Loss for the 10 Gullies and Mean Annual Rainfall Data for Years (2006/07 – 2014/15)

In this section the Cluster Analysis of Observations will take place for the younger rendering of gullies that have been monitored from 2006. The variables examined are the same as the previous analysis with yearly gully change in metre squared per square metre,vegetation loss in m^2, and annual rainfallanalysed for the Orlu, Isinweke, Amucha, Ngwo1, Oguta, Umuahia, Nekede, Ngwo2, Urualla and Nawfia gully sites.

The order of clustering is documented in **Table 32** with the relationships visualised in the dendrogram of **Figure 98**. The same Complete Linkage approach and calculation of Euclidean Distance is incorporated.

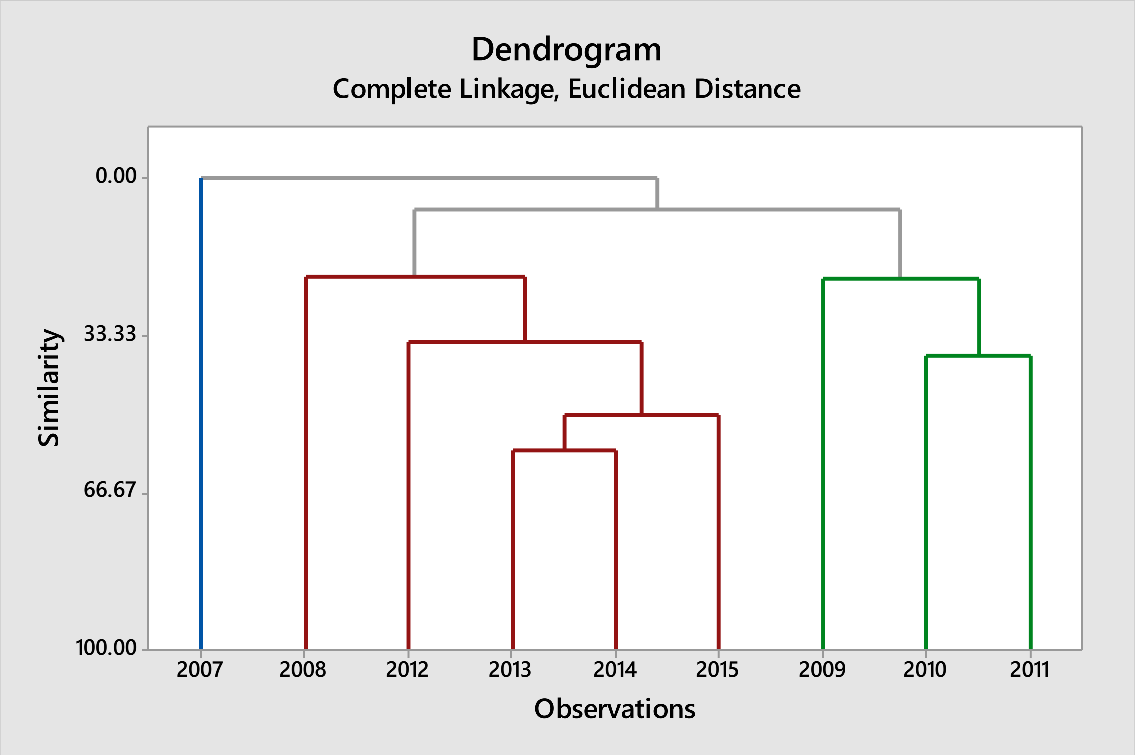


Figure 98: Dendrogram: Cluster Analysis of Observations: yearly gully change in metre squared per square metre for the 10 gullies for Years 2006/07 to 2014/15 with mean annual rainfall data and yearly 10X10 vegetation loss around each gully (**Figure 96**, as well have years 2013, 2014 and 2015 in similar cluster as **Figure 98)**

Table 31: Distances Between Cluster Centroids

	Cluster1	Cluster2	Cluster3
Cluster1	0.00000	7.99971	8.00353
Cluster2	7.99971	0.00000	6.24245
Cluster3	8.00353	6.24245	0.00000

A look at **Tables 31 and 32** detail the distance between cluster centroids, showing distance between the Clusters and the similarities. Small distances indicate similarity while large distances indicate dissimilarity. The years that are clustered together in a single cluster are the ones that show the most similarity exemplifying very high levels of intragroup similarity in terms of rainfall, vegetation loss, and gully area rate of change.

Table 32: Standardized Variables, Euclidean Distance, Complete Linkage

Step	Number of clusters	Similarity level	Distance Level	Clusters joined	New cluster	Number of obs. in new Cluster
1	9	69.8365	3.3822	8 9	8	2
2	8	63.4188	4.1019	8 10	8	3
3	7	58.3257	4.6729	5 6	5	2
4	6	53.4718	5.2172	7 8	7	4
5	5	49.2318	5.6926	5 7	5	6
6	4	43.6147	6.3225	3 4	3	2
7	3	37.0274	7.0611	3 5	3	8
8	2	28.6569	7.9997	1 2	1	2
9	1	0.0000	11.2130	1 3	1	10

5.5.1.5.3 Characteristics of the 9 Cases (2006/2007- 2015)

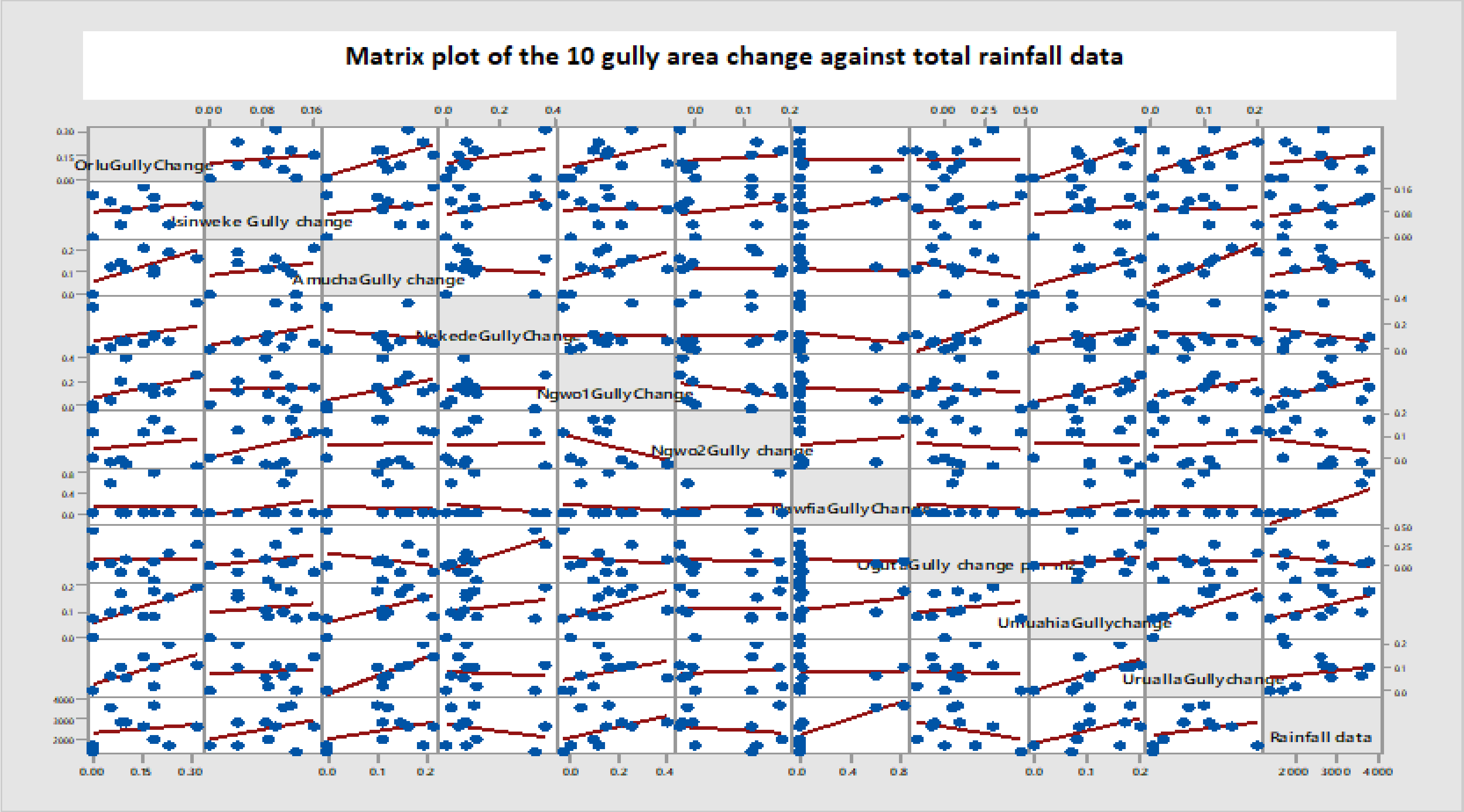


Figure 99: Matrix Graph of 10 gully change against total Rainfall Data

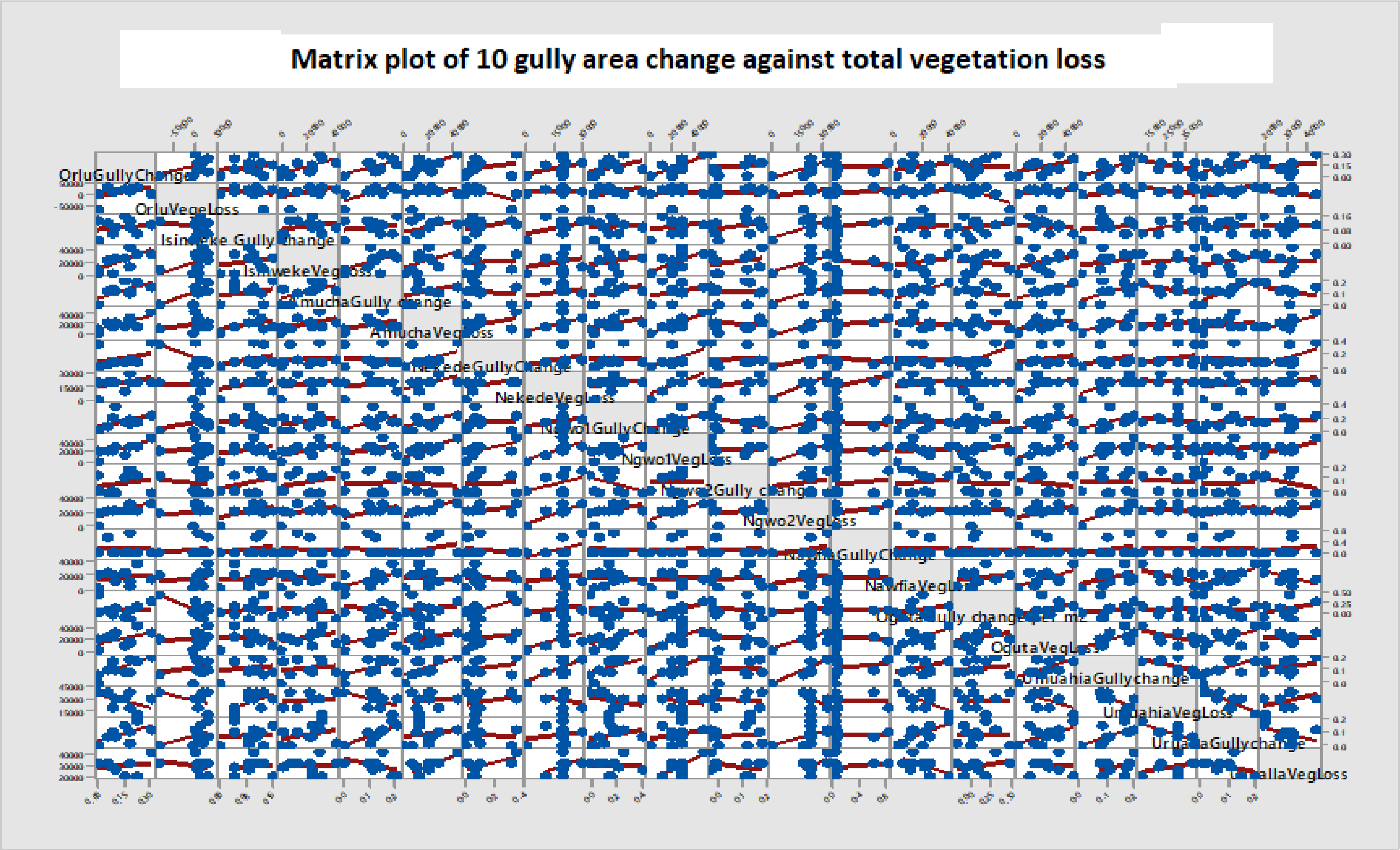


Figure 100: Matrix Graph of 10 gully change against total vegetation loss

Figure 98 will be discussed with yearly gully change in metre squared per square metre of each gully, yearly vegetation loss of each gully and mean annual rainfall data from **Table 9** as the focus of the cluster analysis. Cluster 1 (Blue) contains one (case) year of 2007, with a different characteristic in terms of rate of change per square metre, of which has mean yearly gully change in metre squared per square metre of 0.1 and has high mean vegetation loss of 10373m^2 but low mean annual rainfall of 1398mm. Cluster 2 (Red) with 5 cases comprising 2008, 2012, 2013, 2014 and 2015 have shown almost similar characteristic in terms of yearly gully change in metre squared per square metre of 0.2, 0.2, 0.1, 0.8 and 0.2 respectively with 2014 being the anomaly here with a much larger value presented.

In Cluster 3, comprising 3 cases of 2009, 2010 and 2011, it is revealed that in these years the mean yearly gully changes in metre squared per square metre are 0.2, 0.2, and 0.2 respectively. This is coupled with consistent levels of mean vegetation loss (26622.7m^2, 18133.3m^2, and 25247m^2 respectively) but quite variable annual rainfall data **Table 9**. The clustering is not dominated by the rainfall levels but the relationship with the vegetation loss is less clear. The yearly gully change in metre squared per square metre is very similar across each cluster therefore suggesting that the years cannot be successfully clustered using these variables.

5.6 Principal Component Analysis

This approach was applied in this study to demonstrate the reactions of the variables and their contributions to gully formation and development of the study area. The main purpose of principal component analysis in this study is to obtain a minimal number of independent linear combinations. (PCA) was identified as an appropriate statistical tool to determine the influence of gully factors on gully development, relationships of gully factors and the effects of these gully factors.

The results of the Principal Component Analysis will help to know the weight and relationship of the gully variables. PCA has been used in this manner in studies such as Yu et al. (1998) and Vajcnerova et al. (2011). In a similar way this will be conducted here. The strategy to testing outlined in this section is as follows:

- PCA (a) (Variables used 2015 Gully area, 2014/2015 yearly gully change in metre squared per square metre , 2014/2015 Vegetation Loss, Soil, Slope in degrees, Gully stream order and Elevation.
- PCA (b) (Variables used 2010 Gully area, 2009/2010 yearly yearly gully change in metre squared per square metre, 2009/2010 Vegetation Loss, Soil, Slope in degrees, Gully stream order and Elevation.
- PCA (c) (Variables used 2006 Gully area, 2006/2007 yearly gully change in metre squared per square metre, 2006/2007 Vegetation Loss, Soil, Slope in degrees, Gully stream order and Elevation.

In each case, 7 gully variables are examined across the 14 gully sites. With the yearly gully change in metre squared per square metre the focus. The aim of this PCA is to identify the variables that are closely associated with the rate of change of the gullies using the first two components in this analysis. The expectation is that gully variables like vegetation loss, soil, and gully stream order have a strong impact on the initiation of gully development and yearly gully change in metre squared per square metre in the study area. Again, some researchers such as (Ayanlade and Drake 2015; Odemerho and Sada 2002; Ofomata 2009) have mentioned these environmental variables as being outstanding in gully development and rate of gully change in southeast Nigeria.

This analysis conducted in this section is for the years 2006/2007, 2009/2010 and 2014/2015. The purpose is to properly ascertain if the weight and relationship of the variables are similar in these years with particular regard to year 2014/2015. The years were chosen because from the analysed satellite imageries of the study area, all the gullies have developed by 2006/2007 except some gullies like

Nawfia gully which developed after 2007. Again, 2009/10 was used to check the results between 2006/2007 and 2014/15 the last year of the study.

5.6.1 Principal Component Analysis of the Time Period 2014/15: VegLoss, Slope Degrees, Soil, Elevation, Gully Stream, GullyArea and Yearly Gully Change in Metre Squared per Square Metre

Principal Component Analysis (PCA) was identified as an appropriate statistical tool to determine the influence of gully factors on gully development, relationships of gully factors and the effects of these gully factors. Using the 7 available variables the normalized data (as explained in **section 4.9.1**) of vegetation loss, slope, soil, elevation, gully stream order, gully area and 2014/2015 gully rate of change per m^2 were used. **Table 33** presents the % of variance, cumulative % of variance, and eigenvalues explained by each component. The components represent the variables that are being observed. In the case of, Principal Component (PC) 1 the eigenvalue is 3.5681. The higher eigenvalue indicates a higher explanatory power to explain the variables better than other principal components. The significance and explanatory power of PC1 is highlighted in the % of variance value. This level is given as 51% of all variables variability. PC2 is signified by an eigenvalue of 1.2003 and describes 17% of the total variance. The high eigenvalues both show the significance of these components. The elevated importance of PC1 is clear. Together PC1 and PC2 account for 68% of variance within the variables (Table 33).

Table 33: 2014/15Total Variance Explained from PCA of 7 variables shown for 7 components. Also, shown graphically through the Scree Plot in Figure 101.

Variables	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Eigenvalue	3.5681	1.2003	0.8819	0.6430	0.4413	0.2167	0.0489
Proportion	0.510	0.171	0.126	0.092	0.063	0.031	0.007
Cumulative	0.510	0.681	0.807	0.899	0.962	0.993	1.000

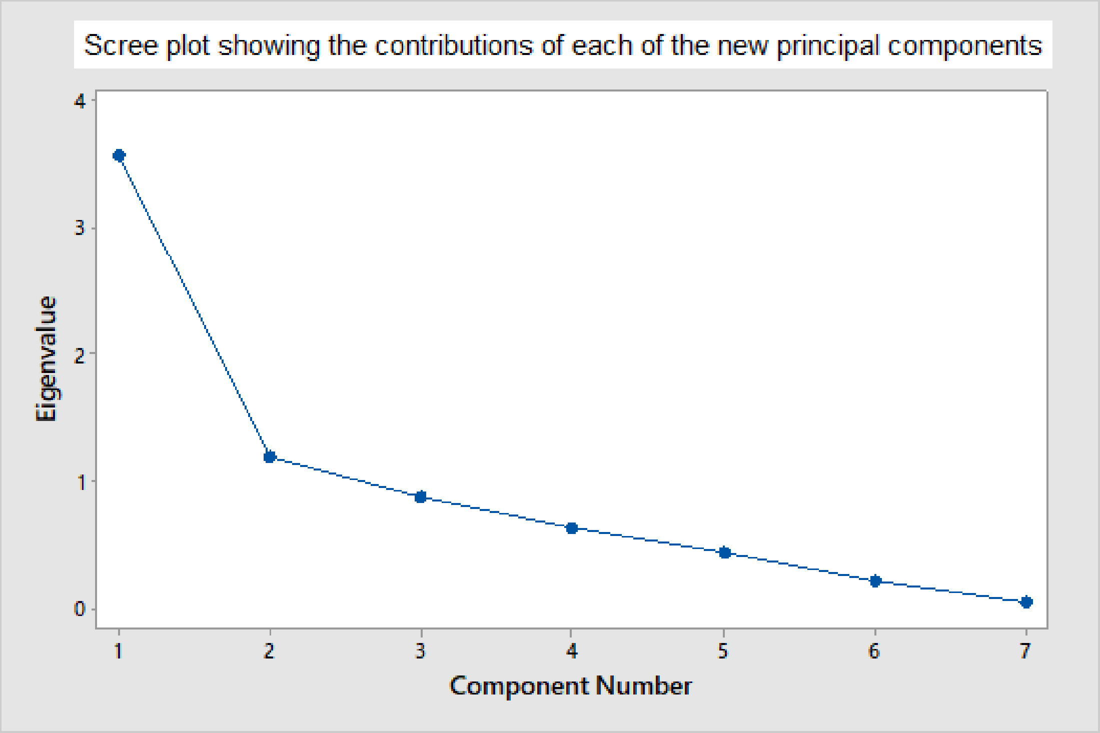


Figure 101: 2014/15 Scree plot showing the contributions of each of the new principal components a graphical representation of the principal components of the data. The blue line represents the eigenvalue associated with the components considered.

The eigenvalues associated with the principle components are shown visually in **Figure 101**. As can be seen in the **figure**, the first 2 components have higher eigenvalues than others.

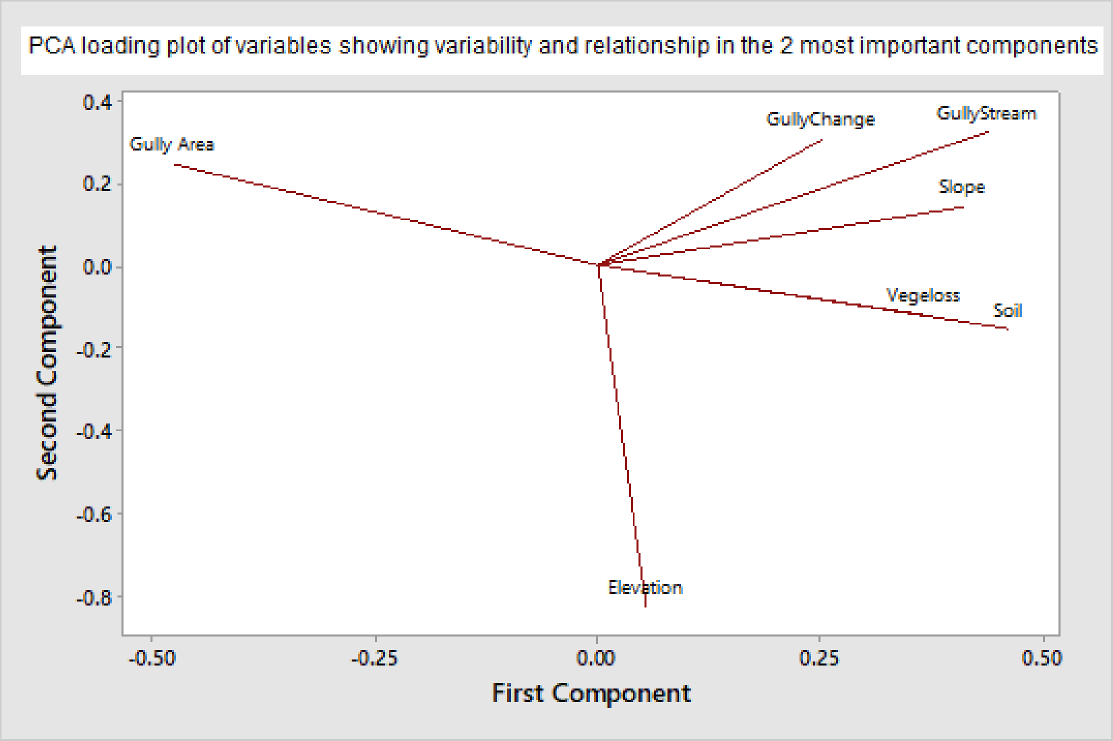


Figure 102: 2014/15 PCA loading plot of variables showing variability and relationship in the 2 most important components (F1 and F2).

In **Figure 102,** the loading plot is presented using the 1st and 2nd component values. The numeric values are presented in **Table 34**. In both cases the results are decomposed on a variable by variable basis. The immediate observation is that the principle component describes a similar level of variance when considering the variables regarding Gully stream order (44%), Soil (46%), Slope (41%), vegetation loss of (37%), yearly gully change in metre squared per square metre (25%) and Gully area (-48%). This is indicative that the variables have their variance explained by PC1 to a similar level albeit all inversely to Gully area. This is particularly the case for the soil and veg loss variables Conversely, Elevation with (6%) show that it was not well explained in the 1st component. The performance of 2nd component shows that Elevation has an exceptional performance in terms of its variance explained by PC2 (-83%). Having almost similar variance explained by PC2 and therefore a close relationship we see yearly gully change in metre squared per square metre (31%) and Gully stream order (32%). In the other way, PC2 shows that Vegetation Loss (-12%), Gully area (25%) and soil (-16%) do not show that they were well explained in PC2 even though they were well explained in PC1. Similarly, Gully area and Soil have a strong inverse relationship. The inverse relationship can be seen when focussing on the Principal component 1, also between Gully area and Gully stream order, Gully area and slope, Gully area and yearly gully change in metre squared per square metre and Gully area and vegetation loss, with this final finding consistent with other knowledge presented in this study, **Figure 102.** Analysis shows high levels of association between most important variables (Gully stream order, soil, slope, vegetation loss, yearly gully change in metre squared per square metre and Gully area) when considering the PC1 with eigenvalue of 3.5681 and explained variance of 51%. However, it is only elevation that appears to be weak in PC1 but stronger in PC2 which has eigenvalue and explained variance of 1.2003 and 17% respectively. The analysis suggests that the levels of association that exist between all the variables shows that they could be combining to exert stronger influence in the model. As a filtering approach the elevation variable would be the most likely candidate to remove as it shows little similarity with our variables of interest, particularly the rate of change and area.

Table 34: Component Score Coefficient Matrix showing the loadings of the components and variables (2014/15)

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Vegeloss	0.367	-0.118	-0.013	0.812	0.411	-0.152	-0.006
Gully Area	-0.476	0.245	-0.094	0.326	-0.174	-0.092	0.748
GullyChange	0.252	0.305	-0.848	0.008	-0.051	0.348	-0.018
Slope	0.410	0.143	0.427	0.209	-0.522	0.546	0.122
Soil	0.461	-0.155	0.062	-0.423	0.412	0.058	0.639
Elevation	0.055	-0.827	-0.290	0.063	-0.449	-0.081	0.128
GullyStream	0.438	0.323	-0.033	-0.089	-0.393	-0.735	0.026

Interpretation of PC1 also shows that the inverse relationship with gully area (size) is exhibited for gully stream order, meaning that larger Gully areas are exhibited in areas with lower gully stream order, and additionally with the other variables so that soil areas with deeply weathered, unconsolidated sandy sediments and friable soils and areas with lower vegetation loss are associated. Note- PCA shows that more vegetation loss is associated with smaller gully areas. Essentially this is where the more rapid gully area changes occur. The large gullies have already lost a lot of vegetation, showing they are fully developed. The observation shows that big gullies mean less vegetation loss. This may be a consequence of the environment at that time or it may be an indication of the need for freshly clear land for gullies to develop. This model assumes that once the gully is big, there is actually very little further vegetation loss.This is expected given the significant outlying data provided by two large gullies as seen in the Matrix plot of **Figure 103**. It can be noticed here that the vegetation loss, slope, soil and gully stream order could be having positive influence on gully development and particularly its rate of increase. The strong capability of component 1 in terms of explaining the variability of these variables, and the complementary and supporting information from component 2, shows both components are capable of explaining the variables.

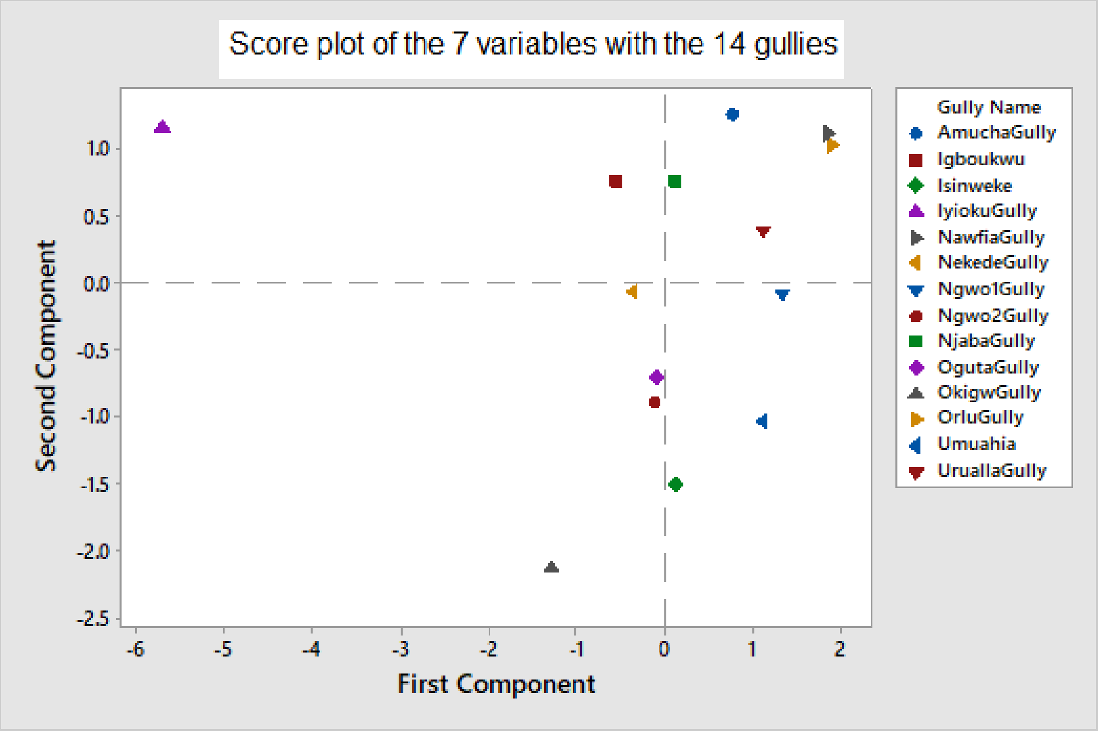


Figure 103: 2014/15 Score plot of the 7 variables with the 14 gullies

The score plot, plots the component 1 scores against the component 2 scores. This is a scatter plot of the values of the new components (PC1 and PC2) with each point showing the individual gullies in the study. In this **Figure 103**, the gully points are concentrating on the 2nd, 3rd and 4th quadrants, with the 1st quadrant having only 2 gully points. The clustering is influenced by all variables with the largest and highest elevated gullies being isolated.

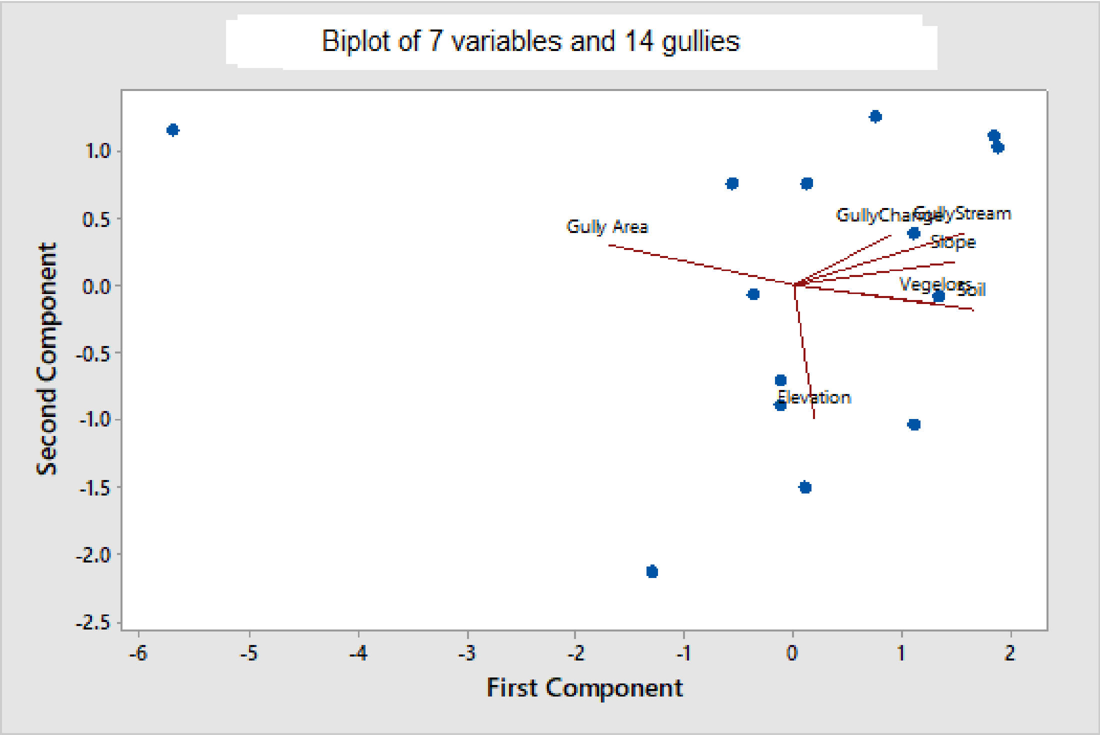


Figure 104: 2014/15 Biplot of 7 variables and 14 gullies

Figure 104 is represented by the first two components which is plot for an overlay of the score and loading plots for the first two components. This plot shows that there are two large gullies that are dominated by gully area (Iyioku and Igboukwu) towards the upper left of the plot. Also, the plot produced 5 gullies (Okigwe, Isinweke, Umuahia, Ngwo2 and Oguta gullies) that are strongly associated with the Elevation. The rest are more dominated by the yearly gully change in metre squared per square metre, veg loss, slope angle, gully stream order and soil, which represents 7 loose clusters here. This can be inferred that the development of these gullies depends more on the relationship of these variables. The importance of these variables and the complexity of these relationships on the gully development are apparent.

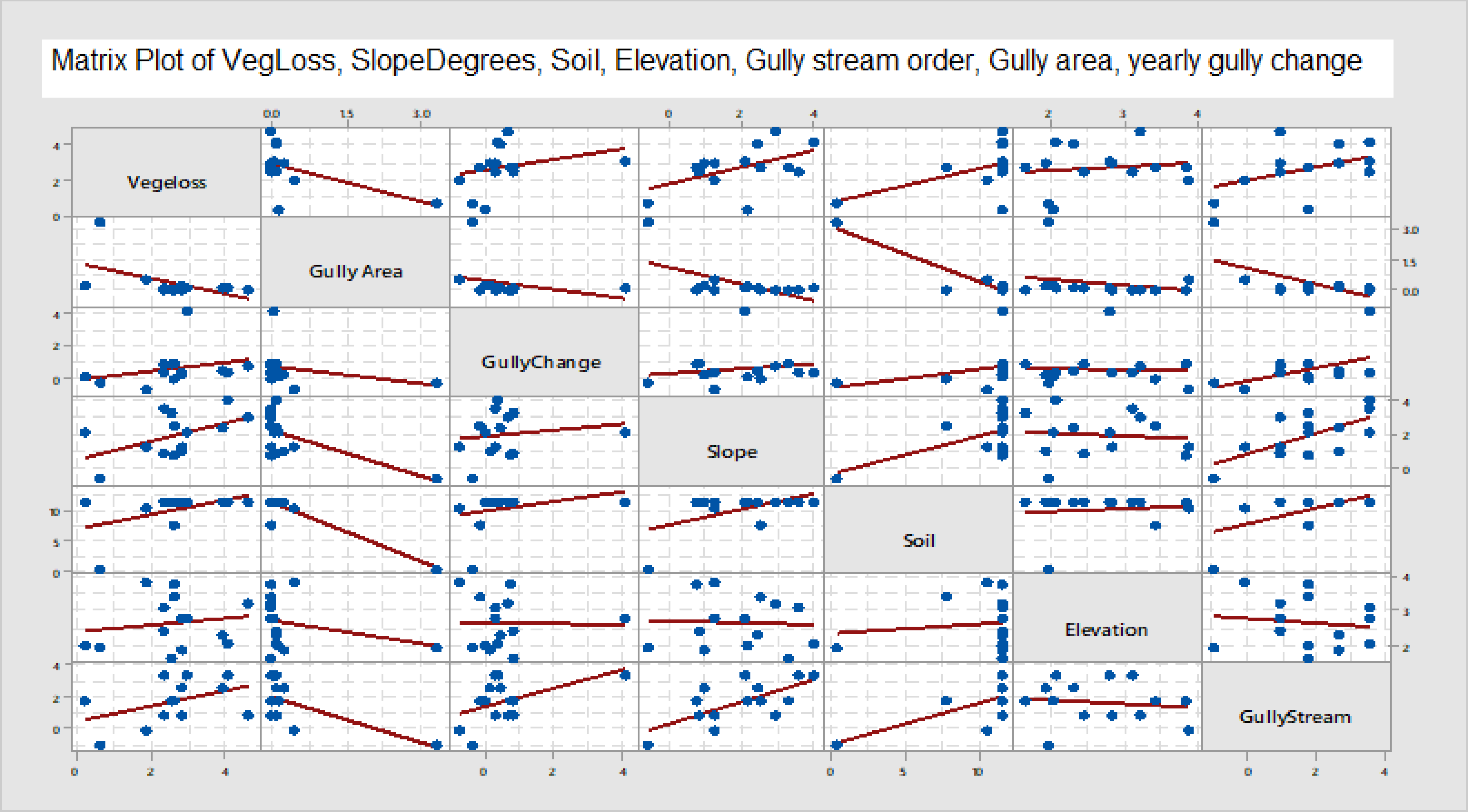


Figure 105: Matrix Plot of 2014/15-VegLoss, SlopeDegrees, Soil, Elevation, Gully stream order, 2015-Gully area, 2014/2015- yearly gully change in metre squared per square metre.

5.6.2 Principal Component Analysis of the Time Period 2009/10: VegLoss, Slope Degrees, Soil, Elevation, Gully Stream, GullyArea and Yearly Gully Change in Metre Squared per Square Metre

Table 35: 2009/2010 Total Variance Explained from PCA of 7 variables shown for 7 components Also, shown graphically through the Scree Plot in Figure 106.

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Eigenvalue	3.5099	1.2083	0.8412	0.6300	0.4734	0.2994	0.0378
Proportion	0.501	0.173	0.120	0.090	0.068	0.043	0.005
Cumulative	0.501	0.674	0.794	0.884	0.952	0.995	1.000

Using the 7 available variables for the time period 2009/10 the normalized data of vegetation loss, slope, soil, elevation, gully stream order, gully area and yearly gully change in metre squared per square metre were used. **Table 35 and Figure 106** present the Proportion of variance, cumulative proportion of variance, and eigenvalues for each component. The components act as representations of the variables being observed. In the case of, Principle Component (PC) 1 the eigenvalue is 3.5099. The higher eigenvalue indicates a higher explanatory power. The significance and explanatory power of PC1 is highlighted in the % of variance value indicated as “Proportion” in the table. This level is given as 50%. PC2 is signified by an eigenvalue of 1.2083 and describes 17% of the total variance. The high eigenvalues both show the significance of these components offering a cumulative proportion of 67%. The high eigenvalue for PC1 indicates the high level of weighting to be given to the associations exhibited in this dimension.

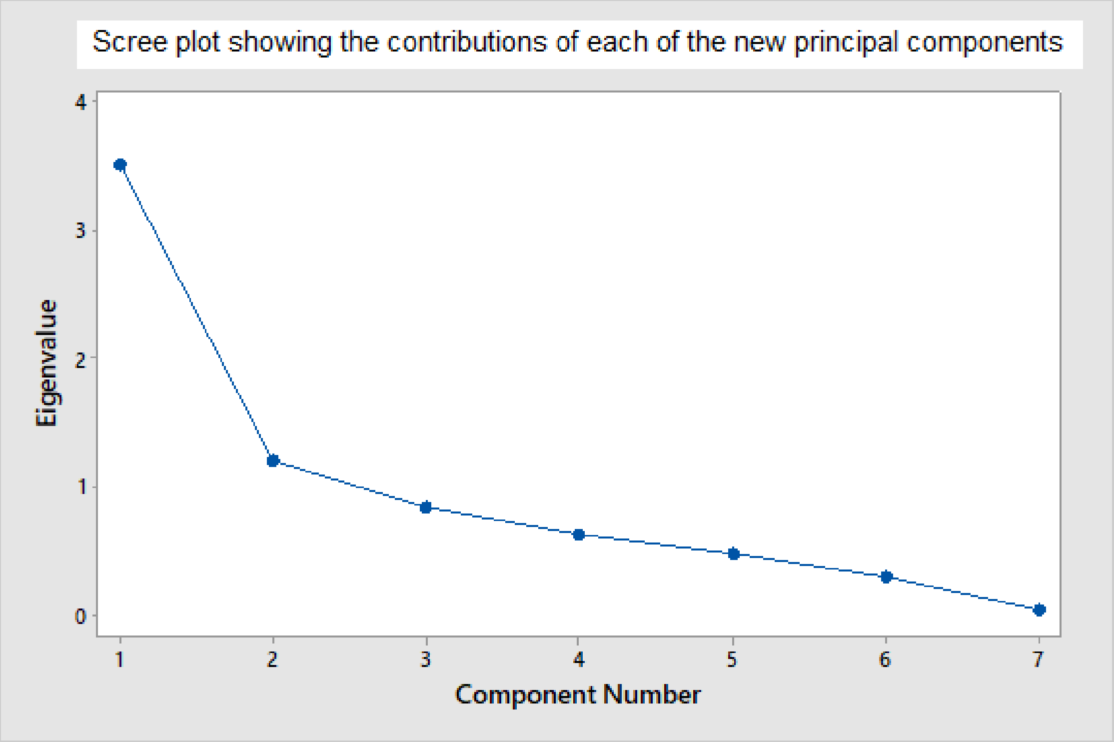


Figure 106: 2009/10 Scree plot showing the contributions of each of the new principal components for the time period 2009/2010. A graphical representation of the principal components of the data. The blue line represents the eigenvalue associated with each component.

Table 36: 2009/2010 Component Score Coefficient Matrix showing the loadings of the components and variables

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7
VegeLoss-m2	0.292	0.329	0.561	0.695	0.017	-0.010	0.091
GullyArea	-0.500	-0.181	0.078	0.123	0.296	-0.127	0.770
Gully change per m2	0.300	-0.182	-0.721	0.529	0.233	0.134	0.073
slope in degrees	0.408	-0.224	0.283	-0.314	0.533	0.553	0.120
soil	0.470	0.084	-0.104	-0.218	-0.588	0.053	0.605
Elevation	0.068	0.818	-0.243	-0.246	0.411	-0.156	0.117
Gully Stream order	0.428	-0.316	0.096	-0.124	0.243	-0.795	-0.011

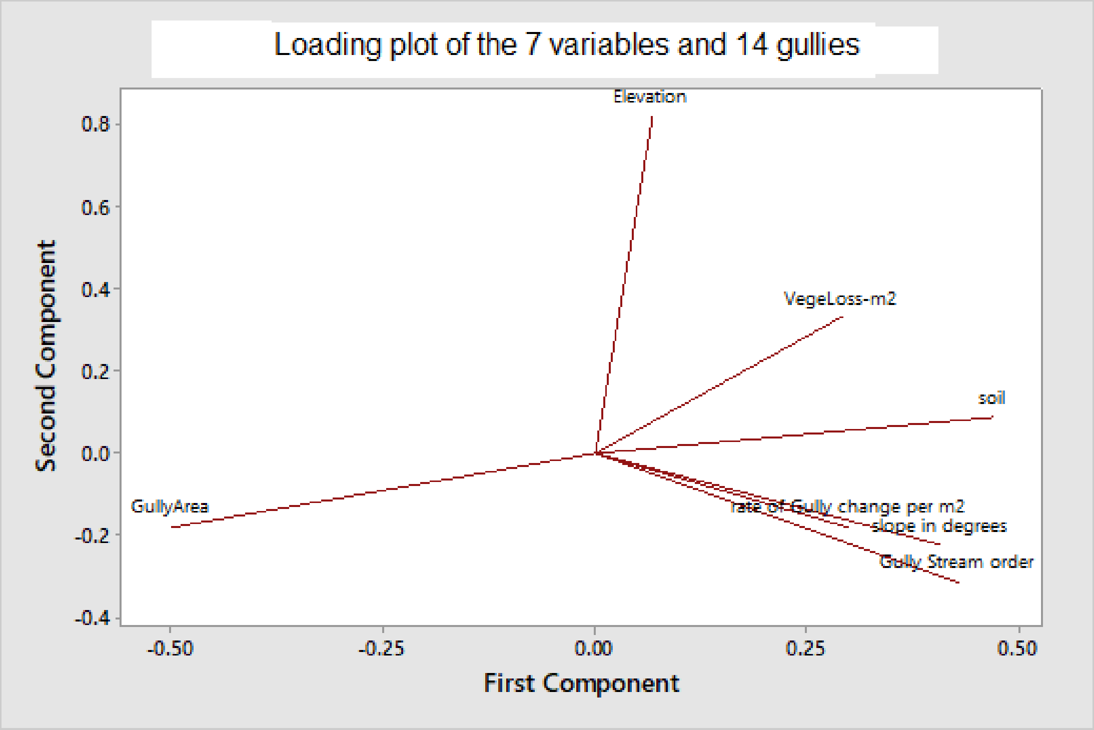


Figure 107: Loading plot of the 7 variables and 14 gullies for the time period 2009/2010

The eigenvalues associated with the principle components are shown visually in **Figure 106**. As can be seen in the figure, the first 2 components all have higher eigenvalues than others. Components beyond 2 have eigenvalues that possess less explanatory power. 67% of the variance in the data is described by the first 2 components. The results in general closely resemble those of Section 5.6.1.

In **Figure 107,** the loading plot is presented using the 1st and 2nd components. The numeric values are presented in **Table 36**. In both cases the results are decomposed on a variable by variable basis to identify their relationships. The immediate observation is that the principle component 1 describes a similar level of variance when considering the variables regarding Gully stream order (43%), Gully area (-50%), soil (47%), slope (41%), Vegetation loss (29%), yearly gully change in metre squared per square metre (30%). This is indicative of higher levels of variance being explained by the principle component for each of the labelled variables and indicative of similarities amongst the variables. Conversely, Elevation with (7%) shows that it once again was not well explained through the 1st component with the other variables clearly dominating.. The performance of

2nd component shows that Elevation performed well in terms of its explained variance of (82%). High scores were also shown for PC2 using Vegetation Loss (33%), and Gully stream order (-32%) showing that they were well explained in both PC1 and PC2. Gully area (-18%), slope (-22), yearly gully change in metre squared per square metre (-18%), performed poorly in relation to PC2. This Analysis in **Table 36** also shows good association between important variables (Gully stream order, soil, slope, vegetation loss, yearly gully change in metre squared per square metre and Gully area) when considering the PC1 with eigenvalue of 3.5099 and explained variance of 50%. However, it is only elevation that appears to be weak in PC1 but stronger in PC2 which has eigenvalue and explained variance of 1.2083 and 17% respectively. The good association that exists in this analysis shows that multiple variables could be having influence on gully development when comparing PC1 and PC2 in the model but again elevation is deemed the least significant and soil showing the strongest relationship with gully area but not necessarily the rate of change.

In terms of inverse relationships, Gully area and Soil show an inverse trend, and Gully area and yearly gully change in metre squared per square metre also have an inverse relationship. The inverse relationship can be seen also between Gully area and Gully stream order, Gully area and soil, PCA shows that more vegetation loss is associated with smaller gully areas **Figure 107**. This is where the more rapid gully area changes occur. Again, the large gullies have already lost a lot of vegetation and therefore, are fully developed.The observation shows that big gullies mean less vegetation loss. This model assumes that once the gully is big, there is actually very little further vegetation loss. For example, Igboukwu gully which is older and larger than Nawfia gully by 2014/2015 has yearly gully change in metre squared per square metre of 0.003m2, while Nawfia has 0.61m2 in the same period, section 5.6.2. Gully area and yearly gully change in metre squared per square metre with trends almost mimicking those from the 2014/2015-time period**.** Gully areas are developing/changing more rapidly in areas with high gully stream order, soil areas with deeply weathered, unconsolidated sandy sediments and friable soils and areas with high vegetation loss. Rates of change appear higher for smaller gullies. Again, a set of trends familiar to these chosen gullies in other time periods. An increase in the numerical class of the soil resulted in an increased rate of change per sq. metre. Evidence suggests that the higher gully stream orders produce a higher gully rate of change. Again, the yearly gully change in metre squared per square metre depends inversely on the area size of the gully with larger areas associated with a lower yearly gully change in metre squared per square metre. Perhaps because these larger gullies have no room to expand, probably fully developed, some of them are being managed, and are less efficient when older/larger. Filtering of less significant variables could not be carried out because all the variables appeared strongly in either PC1 or PC2 and influence the clustering seen in Figure 108 but again elevation appears with the least significant correlation to the gully variables of area and rate of change.

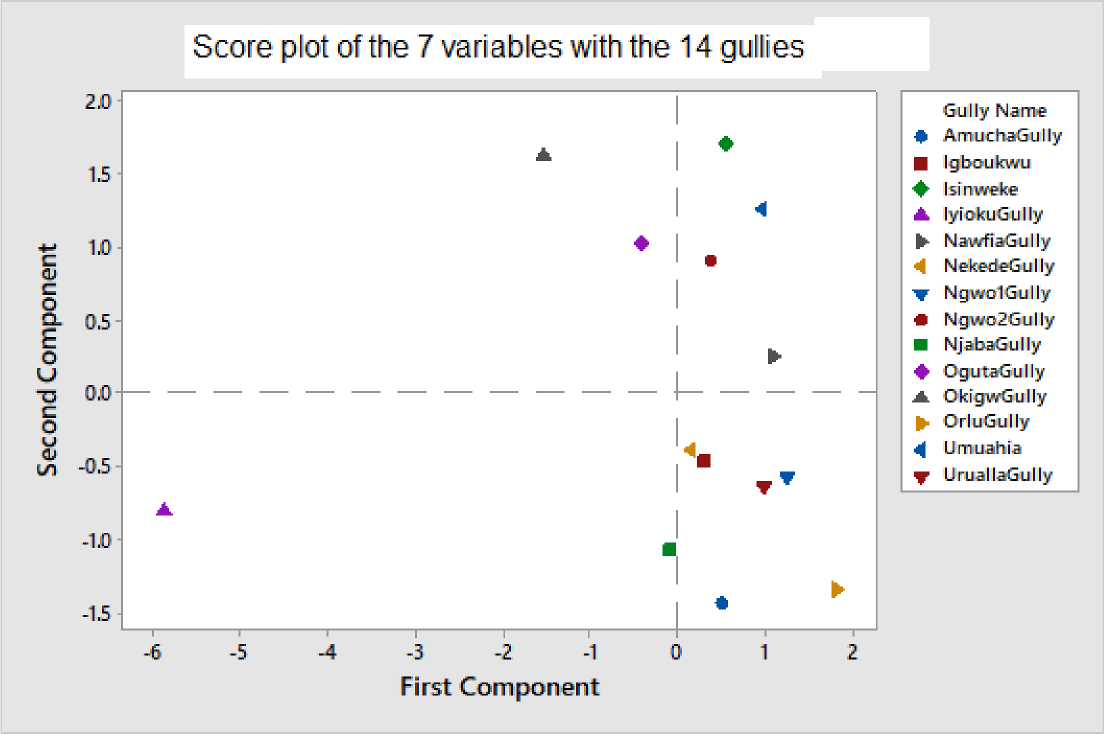


Figure 108: Score plot of the 7 variables with the 14 gullies (2009/2010)

The score plot, plots the component 1 scores against the component 2 scores. This is a scatter plot of the values of the new components (PC1 and PC2) with each point showing the individual gullies in the study. In this **Figure 108**, the gully points are spread between the four quadrants and as with the 2014/15 data the gullies Iyioku and Okigwe are outlying with clear influence from the variable gully area upon their location in the score plot. Other gullies are being dominated by other variables but the clustering is strongly influenced by elevation where there are clear differences between the gullies although no link is apparent with the gully variables of interest.

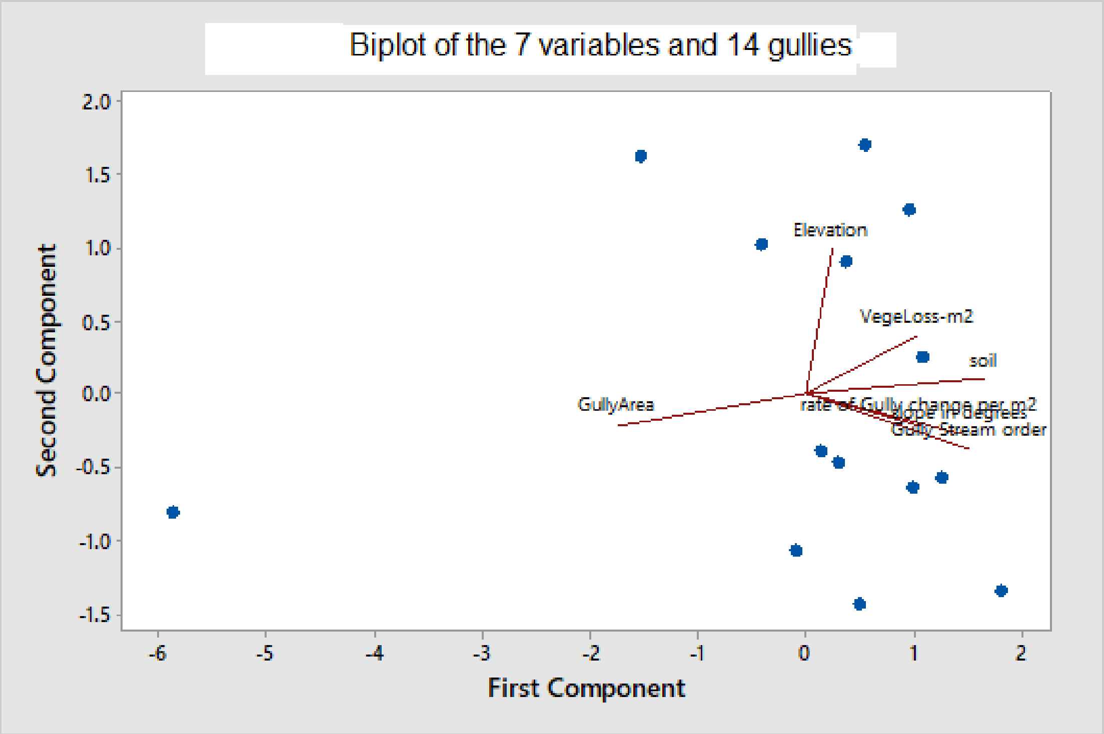


Figure 109: Biplot of the 7 variables and 14 gullies (2009/2010)

From the biplot **figure** 109, there are two large gullies that are dominated by gully area Iyioku and Okigwe gullies **Figure 108**. Four gullies seem to be dominated by Elevation (Ngwo2, Oguta, Isinweke and Umuahia **Figure 109**) while one gully is clustering around vegetation loss and soil (Nawfia). The other 7 gullies (Ngwo1, Urualla, Igboukwu, Orlu, Amucha, Njaba, and Nekede gullies **Figure 109)** seem to be split between the other 3 variables of Gully stream order, yearly gully change in metre squared per square metre and slope, meaning that their relationship is influencing the gullies more. This shows different groups of gullies behaving differently, it can then be said that the individual gullies are clustering around the variables of most influence.

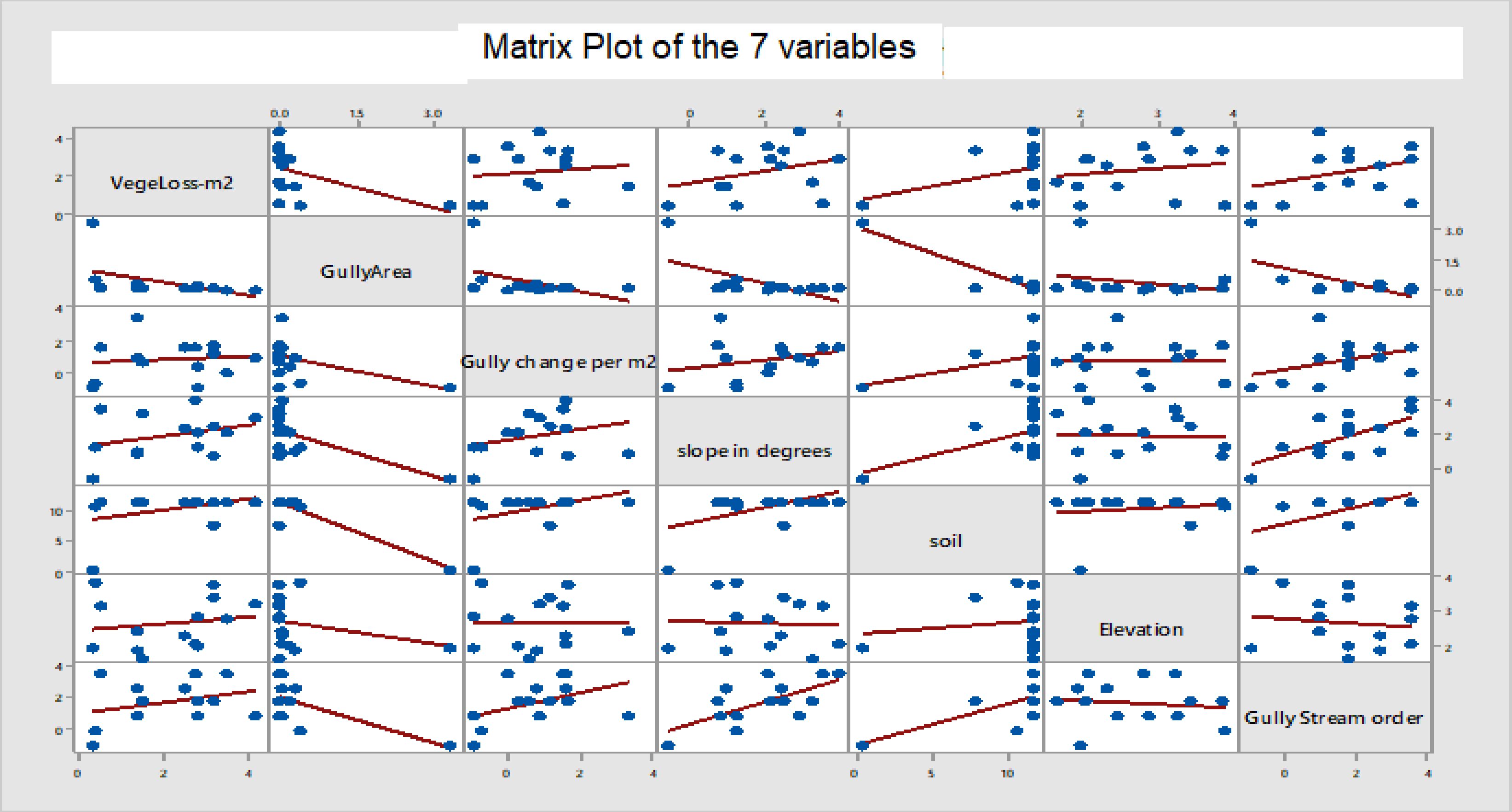


Figure 110:Matrix Plot of 2009/10-VegLoss, SlopeDegrees, Soil, Elevation, Gully stream order, 2010-Gully area, 2009/2010- yearly gully change in metre squared per square metre. In Figure 107 the strong linear relationship between rate of change and gully stream order is evident but less reliable correlations are exhibited with Gully Area due to the significant outliers, similarly for soil. Vegetation loss retains a strong link with the rate of change per sq.metre.

5.6.3 Principal Component Analysis for the Time Period 2006/07: VegLoss, Slope Degrees, Soil, Elevation, Gully Stream, GullyArea and Yearly Gully Change in Metre Squared per Square Metre

Table 37: Eigenanalysis of the Correlation Matrix. 2006/2007 Total Variance Explained from PCA of 7 variables shown for 7 components. Also, shown graphically through the Scree Plot in Figure 111.

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Eigenvalue	3.1065	1.3629	0.9952	0.7825	0.4121	0.2999	0.0410
Proportion	0.444	0.195	0.142	0.112	0.059	0.043	0.006
Cumulative	0.444	0.638	0.781	0.892	0.951	0.994	1.000

The normalized 7 available variables of 2006/07 vegetation loss, slope, soil, elevation, gully stream order, gully area and yearly gully change in metre squared per square metre were used. **Table 37 and figure 111** presents the % of variance (Proportion), cumulative % of variance, and eigenvalues explained by each component. The components represent the variables observed. In Principle Component (PC) 1 the eigenvalue is 3.1065 and the higher eigenvalue indicates a higher explanatory power to explain the variability of the variables better than other principle components. The significance and explanatory power of PC1 is highlighted in the proportion of variance value. This level is given as 44%. PC2 is signified by an eigenvalue of 1.3629 and describes 20% of the total variance. The high eigenvalues both show the explanatory power of these components.

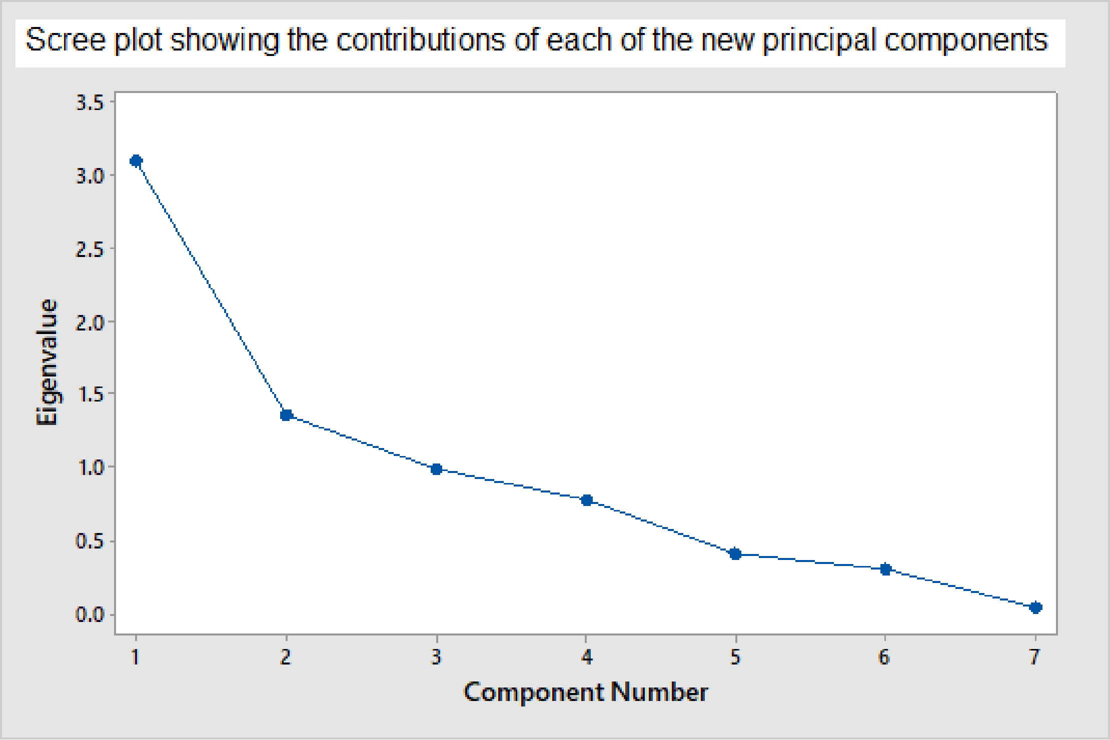


Figure 110: 2006/2010 Scree plot showing the contributions of each of the new principal components; a graphical representation of the principal components of the data. The blue line represents the eigenvalues for each component

Table 38: 2006/2007 Component Score Coefficient Matrix showing the loadings of the components and variables

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7
VegeLoss	-0.072	0.588	-0.495	-0.530	0.333	0.100	0.043
GullyArea	-0.528	-0.204	-0.090	0.126	0.256	-0.140	0.755
Gully change	0.205	0.415	-0.362	0.799	0.073	-0.100	0.036
slope in degrees	0.449	-0.308	0.012	0.067	0.566	0.599	0.140
soil	0.510	0.151	0.002	-0.177	-0.539	0.079	0.624
Elevation	0.068	0.500	0.771	0.016	0.331	-0.155	0.131
Gully Stream order	0.456	-0.270	-0.149	-0.168	0.312	-0.756	0.010

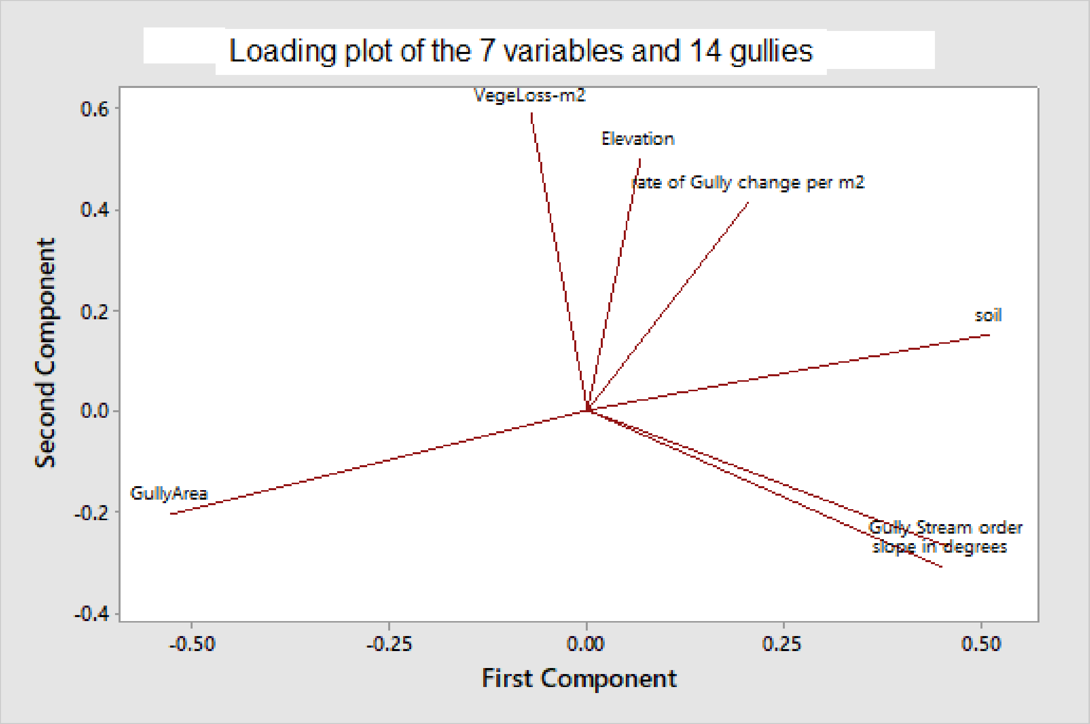


Figure 111: Loading plot of the 7 variables and 14 gullies (2006/2007)

In **Figure 112,** the loading plot is presented using the 1st and 2nd component values. The values are presented in **Table 38**. In both cases the results are explained on a variable by variable basis. The first observation is that the principle component describes a similar level of absolute variance when showing variables of Gully area (-53%), soil (51%), slope (45%) and Gully stream order (46%). Again, highlighting the inverse relationship between gully area and these three variables.

Conversely, yearly gully change in metre squared per square metre (21%) is explained to a lesser level while Vegetation loss (-7%) and Elevation with (7%) showing that the performance in PC1 was poor and they were not well explained. The performance of 2nd component shows that Vegetation loss variability and yearly gully change in metre squared per square metre were explained well in terms of its variance of (53%) and (42%) respectively. In the other way, PC2 shows that Gully area (-20%), and Gully stream order (-27%) indicate similarities through having a reasonable level of variability explained by PC2 but the component is clearly not dominated by these variables. In this analysis, it shows high levels of association between 5 of the variables which include Gully stream order (66%), yearly gully change in metre squared per square metre (21%), soil and slope (51% and 41% respectively), when considering the PC1 scores with eigenvalue of 3.1065 and total explained variance of 44% respectively. This time, vegetation loss and elevation appear to have similar association exploring very little of the variables' variance, Table 38 and Figure 112. In PC2, both vegetation loss (59%) and elevation (50%) appear to have high levels of explained variance suggesting that vegetation loss in this year is correlated with elevation, but care must be taken with this inference as PC2 has eigenvalue and total explained variance of only 1.3629 and 20% respectively. Analysis suggests that the levels of association that exist between Gully stream order, yearly gully change in metre squared per square metre, soil and slope variables in PC1, vegetation loss and elevation in PC2 show that they could be combining to influence the model in a complex manner. There is no clear evidence of a singular variable dominating gully area and development.

In terms of inverse relationships, Vegetation loss and slope are also inversely related which would indicate in this particular year the increased loss of vegetation was associated with areas on lower elevation slopes. The inverse relationship of Gully area with other variables not including vegetation loss highlights again that gully size is greater in areas with low gully stream order, soil areas with lower soil value which is Feralsols and Nitosols less deeply weathered with sandy sediments and Gleysols and Fluvisols (hydromorphic properties and recent alluvial deposits) and slope degrees. Filtering of less significant variables could not be carried out because all the variables appeared strongly in either PC1 or PC2 although the lower significance of vegetation loss in this year is interesting to highlight as it contradicts previous identified trends.

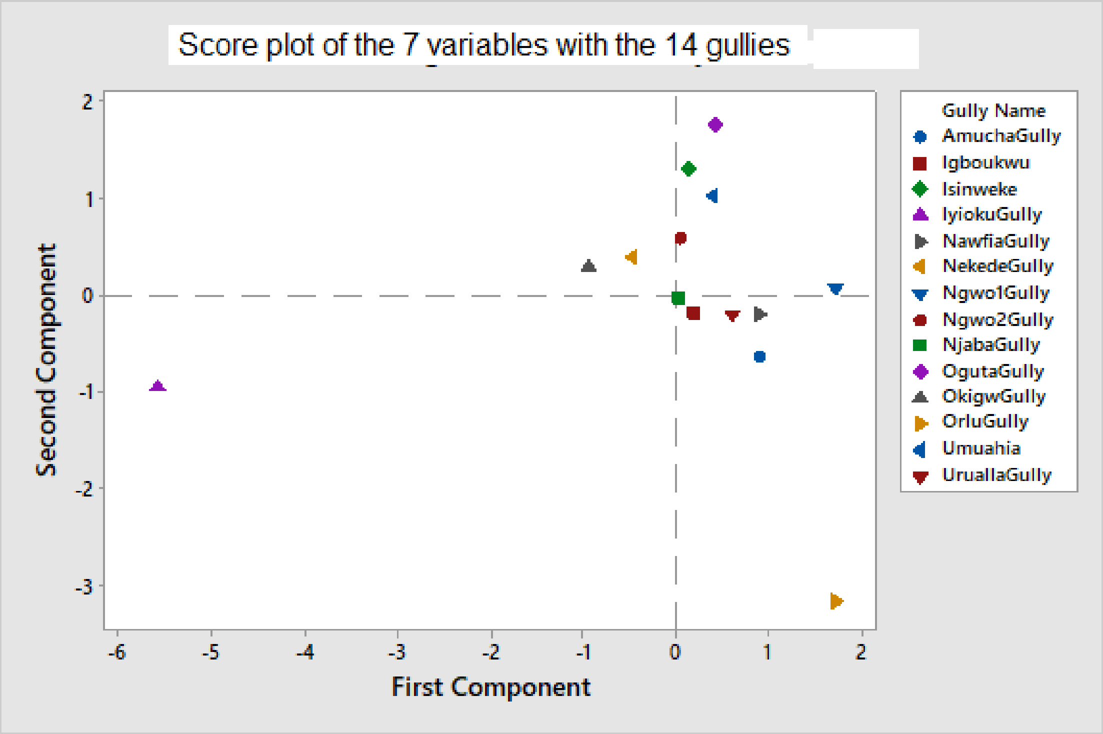


Figure 112: Score plot of the 7 variables with the 14 gullies (2006/2007)

In this reported time period there is distinct clustering of gullies with yearly gully change in metre squared per square metre, elevation and vegetation loss appearing to be a large influence on the largest cluster, also, slope, soil and Gully stream order having influence on some gully cluster. The outlying gullies of Iyioku are still influenced by the gully area variable while the Orlu gully appears to outlie in this time period, being influenced by the significant variables of PC2 **Table 113**.

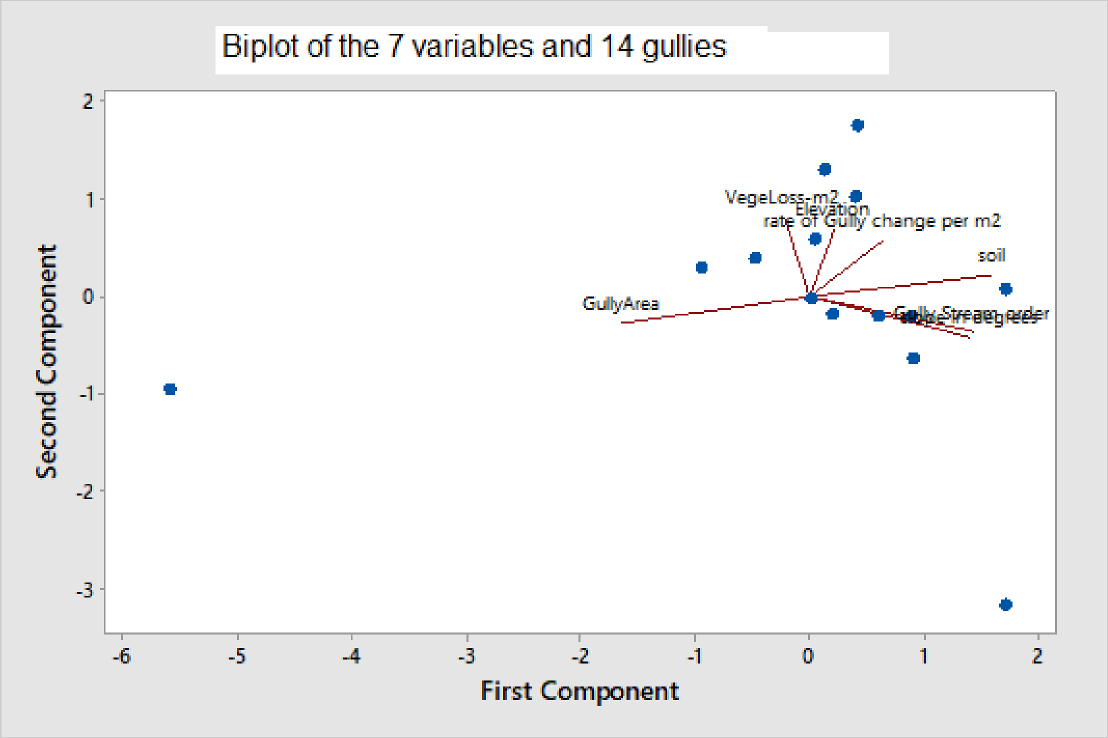


Figure 113: Biplot of the 7 variables and 14 gullies (2006/2007)

Figure 114 shows these clustering trends more clearly in relation to the variables. The outlying gully is evident as previously discussed. The other gullies are dominated by vegetation loss, yearly gully change in metre squared per square metre, soil, gully stream order and slope. Although, 2 gullies (Nekede and Okigwe), are being dominated more by vegetation loss and Gully area.

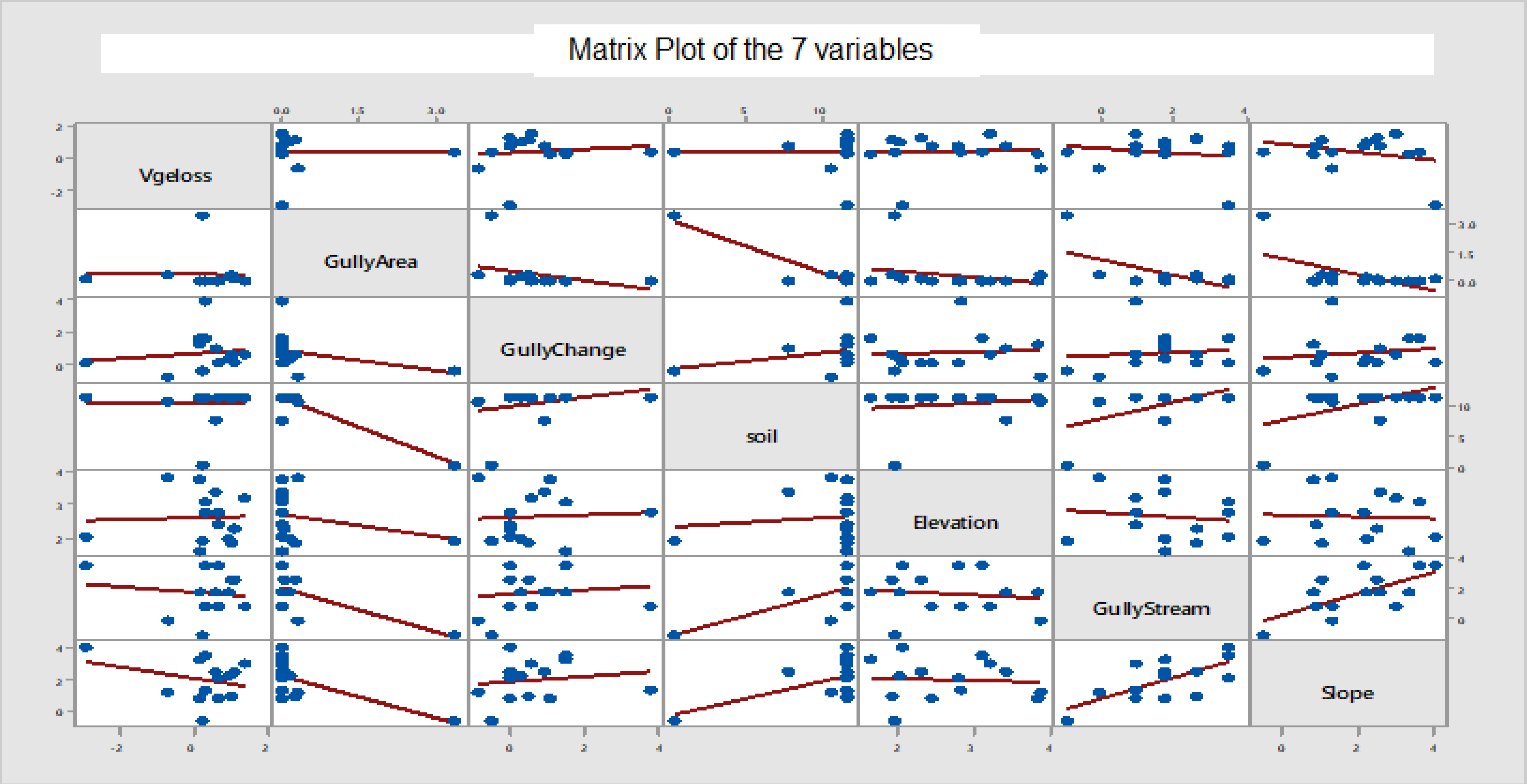


Figure 114: Matrix Plot of 2006/07-VegLoss, SlopeDegrees, Soil, Elevation, Gully stream order, 2007-Gully area, 2006/2007- yearly gully change in metre squared per square metre

5.6.4 Comparison of PCA Analysis of 2014/2015, 2009/2010 and 2006/2007 Variables

From Table 39, looking at PC1 some of the variables appeared with high explanation of variance in 2014/2015 also repeated the same feat in 2009/2010 but to a lesser extent in 2006/2007. For example, Vegetation loss (37%, 29% respectively, and with reduced variance in 2006/07 of -7% but appeared stronger in PC2 with 59%). Soil (46%, 47% and 51% respectively), but Soil performed poorly in PC2 variance of all the years. Gully stream order (44%, 43% and 45%) respectively, in PC2, Gully stream order equally repeated the same feat with variance of 32%, -32% and -27% respectively. Gully area (48%, -50%, and -53%) respectively, but PC2 results for 2014/15, 2009/2010 and 2006/07 all produced weak variance. yearly gully change in metre squared per square metre was explained in the three time periods to the values of 25%, 30% and 20% for 2014/15, 2009/10, and 2006/07 respectively. Slope has 41%, 47% and 51% respectively. Elevation produced weak variance through out PC1 of the years 6%, 7% and 7% respectively, but was strong in the PC2 of all the years -83%, 82% and 50% respecrively.

It can be noticed that all the variables identified to have their variance explained to a high level by PC1 2014/2015, 2009/10 and 2006/2007, appeared to be weak in PC2 of all the years. Those that appeared strongly in PC2, appeared with weak variance in PC1 of all the years, with an exception of Gully stream order that has high variance through out the years, showing how consistent its influence is on gully development. The same environmental variables operational in 2014/2015 appear to have been the major gully factors responsible for gully development and yearly gully change in metre squared per square metre in the study area for the overall encompassing time period although the influence of vegetation loss was less significant in 2006/7. From the biplot **figures 104, 109 and 114** of 2014/15, 2009/2010 and 2006/07, two large gullies dominate the effect of gully area, these are the Iyioku and Igboukwu, Okigwe and Oguta and only Iyioku gully for 2006/2007. These gullies appear to behave in a different fashion to the other studied gullies. This is evident by looking at the Score plots for the three time periods when excluding these gullies, **Figures 103, 108 and 113**. Also, from the biplots all the gullies, they continually appear to be dominated by all the variables. There is no need removing the less significant ones to rerun the PCA model again since all the variables entered in all the years appeared strongly in either PC1 or PC2 or both. The reason for all these will be discussed more in the discussion section of the study.

Table 39: Comparison of Component Score Coefficient Matrix
(for 2014/15, 2009/10 and 2006/07 of the 7 variables from PCA component Score Coefficient Matrix of **Tables 34, 36 and 38-data output.** The PC1 has eigenvalue of 3.5681 in 2014/2015, 3.5099 in 2009/2010 and 3.1065 in 2006/2007 **Tables 33, 35** and 37 respectively.)

	2014/2015		2009/2010		2006/2007	
Components	1	2	1	2	1	2
Vegetation Loss	0.367	-0.118	0.292	0.329	-0.072	0.588
Slope	0.410	0.143	0.408	-0.224	0.449	-0.308
Soil	0.461	-0.155	0.470	0.084	0.510	0.151
Elevation	0.055	-0.827	0.068	0.818	0.068	0.500
GullyStreamOrder	0.438	0.323	0.428	-0.316	0.456	-0.270
Gully_Area	-0.476	0.245	-0.500	-0.181	-0.528	-0.204
yearly gully change	0.252	0.305	0.300	-0.182	0.205	0.415

5.7 Multiple Linear Regression Analysis (MLRA)

Multiple linear regression (MLR) is used in this study to determine how specific factors such as, Vegetation loss, Slope, Soil, elevation, gully stream order and gully area influence yearly gully change in metre squared per square metre. All the listed variables have been deemed influential on the formation of gullies in different studies published in the literature. Their level of influence is typically varied according to site specific conditions. In this MLR all the gullies will be considered in a singular analysis, being all gullies found within the region, before using the clusters identified in the PCA and cluster analyses to look at trends within the clustered gullies. MLR could be used to model the impact that each of these variables has on gully area development in terms of absolute area and rates of change per square metre. It may be the case that different trends are identified according to the identified clusters. This may be a clear indication that distinct types of gullies exist dependent on the specific variables that cluster which define the erosion. The result of the regression analysis will help identify the significant variables that are responsible for yearly rate of change per square metre. This analysis was carried out for years 2006/2007, 2009/2010 and 2014/2015. The years were chosen because from the analysed satellite imageries of the study area, all the gullies have developed by 2006/2007 except some gullies like Nawfia, and Nekede gullies which developed after 2007. Again, 2009/10 was used to check the results between 2006/2007 and 2014/15 the last year of the study. These years are also nicely located to provide a snapshot of what has been happening in the past and to find out if those variables that are responsible for yearly gully change in metre squared per square metre in each of the clusters are still the same across the years.

The following analyses will be conducted in this section:

- MLRA (a) covering the 2014/15 time period (Variables used Gully area, yearly gully change in metre squared per square metre, Vegetation Loss, Soil, Slope in degrees, Gully stream order and Elevation.
- MLRA (b) covering the 2009/10 time period (Variables used Gully area, yearly gully change in metre squared per square metre,

Vegetation Loss, Soil, Slope in degrees, Gully stream order and Elevation.

- MLRA (c) covering the 2006/07 time period ((Variables used Gully area, yearly rate of change per unit area of gully, Vegetation Loss, Soil, Slope in degrees, Gully stream order and Elevation.

In each analysis 7 gully variables are examined. 6 independent variables (Vegetation loss, slope, soil, gully stream order, elevation and gully area) and one dependent variable (yearly gully change in metre squared per square metre). The analysis is being conducted to determine the predictive capability of the independent variables (vegetation loss, soil and gully stream order) recognised for 2014/15, 2009/10 and 2006/07, in the previous Cluster Analysis and PCA, to have similarities with the dependent variable, yearly rate of change per unit area of gully.

Due to the results from the previous multivariate analysis it is expected that vegetation loss, soil, slope and gully stream order will have a positive impact on the rate of change per sq. metre.Those that showed a low similarity in previous analyses will be expected to be removed from the MLR at an early stage. All the variables were analysed using MLRA because they appeared with strong variance in PC1 or PC2 of Principal Component Analysis. The expectation is that there is no single variable responsible for influencing the rate of change but that it is a truly multivariate relationship.

5.7.1 Multiple Linear Regression Analysis (2014/2015)

Table 40: depicts the variables that will be used as independent and dependent variables in the analysis

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	GullyStreamOrder, Elevation, Slope, VegLoss2015, Soil, GullyArea2015[b]	.	Enter

a. Dependent Variable: RateOfChange2015

b. All requested variables entered.

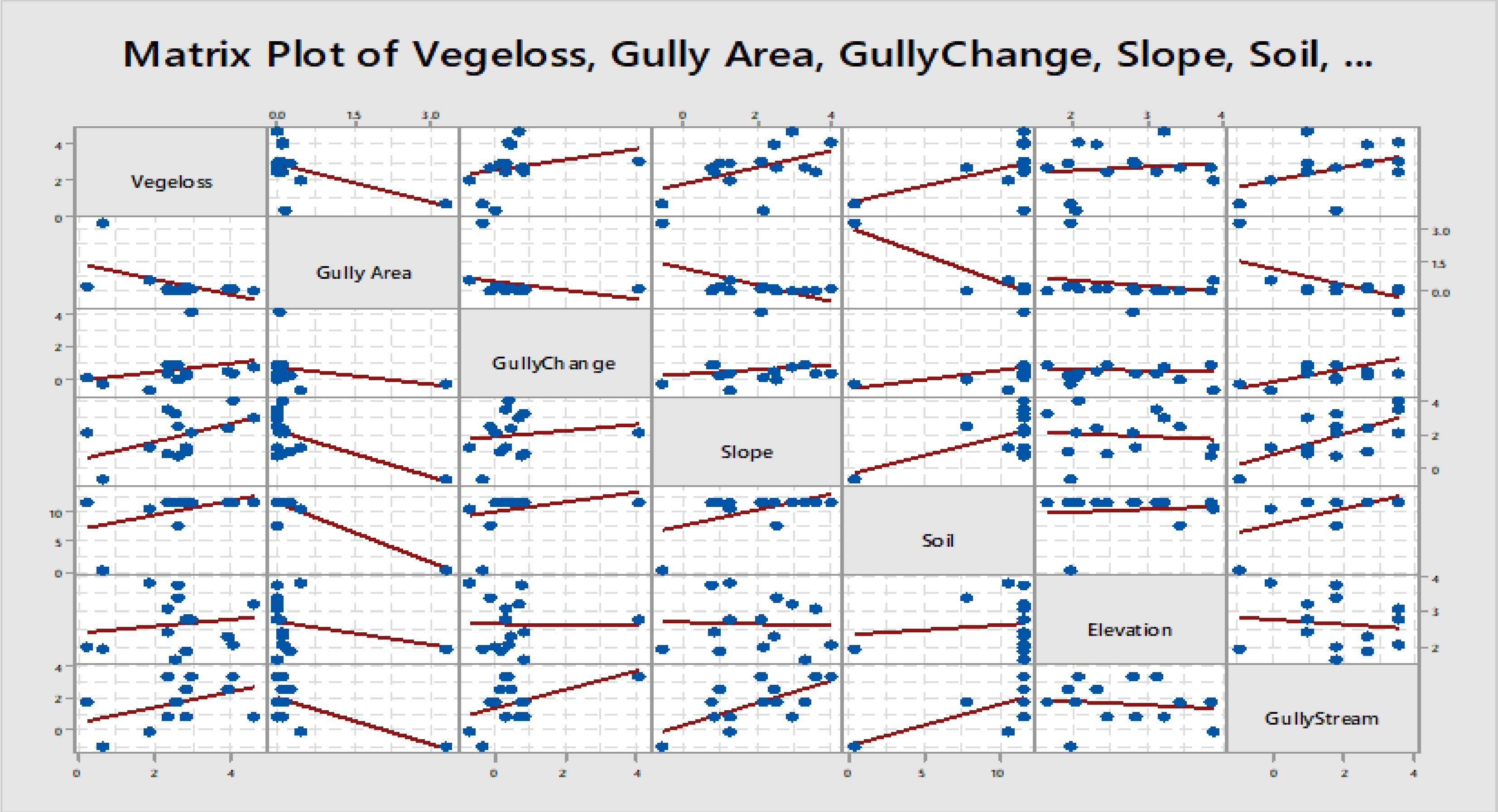


Figure 115: Matrix Plot of 2014/15-VegLoss, SlopeDegrees, Soil, Elevation, Gully stream order, 2015-Gully area, 2014/2015- yearly gully change in metre squared per square metre

Table 41: depicts the variables that will be used as independent and dependent variables in the analysis

Correlations

		Veg_Loss	Slope	Soil	Elevation	GullyStream	Gully_Area	GullyChange
Veg_Loss	Pearson Correlation	1	.508	.476	.147	.433	-.515	.279
	Sig. (2-tailed)		.063	.085	.617	.122	.059	.334
	N	14	14	14	14	14	14	14
Slope	Pearson Correlation	.508	1	.531	-.067	.676**	-.613*	.155
	Sig. (2-tailed)	.063		.051	.820	.008	.020	.597
	N	14	14	14	14	14	14	14
Soil	Pearson Correlation	.476	.531	1	.132	.602*	-.932**	.303
	Sig. (2-tailed)	.085	.051		.653	.023	.000	.292
	N	14	14	14	14	14	14	14
Elevation	Pearson Correlation	.147	-.067	.132	1	-.139	-.259	-.033
	Sig. (2-tailed)	.617	.820	.653		.635	.372	.911
	N	14	14	14	14	14	14	14
GullyStream	Pearson Correlation	.433	.676**	.602*	-.139	1	-.619*	.489
	Sig. (2-tailed)	.122	.008	.023	.635		.018	.076
	N	14	14	14	14	14	14	14
Gully_Area	Pearson Correlation	-.515	-.613*	-.932**	-.259	-.619*	1	-.270
	Sig. (2-tailed)	.059	.020	.000	.372	.018		.350
	N	14	14	14	14	14	14	14
GullyChange	Pearson Correlation	.279	.155	.303	-.033	.489	-.270	1
	Sig. (2-tailed)	.334	.597	.292	.911	.076	.350	
	N	14	14	14	14	14	14	14

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

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

Out of the 6 independent variables, it is only gully stream order that displays moderate correlation with yearly gully change in metre squared per square metre, the dependent variable having a moderate positive correlation of 0.489, but not significant enough to predict yearly gully change in metre squared per square metre. No Other significant correlations are evident between them and yearly gully change in metre squared per square metre.

Table 42: Anova Table (test using alpha = 0.05)

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	5.352	6	.892	.562	.750[b]
	Residual	11.104	7	1.586		
	Total	16.456	13			

a. Dependent Variable: GullyChangePer_sqmtr

b. Predictors: (Constant), Gully_Area, Elevation, Veg_Loss, Slope, GullyStreamOrder, Soil

According to **Table 42** , the overall regression model was not significant, for regression F= 0.596, p=0.750. This indicates the statistical significance of the regression model that was run. Here, p = 0.750, which is more than 0.05, and indicates that, overall, the regression model is not statistically significant for predicting the outcome variable. This means some of the predictors are not able to account for a significant amount of variance in predicting gully rate of change per sq. metre. This is expected due to the lack of linearity evident between the dependent and independent variables.

Table 43:Measure of variance of the variables entered in Multiple linear regression

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.570[a]	.325	-.253	1.25945971

a. Predictors: (Constant), Gully_Area, Elevation, Veg_Loss, Slope, GullyStreamOrder, Soil

b. Dependent Variable: RateOfChange

Table 43, provides the R and R^2 values. The R value represents the simple Pearson's correlation and is 0.570 (the "R" Column), which indicates a medium degree of correlation between the model and the actual data. The R^2 value (the "R Square" column) indicates how much of the total variation in the dependent variable, can be explained by the independent variables.In this case, 33% can be explained, but it doesn't appear significant enough, which is probably a consequence of a low number of samples available for each variable.Taken as a set, the predictors vegetation loss, slope, soil, gully stream order, elevation and gully area account for 33% of the variance in yearly gully change in metre squared per square metre. R^2 is a measure of the amount of variance in dependent variable that independent variables or predictors account for when taken as a group. **Table 44** outlines the significance of each variable in this model construct with only Gully Stream Order being deemed better than other predictor. This is as expected looking at the scatterplot matrix.

Table 44: Coefficients of the variables showing significance in Multiple linear regression

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-1.141	5.066		-.225	.828
	Veg_Loss	.172	.361	.182	.477	.648
	Slope	-.321	.422	-.369	-.761	.471
	Soil	.065	.337	.180	.192	.853
	Elevation	.054	.578	.035	.093	.928
	GullyStreamOrder	.555	.390	.675	1.422	.198
	Gully_Area	.247	1.369	.192	.180	.862

a. Dependent Variable: GullyChangePer_sqmtr

It can be concluded that gully stream order at p= 0.198 is the closest variable to showing significance above 80%. Other gully factors; vegetation loss, soil, slope, elevation and Gully area are far from being statistically significant within the regression. This indicates that they do not have much of a linear relationship with the dependent variable. To improve the analysis, variables that are less significant variables were removed and only guly stream order and slope were tested with yearly gully change in metre squared per square metre, gully stream order improved in the prediction with P=0.064 and no improvement was found in slope which is p= 0.367 **Appendix X Table 104.**

5.7.2 Multiple Linear Regression Analysis (2009/2010)

The variables used in this specific analysis are identified in **Table 45**. The dependent variable is yearly gully change in metre squared per square metre.

Table 45: 2009/2010 Dependent and independent variables entered for (MLR)

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	GullyStreamOrder, Elevation, Slope, Soil, VegLoss2010, GullyArea2010[b]	.	Enter

a. Dependent Variable: RateOfChange2010

b. All requested variables entered.

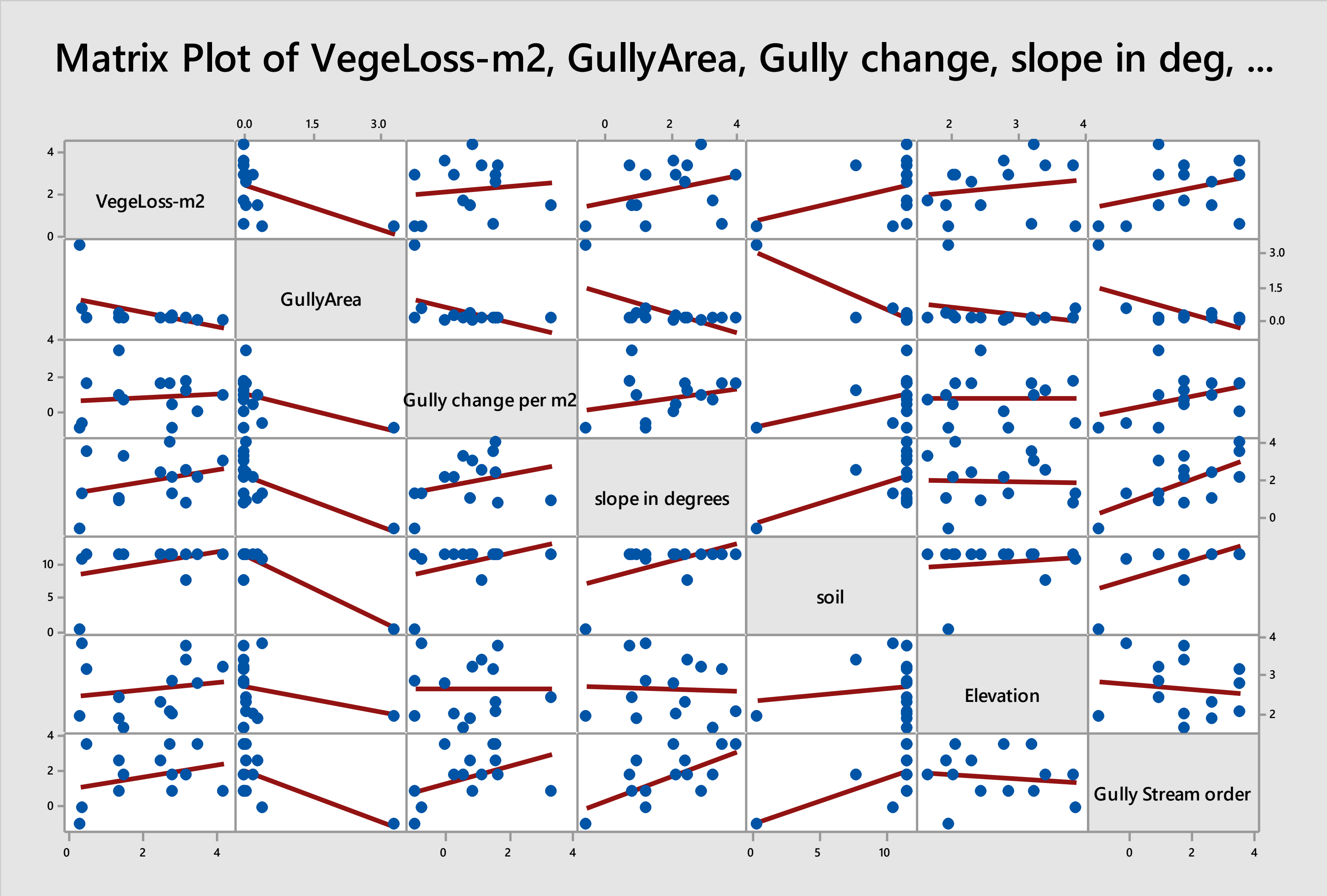


Figure 117: Matrix Plot of 2009/10-VegLoss, SlopeDegrees, Soil, Elevation, Gully stream order, 2010-Gully area, 2009/2010- yearly gully change in metre squared per square metre

Table 46 2009/2010 Anova Table (test using alpha = .05)

ANOVA[a]						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	5.590	6	.932	.502	.790[b]
	Residual	12.991	7	1.856		
	Total	18.581	13			
a. Dependent Variable: GullyChange						
b. Predictors: (Constant), GullyStream, Elevation, Vegeloss, Soil, Slope, GullyArea						

According to **Table 46**, the overall regression model was not significant for this time period, with the result producing p = 0.790. This indicates the regression model is not statistically significantly to predict the outcome variable. The combination of predictors does not account for a significant amount of variance in predicting yearly gully change in metre squared per square metre when considering a linear relationship.

Table 47: Correlation Table of the year 2010 variables

Correlations								
		Vegeloss	Gully Area	Gully Change	Slope	Soil	Elevation	Gully Stream
Vegeloss	Pearson Correlation	1	-.489	.128	.328	.368	.176	.309
	Sig. (2-tailed)		.076	.662	.252	.195	.547	.282
	N	14	14	14	14	14	14	14
GullyArea	Pearson Correlation	-.489	1	-.463	-.615*	-.933**	-.266	-.622*
	Sig. (2-tailed)	.076		.096	.019	.000	.358	.018
	N	14	14	14	14	14	14	14
Gully Change	Pearson Correlation	.128	-.463	1	.283	.405	-.004	.415
	Sig. (2-tailed)	.662	.096		.327	.150	.990	.140

	N	14	14	14	14	14	14	14
Slope	Pearson Correlation	.328	-.615*	.283	1	.531	-.055	.676**
	Sig. (2-tailed)	.252	.019	.327		.051	.852	.008
	N	14	14	14	14	14	14	14
Soil	Pearson Correlation	.368	-.933**	.405	.531	1	.136	.602*
	Sig. (2-tailed)	.195	.000	.150	.051		.644	.023
	N	14	14	14	14	14	14	14
Elevation	Pearson Correlation	.176	-.266	-.004	-.055	.136	1	-.126
	Sig. (2-tailed)	.547	.358	.990	.852	.644		.667
	N	14	14	14	14	14	14	14
Gully Stream	Pearson Correlation	.309	-.622*	.415	.676**	.602*	-.126	1
	Sig. (2-tailed)	.282	.018	.140	.008	.023	.667	
	N	14	14	14	14	14	14	14
*. Correlation is significant at the 0.05 level (2-tailed).								
**. Correlation is significant at the 0.01 level (2-tailed).								

Table 47 shows that all the independent variables like vegetation Loss, soil, slope, gully stream order, gully area and Elevation did not correlate well with yearly gully change in metre squared per square metre and it is likely that any model will fail to meet the assumption of linearity and additivity.

Table 48: : Measure of variance of the 2009/2010 variables entered in Multiple linear regression

Model Summary				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.549[a]	.301	-.298	1.3622883
a. Predictors: (Constant), GullyStream, Elevation, Vegeloss, Soil, Slope, GullyArea				

Table 48 provides the R and R^2 values. The R value represents the simple correlation and is 0.549 (the "**R**" Column). The R^2 value (the "**R Square**" column)

indicates how much of the total variation in the dependent variable, yearly gully change in metre squared per square metre, can be explained by the independent variables, vegetation loss, gully area, slope, elevation, soil, and gully stream order. In this case, 30% can be explained. The adjusted R squared value is low, indicating the ineffectiveness of the variables used in the model.

Table 49: 2009/2010 Coefficients of the variables showing significance in Multiple linear regression

Coefficients[a]						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	4.747	5.957		.797	.452
	Vegeloss	-.172	.360	-.180	-.477	.648
	GullyArea	-1.508	1.615	-1.115	-.934	.381
	Slope	-.197	.441	-.213	-.446	.669
	Soil	-.224	.385	-.584	-.582	.579
	Elevation	-.272	.618	-.169	-.440	.673
	GullyStream	.220	.421	.252	.524	.617

a. Dependent Variable: GullyChange

Looking at the p-value of the t-test for each predictor in **Table 49**, it is obvious that none of the gully factors contributes significantly to the model at the 95% confidence level, or even approaches this significance. Therefore, non of the independent variables performed well and could not go for further MLRA test

5.7.3 Multiple Linear Regression Analysis (2006/2007)

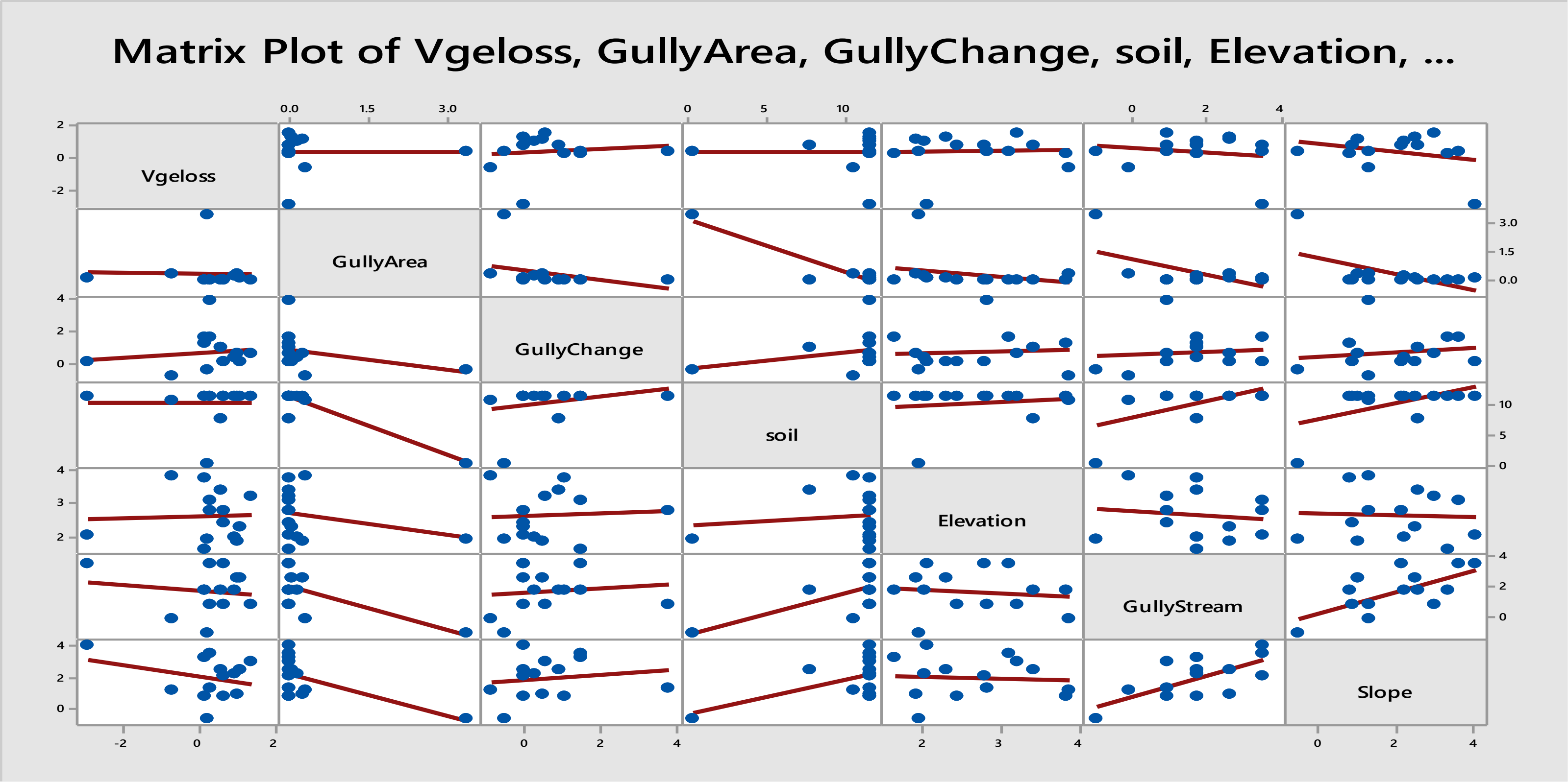


Figure 116: Matrix Plot of 2006/07-VegLoss, SlopeDegrees, Soil, Elevation, Gully stream order, 2007-Gully area, 2006/2007- yearly gully change in metre squared per square metre.

Table 50: : 2006/2007 Dependent and independent variables entered for (MLRA)

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	GullyStreamOrder, Elevation, VegLoss2007, Soil, Slope, GullyArea2007[b]	.	Enter

a. Dependent Variable: RateOfChange2007

b. All requested variables entered.

Table 51: 2006/2007 Anova Table (test using alpha = .05)

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	2.515	6	.419	.198	.967[b]
	Residual	14.856	7	2.122		
	Total	17.371	13			

a. Dependent Variable: GullyChangePer_sqmtr

b. Predictors: (Constant), Gully_Area, Veg_Loss, Elevation, GullyStreamOrder, Slope, Soil

As with the other iterations, according to **Table 51**, the overall regression model was not significant, for regression F= 0.198, p = 0.967. This indicates the statistical significance of the regression model that was run. Here, p = 0.967, which is far more than 0.05, and indicates that, overall, the regression model is not statistically significantly to predict the outcome variable. This could mean that, in this configuration, the predictors do not account for a significant amount of variance in yearly gully change in metre squared per square metre.

Table 52: Correlation Table of the year 2006/2007 variables

Correlations

		Veg_Loss	Slope	Soil	Elevation	Gully Stream	Gully Area	Gully Change
Veg_Loss	Pearson Correlation	1	-.285	.008	.040	-.155	-.020	.140
	Sig. (2-tailed)		.323	.978	.893	.596	.945	.634
	N	14	14	14	14	14	14	14
Slope	Pearson Correlation	-.285	1	.531	-.067	.676**	-.607*	.149
	Sig. (2-tailed)	.323		.051	.820	.008	.021	.612
	N	14	14	14	14	14	14	14
Soil	Pearson Correlation	.008	.531	1	.132	.602*	-.937**	.280
	Sig. (2-tailed)	.978	.051		.653	.023	.000	.332
	N	14	14	14	14	14	14	14
Elevation	Pearson Correlation	.040	-.067	.132	1	-.139	-.270	.063
	Sig. (2-tailed)	.893	.820	.653		.635	.350	.830
	N	14	14	14	14	14	14	14
GullyStream	Pearson Correlation	-.155	.676**	.602*	-.139	1	-.611*	.118
	Sig. (2-tailed)	.596	.008	.023	.635		.020	.687
	N	14	14	14	14	14	14	14
Gully_Area	Pearson Correlation	-.020	-.607*	-.937**	-.270	-.611*	1	-.328
	Sig. (2-tailed)	.945	.021	.000	.350	.020		.253
	N	14	14	14	14	14	14	14
Gully Change	Pearson Correlation	.140	.149	.280	.063	.118	-.328	1
	Sig. (2-tailed)	.634	.612	.332	.830	.687	.253	
	N	14	14	14	14	14	14	14

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

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

Table 52, shows all the independent variables vegetation Loss, gully stream order, soil, slope, gully area and Elevation did not correlate well with yearly gully change in metre squared per square metre.

Table 53: Measure of variance of the 2006/2007 variables entered in Multiple linear regression

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.381[a]	.145	-.588	1.45681573

a. Predictors: (Constant), Gully_Area, Veg_Loss, Elevation, GullyStreamOrder, Slope, Soil

This **table** provides the R and R2 values. The R2 value (the "R Square" column) indicates how much of the total variation in the dependent variable, yearly gully change in metre squared per square metre, can be explained by the independent variables.In this case, 38% can be explained, which is poor representation.

From the model summary **Table 53** above, the R^2, which is the overall measure of variance of yearly gully change in metre squared per square metre accounted for, is recorded at a value of 0.145, which indicates a very poor prediction capability for determining yearly gully change in metre squared per square metre.

Table 54: 2006/2007 Coefficients of the variables showing significance in Multiple linear regression

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	2.826	6.343		.445	.669
	Veg_Loss	.111	.413	.103	.269	.796
	Slope	-.026	.505	-.029	-.051	.960
	Soil	-.113	.417	-.304	-.270	.795
	Elevation	-.191	.687	-.122	-.279	.789
	GullyStreamOrder	-.113	.450	-.134	-.251	.809
	Gully_Area	-.958	1.684	-.743	-.569	.587

a. Dependent Variable: GullyChangePer_sqmtr

Looking at the p-value of the t-test for each predictor in **Table 54**, it is obvious that none of the gully factors in the model contribute significantly in this combination. As a model, they do not prove statistically significant in predicting the yearly gully change in metre squared per square metre. Therefore, non of the independent variables performed well and could not go for further MLRA test.

These time periods did not have any variable that predicted the models in the different years, the 6 variables clearly don’t work as a group to predict the yearly rate of change per unit area of gully based on this model. This presents quite significant evidence that the relationship is not linear. The dependent variables were refined and those variables that appeared least significant with yearly gully change in metre squared per square metre were removed to increase the significance of variables entered. It was observed that among all the independent variables entered with yearly gully change in metre squared per square metre for 2014/15, 2009/2010 and 2006/2007 there was no significant linear predictor and that the overall performance of the regressions was not improved using Step Wise Regression.

The signifant findings of these four analyses were thus: Cluster Analysis, PCA and Multiple linear regression analysis and additional nonlinear Regression Analysis (reported in Appendix VIII) confirm that vegetation loss, gully stream order, soil, slope, and gully area variables have more relationship and significance to yearly gully change in metre squared per square metre than elevation variable. It is obvious that most of the variables do present quite significant evidence that the relationship is nonlinear, therefore, nonlinear analysis was used to find out again the relationship and behaviour each of the independent variables against dependent variable (yearly gully change in metre squared per square metre). It was used in the same manner as in Archontoulis and Miguez (2015) and Niu (1996) where Nonlinear Regression Models where used in Agricultural Research and Environmental Time Series respectively. The application in this study reveals thus for 2014/15 variables: In **Appendix VI Figure 179** where nonlinear regression reported that an exponential increase in the yearly gully change in metre squared per square metre is expected as the Vegeloss increases.

Conversely, in the same year 2014/15, slope reported an exponential decrease in the yearly gully change in metre squared per square metre as the slope degree increase **Figure 180.** For soil and yearly gully change in metre squared per square metre, it shows that there is an asymptotic relation between the yearly gully change in metre squared per square metre and the soil. As the soil value increases towards infinity, the yearly gully change in metre squared per square metre also increases **Figure 181.** In the same vain, **Figure182** shows that increase in elevation has no significant effect on yearly gully change in metre squared per square metre. In the nonlinear regression analysis of gully stream order and yearly gully change in metre squared per square metre **Figure 183, a**n exponential increase in the yearly gully change in metre squared per square metre is expected as the gully stream order increases. For Gully area and yearly gully change in metre squared per square metre **Figure 184** an inverse relationship exists between the yearly gully change in metre squared per square metre and the gully area. The yearly gully change in metre squared per square metre reduces as the gully area increases. The result could be linked to gully control measures carried out in most of the gullies as was discussed in the discussion section.

In the year 2009/10, **Appendix VII Figure 185** yearly gully change in metre squared per square metre change per sq.metre versus VegLoss 2009/10. The analysis shows that there is an asymptotic relation between the yearly gully change in metre squared per square metre and the veg loss. As the veg loss increases towards infinity, the yearly gully change in metre squared per square metre also increases. Again, for **Figure 186,** there is an exponential decrease in the yearly gully change in metre squared per square metre as the slope degree increases. In the case of yearly gully change in metre squared per square metre versus Soil **Figure 187,** the analysis shows that there is an asymptotic relation between the yearly gully change in metre squared per square metre and the soil. As the soil value increases towards infinity, the yearly gully change in metre squared per square metre also increases. For Elevation, the analysis shows that increase in elevation has no significant effect on the yearly gully change in metre squared per square metre **Figure 188**. Gully stream order reported that an exponential increase in the yearly gully change in metre squared per square metre is expected as the gully stream order increases **Figure 189**. There is an inverse relationship between the yearly gully change in metre squared per square metre and the gully area. The yearly gully change in metre squared per square metre reduces as the gully area increases **Figure 190**.

In the year 2006/07, **Appendix VIII** yearly gully change in metre squared per square metre versus VegeLoss **Figure 191,** The analysis shows that there is an asymptotic relation between the yearly gully change in metre squared per square metre and the veg loss. Nonlinear analysis of slope degrees and yearly gully change in metre squared per square metre, shows that there is an asymptotic relation between the yearly gully change in metre squared per square metre and the slope degree. As the slope degree increases towards infinity, the yearly gully change in metre squared per square metre decreases (Gullies form mainly at the base of slopes, as the runoff gather up slope they come down to cause gullies).

Figure 192. The soil versus yearly gully change in metre squared per square metre **Figure 193,** the analysis shows that there is an asymptotic relation between the yearly gully change in metre squared per square metre and the soil. As the soil value increases towards infinity, the yearly gully change in metre squared per square metre also increases. In the elevation, the analysis reveals that increase in elevation has no significant effect on the yearly gully change in metre squared per square metre **Figure 194**. An exponential increase in the yearly gully change in metre squared per square metre is expected as the gully stream order increases as can be observed in **Figure 195.** For gully area versus yearly gully change in metre squared per square metre **Figure 196,** an inverse relationship exists between the yearly gully change in metre squared per square metre and the gully area. The yearly gully change in metre squared per square metre reduces as the gully area increases. As reported earlier, perhaps the larger gullies have no room to expand, may be fully developed, some of them are being managed and are less efficient when older/larger.

5.7.4 The Significant Findings from the Statistical Analysis

The significant findings from these statistical analyses were the similarities and close association that mainly exist between vegetation loss, soil, slope and gully stream order with yearly gully change in metre squared per square metre.

For example, in 2014/15, 2009/10 and 2006/07 these variables show more similarity between them and yearly gully change in metre squared per square metre in **Figure 91, 93 and 95** of Cluster analysis. Again, for PCA, these variables show more relationship than others in **Table 40,** these variables show that there are relationships that exist between them and yearly gully change in metre squared per square metre in nonlinear regression **in Appendixes VI, VII and VIII Figures (179, 180, 181 and 183), (185,186, 187 and 189), (191, 192, 193 and 195)** respectively. In MLRA, no independent variables in the years 2014/15, 2009/10 and 2006/07 could predict yearly gully change in metre squared per square metre with confidence level of 95% or greater. The above observations from Cluster analysis, PCA and Nonlinear anlysis in this study, align with the research work of Igwe (2005); Ijeoma and Okey (2005) that the initiation of gullies in southeast Nigeria starts from vegetation removal which exposes the soil to rainfall runoff for gullies to develop. Research works such as Onyekwere (2001), maintained that the removal of vegetation was the reason why other gully factors set in to cause gully development. This observation as well agrees with **(Nwafo 2014)** that gullies started to develop in southeast Nigeria after the discovery of coal and oil deposits in the area, the result was massive clearance of vegetation area occasioned by vegetation loss (variable), leaving the land bare, in conjuction with other variables, gullies start to develop. This analysis strongly rejects the assertion put across by Ofomata (1998) that gully erosion in southeast Nigeria can only be linked to physical causes not anthropogenic nor both.

5.8 Using Open Source as an Alternative Approach

This section is the application of objective 7 “Identify the feasibility of establishing an open source methodology, comparing with commercial one to incorporate those living in low GDP countries like Nigeria” This section looks at how this methodology can be applied in developing countries. In this section and its other subsections, all the analysis done with commercial GIS software were repeated in Open source software, they include slope, slope aspect, slope curvature, gradient of the slope of the gullies, gully stream order, gully cross profile, regional landcover classification and extracting gully test sites for analysis.

The process was repeated with an Open Source Remote Sensing and GIS software to check for its efficiency and effectiveness in the application for low GDP countries like Nigeria.

5.8.1 Open Source Regional Topographical Analysis of the Study Area

The regional topographical processes carried out in Arc GIS software were carried out in free open source software. The processing was carried out on different Open source software and below are the software used and why they were used

Table 55: Comparison of open source software and their uses in this study

Open source software used	Processing used in this study	Why they were used	Similar Open source software	Why they were not used
Quantum GIS (QGIS)	-Pixel classification -Digitisation of raster	-Plugins are the key to QGIS success which can rival that of ArcGIS Tools -Easy Raster manipulation -Beautiful labelling options -Wide range of GIS analysis tools - compatibility with raster and vector formats. -Amazing data consumption -User-friendly and robustness	1. GRASS: Geographic Resources Analysis Support System 2. ILWIS: Integrated Land and Water Information System 3. OSSIM: Open Source Software Image Map	All of them can carry out the same processing done in QGIS but not as user friendly as in QGIS. For example QGIS is connected to online GIS where you can download Landsat, SAR and Google images.
SAGA GIS: System for Automated Geoscientific Analyses	-OBIA -Object Based Image Analysis Classification -Terrain analysis	-quick and reliable in raster processing -Beautiful 3D rendering options -Plentiful for Geoscientific tools -Good data interoperability -Geostatistics, modelling and prediction - compatibility with raster and vector formats. -User-friendly and robustness	6. gvSIG: Generalitat Valenciana Geographic Information System 7. Opticks GIS	These Remote Sensing/GIS software can do terrain analysis but requires special plug in to carry out OBIA classification. This is different in SAGA which has OBIA processing tools in it and processing of data is faster.

5.8.2 Open Source Slope Profile of the Study Area

Figure 119 of Open Source software is similar to **Figure 50** of Arc, slope map of the study area shown as a degree gradient

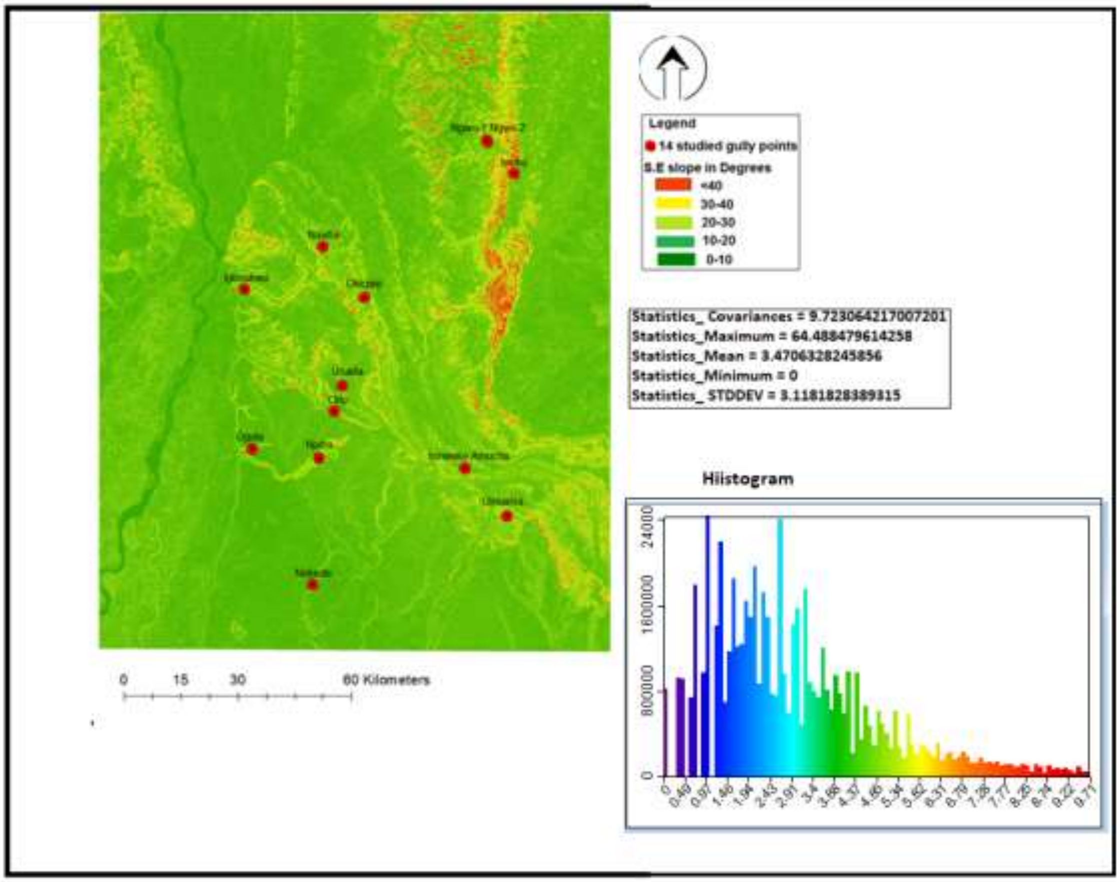
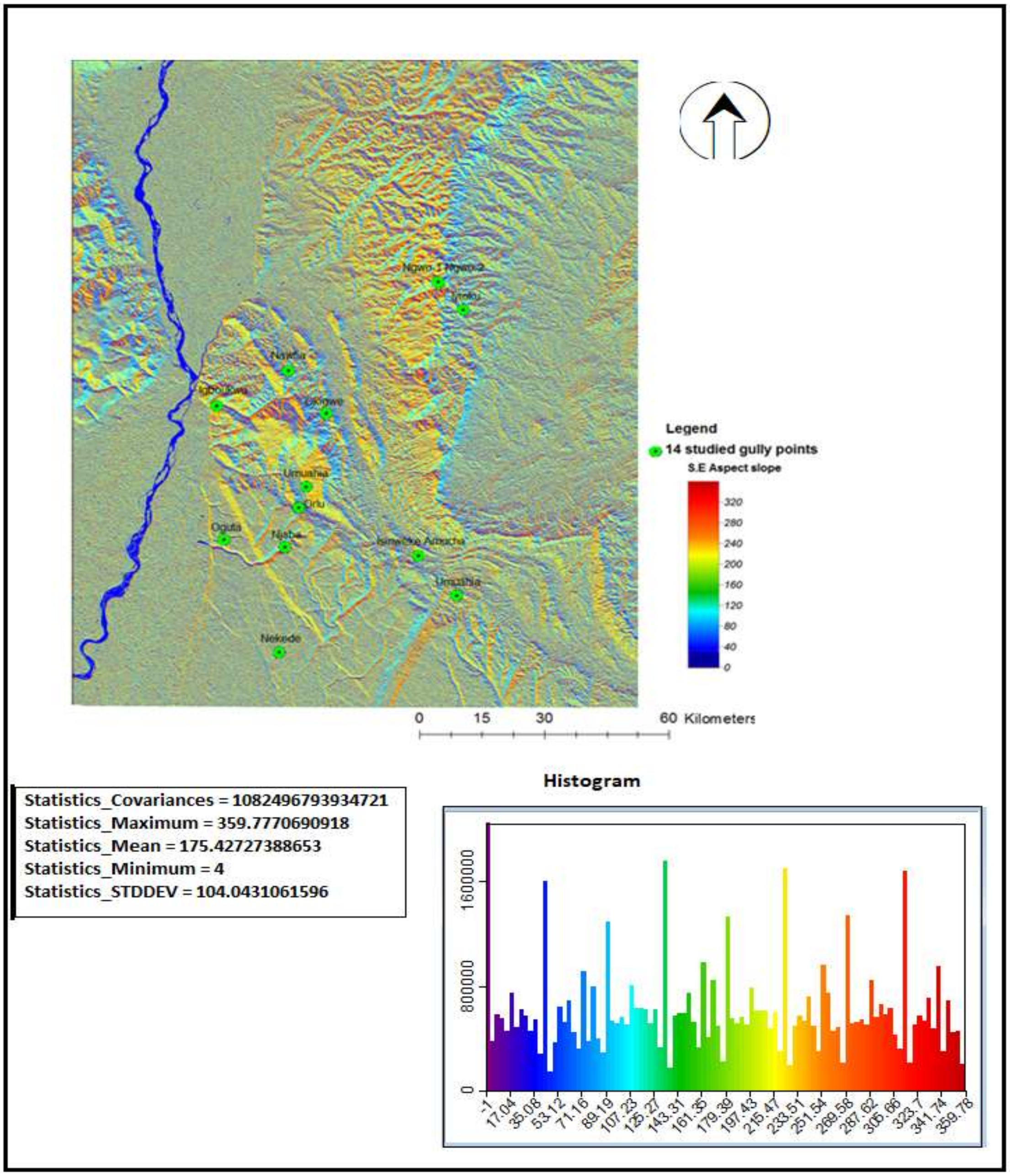


Figure 117: Open source Maximum slope map of the study area shown as a degree gradient (flat areas have 0 – 10 and 10 - 20^0, gentle slope has 20 – 30^0 while slope 40^0 and greater are higher areas).

5.8.3 Open Source Slope Aspect of the Study Area

Figure 120 of Open Source software is similar to **Figure 52** of Arc, Slope Aspect map of the study area.



Statistics_Covariances = 1082496793934721
Statistics_Maximum = 359.7770690918
Statistics_Mean = 175.42727388653
Statistics_Minimum = 4
Statistics_STDDEV = 104.0431061596

Figure 118: Open source Aspect map overlayed by the gully points observed gully shapefiles and gully points

5.8.4 Open Source Slope Plan Curvature of the Study Area

Figure 121 of Open Source software is similar to **Figure 53** of Arc, Curvature of the slope of the study area.

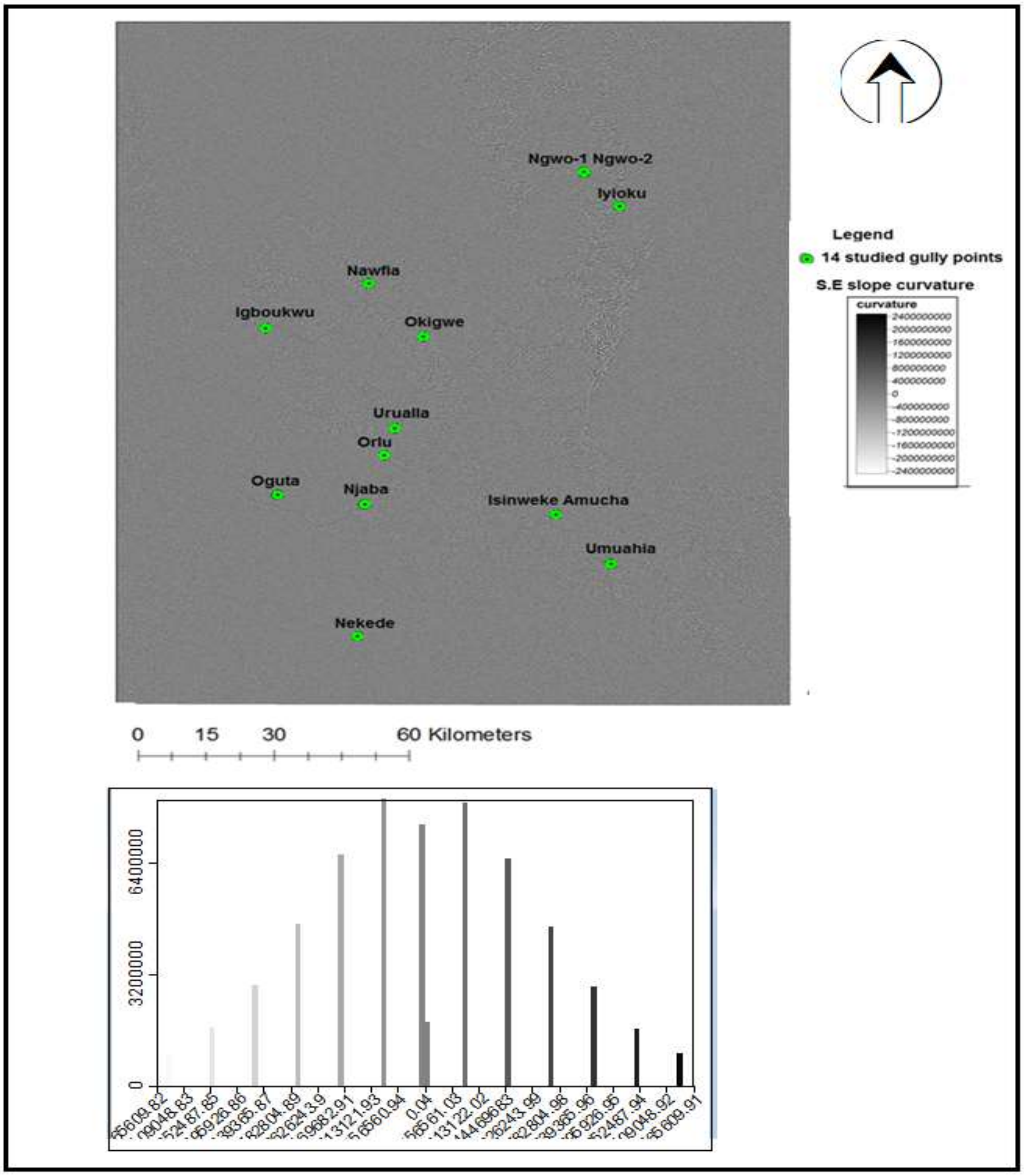


Figure 119: Open source Curvature of the slope of the study area white areas are low while grey areas are higher overlaid with gully points from the field. Here the maximum is 6 while the minimum is -5.

5.8.5 Open Source Gradient of the Slope of the Gullies

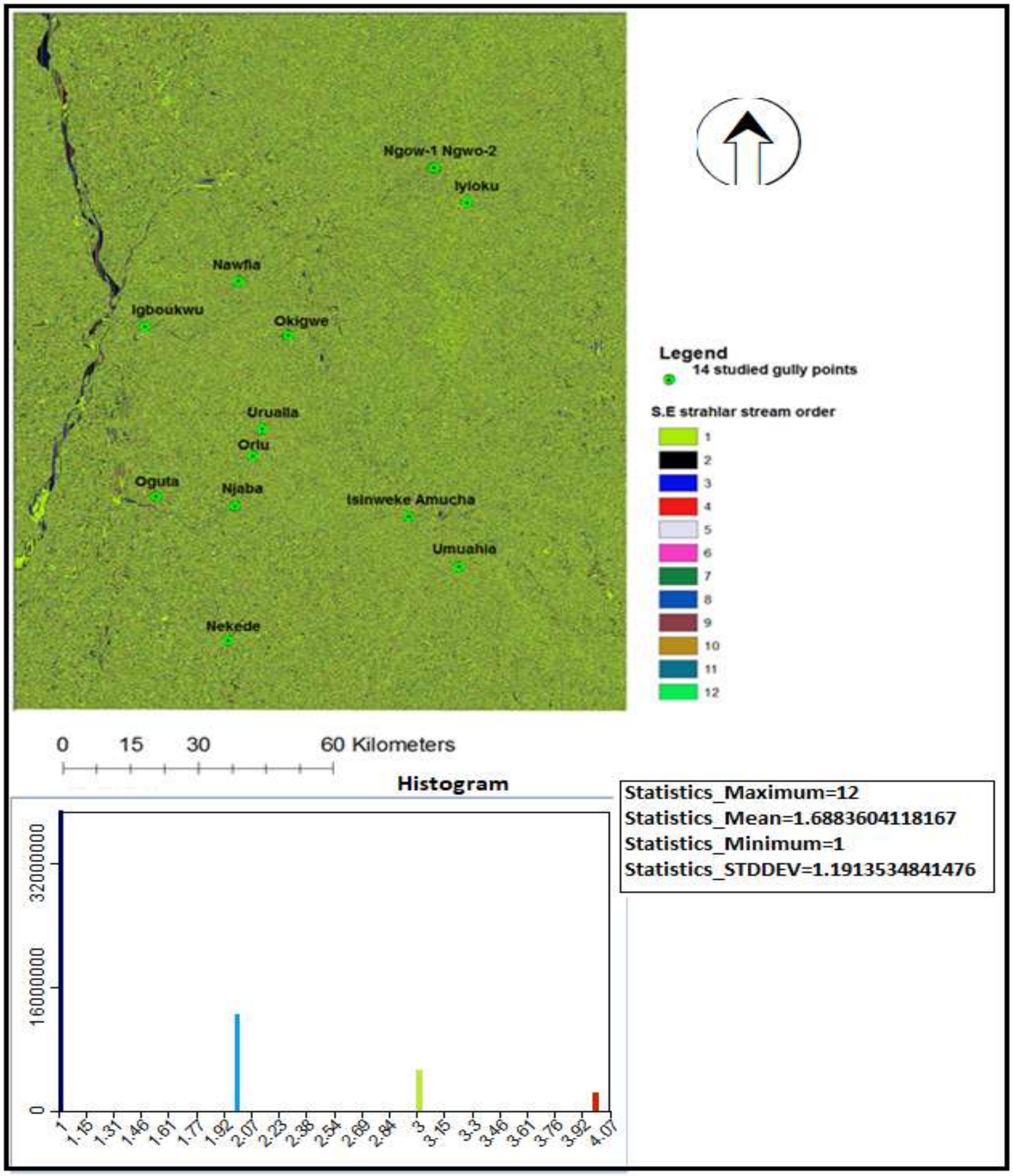
Table 56 Open Source software is similar to **Table 10** of Arc, Calculated gradient of gullies for the gullies and Soil types of the study area.

Table 56: Calculated gradient of gullies for the 4 specific gullies and Soil types are shown

	Gully Name	Calculated Gradient (m)	Soil Type found
1	Iyioku	1 in 44m	Gleysols and Fluvisols
2	Okigwe	1 in 99m	Ferralic-Arenosols soils
3	Njaba	1 in 13m	Feralsols and Nitosols
4	Igboukwu	1 in 12m	Ferralic-Arenosols soils

5.8.6 Open Source Gully Strahler Stream Order

Figure 122 of Open Source software is similar to **Figure 56** of Arc, The Strahler stream order Drainage pattern of the study area



Statistics_Maximum=12
Statistics_Mean=1.6883604118167
Statistics_Minimum=1
Statistics_STDDEV=1.1913534841476

Figure 120: Open source Strahler stream order Drainage pattern of the study area overlaid by the gully points.

5.8.7 Gully Cross Profile

Figures 123 and 124 of Open Source software is similar to Figures 40 and 41 of Arc, the cross profile of 4 gullies was carried out with DEM of the study area.

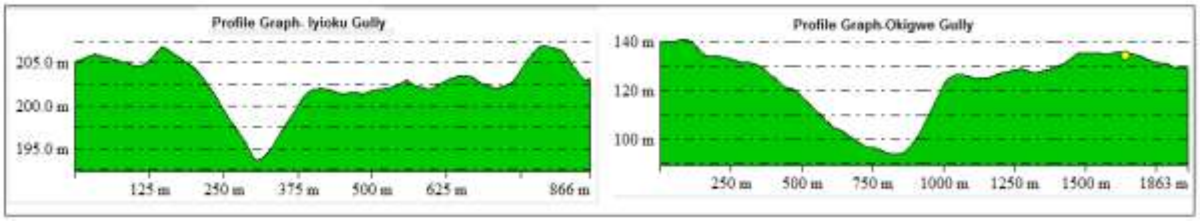


Figure 121: Open source Cross profile of the Iyioku and Okigwe gullies in metres

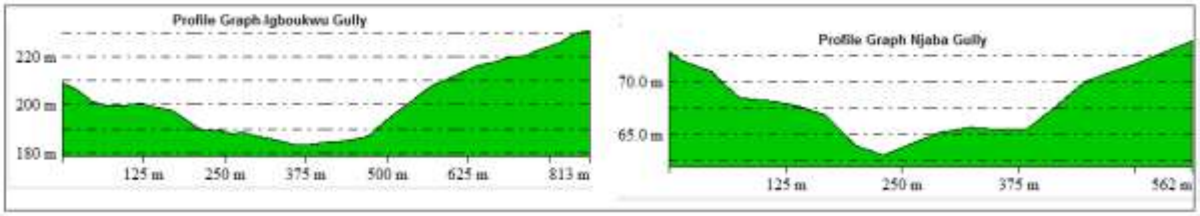


Figure 122: Open source Cross profile of the Igboukwu and Njaba gullies in metres

5.8.8 Open Source Regional Land-Cover Classification of the Study Area

This is repeated with the same images used in ArcGIS, both Landsat and ALOSPALSAR images.

5.8.8.1 Pixel-based Classification

Figures 125 (a) and **(b)** of Open Source software is similar to **Figures 28 (a)** and **(b)** of Arc, result of Reclassified images of Landsat 2008 ALOSPALSAR 2008 images of the study area. The result is shown in **Table 57** as can be compared with **Table 12.** Also **Figure 126** and **Table 58** can be compared with **Figure 59 (a)** (Top) and **Table 17 (a**) respectively**.**

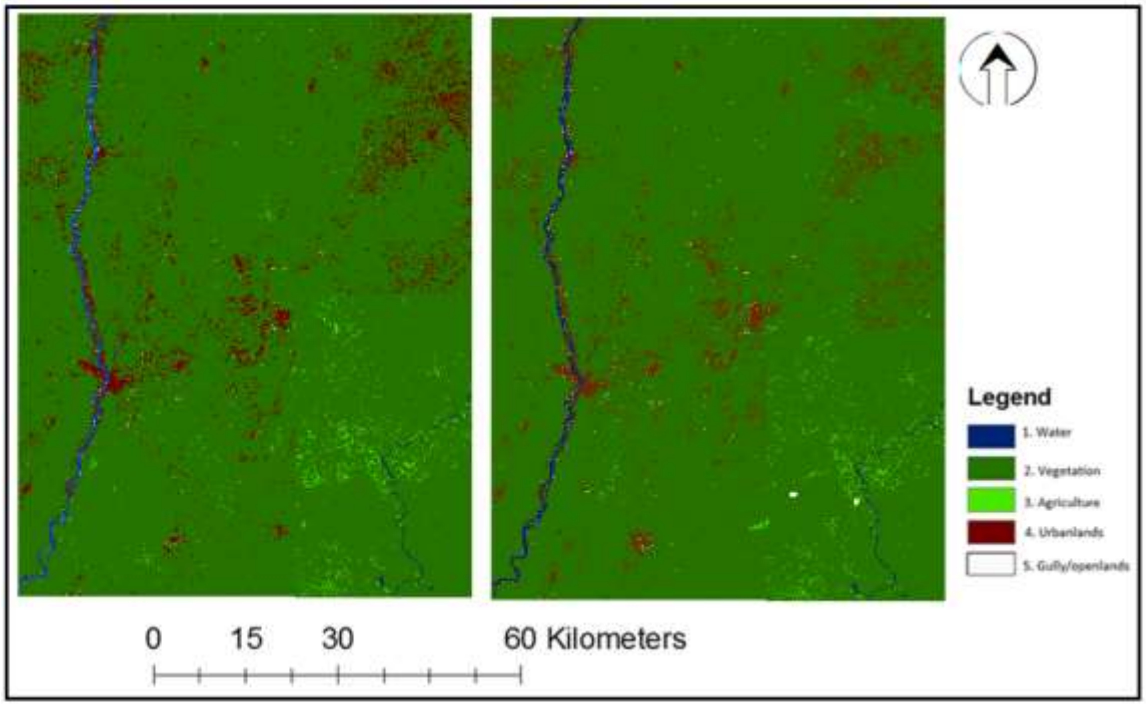


Figure 123: Open source (a) and (b) Example of the result of Reclassified pixel based images of Landsat 2008 ALOSPALSAR 2008 images of the study area

Table 57: Pixel based Classification Result as Percentage of total area classified from 1986-2015. Sums may exceed 100% due to rounding.

	Classes	‘86	‘87	‘88	‘89	‘90	‘91	‘92	‘93	‘00	‘01	‘02	‘03
		%	%	%	%	%	%	%	%	%	%	%	%
1	Water	1%	1%	1%	1%	1%	1%	2%	1%	1%	2%	2%	2%
2	Vegetation	84%	80%	78%	77%	76%	73%	72%	69%	61%	60%	58%	57%
3	Agriculture	7%	7%	8%	7%	7%	8%	6%	7%	10%	10%	10%	10%
4	Urban-Lands	4%	6%	7%	9%	10%	11%	13%	15%	18%	19%	20%	21%
5	Gully/openland	4%	6%	6%	6%	6%	7%	7%	8%	10%	9%	10%	10%
		‘04	‘05	‘06	‘07	‘08	‘09	‘10	‘11	‘12	‘13	‘14	‘15
		%	%	%	%	%	%	%	%	%	%	%	%
1	Water	1%	2%	2%	2%	2%	1%	2%	2%	2%	2%	2%	2%
2	Vegetation	56%	53%	52%	50%	48%	47%	45%	44%	42%	39%	37%	35%
3	Agriculture	9%	9%	8%	9%	8%	9%	9%	8%	8%	8%	8%	8%
4	Urban-Lands	23%	26%	27%	28%	30%	31%	32%	33%	35%	38%	39%	41%
5	Gully/openland	11%	10%	11%	11%	12%	12%	12%	13%	13%	13%	14%	14%

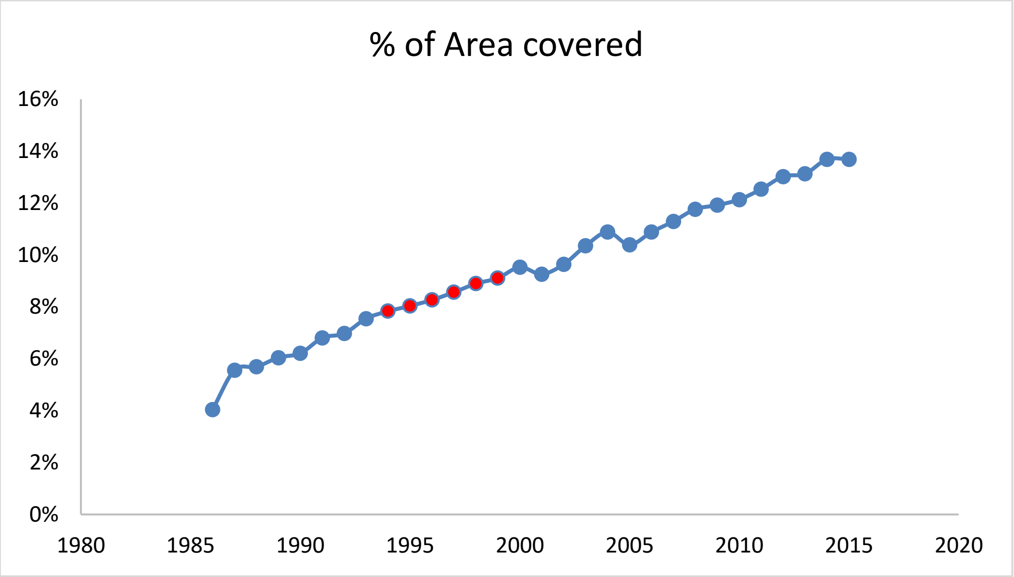


Figure 124: Open source Pixel classification based Area in pixel count change over time of Gully/open-land showing from 1986 to 2015 (observed images are in red circle points while interpolated points are in red circle points). Pixel size equivalent to 900m^2.

Table 58: Calculated Pixel based Area and % covered by Gully/Openland class from 1986-2015 (red = interpolated)

Years	Gully/openland pixel count	% of Area covered		Years	Gully/openland pixel count	% of Area covered
1986	2593362	4%		2001	5944361	9%
1987	3568893	6%		2002	6186361	10%
1988	3652040	6%		2003	6644361	10%
1989	3879023	6%		2004	6982407	11%
1990	3986316	6%		2005	6670452	10%
1991	4365352	7%		2006	6982819	11%
1992	4476522	7%		2007	7248492	11%
1993	4844361	8%		2008	7548492	12%
1994	5025512	8%		2009	7648483	12%
1995	5156776	8%		2010	7788493	12%
1996	5303860	8%		2011	8043541	13%
1997	5495360	9%		2012	8356852	13%
1998	5707795	9%		2013	8424567	13%
1999	5845318	9%		2014	8782388	14%
2000	6112417	10%		2015	8784578	14%

5.8.8.2 Object Based Image Classification (OBIA)

Figure 127 (a) and (b) of Open Source software is similar to **Figures 30 (a)** and **(b)** of Arc, result of object-oriented classification of Landsat of year 2009 and ALOSPALSAR of year 2009 images of the study area. **Table 59** as can be compared with **Table 13.** Also **Figure 128** and **Table 60** can be compared with **Figure 59 (b)** (down) and **Table 17 (b)** respectively**.**

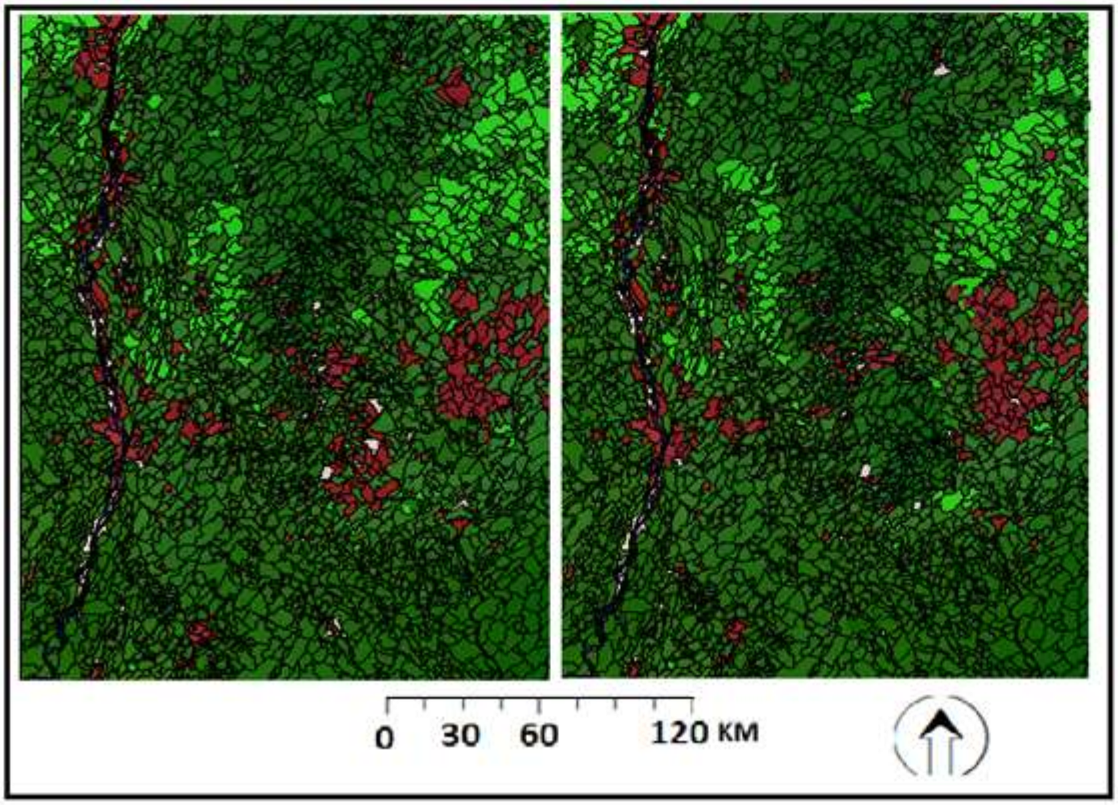


Figure 125: Open source (a) and (b) shows result of object-oriented classification of Landsat of year 2009 and ALOSPALSAR of year 2009 images of the study area

Table 59: OBIA classification Result as percentage of total area classified

	Classes	‘86	‘87	‘88	‘89	‘90	‘91	‘92	‘93	‘00	‘01	‘02	‘03
		%	%	%	%	%	%	%	%	%	%	%	%
1	Water	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
2	Vegetation	84%	80%	78%	79%	77%	75%	74%	71%	69%	67%	66%	65%
3	Agriculture	6%	7%	7%	7%	8%	9%	9%	10%	9%	10%	10%	9%
4	Urban-Lands	5%	6%	8%	7%	7%	8%	9%	10%	12%	14%	15%	17%
5	Gully/openland	4%	6%	6%	6%	7%	7%	7%	8%	9%	8%	8%	8%
		‘04	‘05	‘06	‘07	‘08	‘09	‘10	‘11	‘12	‘13	‘14	‘15
		%	%	%	%	%	%	%	%	%	%	%	%
1	Water	1%	2%	2%	2%	2%	2%	2%	2%	3%	2%	2%	2%
2	Vegetation	61%	55%	52%	48%	45%	43%	40%	39%	38%	37%	35%	33%
3	Agriculture	9%	9%	9%	9%	10%	10%	11%	10%	9%	8%	8%	8%
4	Urban-Lands	20%	24%	27%	30%	32%	34%	36%	37%	38%	39%	41%	43%
5	Gully/openland	9%	10%	10%	11%	11%	11%	11%	12%	12%	14%	14%	14%

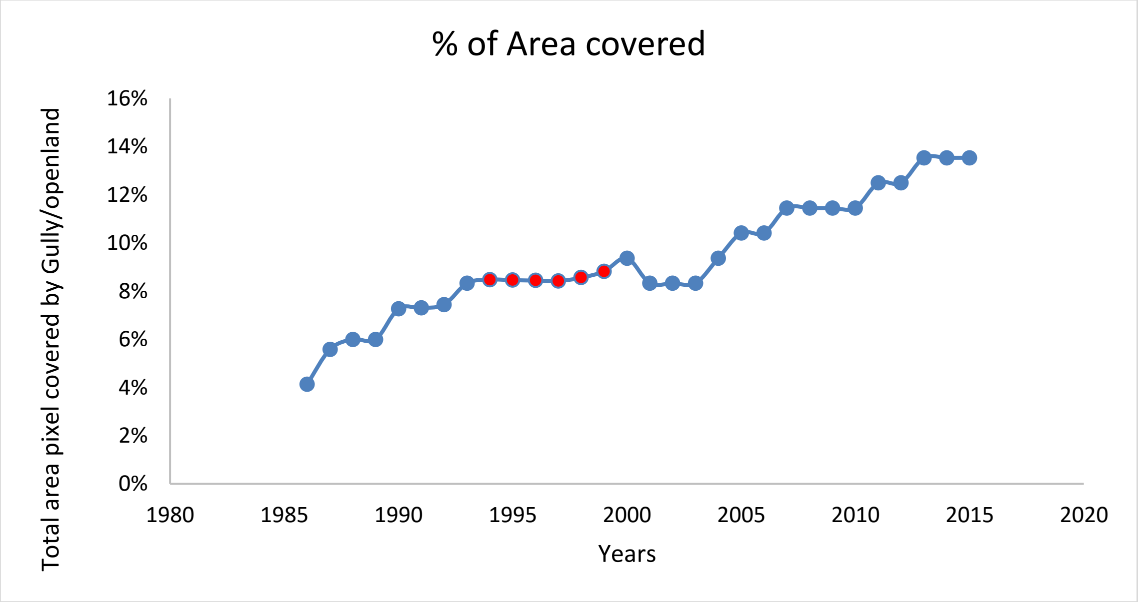


Figure 126: Open source OBIA classification pixel count changes over time of Gully/open-land showing from 1986 to 2015 (Observed Gully/openland class is in circle points while interpolated Gully/openland class is in square points). Pixels equivalent to 900m².

Table 60: Calculated OBIA Area and % covered by Gully/Openland class from 1986-2015 (red = interpolated)

Years	Gully/openland pixel count	% of Area covered		Years	Gully/openland pixel count	% of Area covered
1986	2653360	4%		2001	5344361	8%
1987	3579894	6%		2002	5344375	8%
1988	3849040	6%		2003	5344361	8%
1989	3849040	6%		2004	6012407	9%
1990	4666316	7%		2005	6680451	10%
1991	4686316	7%		2006	6682816	10%
1992	4776526	7%		2007	7348496	11%
1993	5344361	8%		2008	7348477	11%
1994	5439796	8%		2009	7348497	11%
1995	5426162	8%		2010	7348488	11%
1996	5414479	8%		2011	8016542	12%
1997	5404462	8%		2012	8017752	12%
1998	5491311	9%		2013	8684682	14%
1999	5661188	9%		2014	8684577	14%
2000	6012406	9%		2015	8686683	14%

5.8.9 Open Source Extracting Gully Test Sites for Analysis

The 4 main gullies area values in square metres **Table 61** can be compared with Table 91 which are represented in Open source Figures 129, 130, 131 and 132 as can be compared with **Figures 62, 63, 64 and 65** respectively.

Table 61: Opensource Area covered in m2 by the 4 main Gullies from 1986-2015

No of Years	Iyioku m^2	Okigwe m^2	Njaba_m^2	Igboukwu_m^2
1986	1306860	157543	38286	27008
1987	1319890	166453	38935	29240
1988	1325453	189123	42389	30779
1989	1326842	209856	43079	32046
1990	1338644	234762	45279	33949
1991	1339812	260967	45982	34934
1992	1341674	280849	46190	37729
1993	1344004	297563	46806	38034
1994	1346634	301693	48760	39434
1995	1355543	303870	49613	40914
1996	1356042	337453	50175	41639
1997	1356784	358977	50362	42784
1998	1357643	369345	50979	44995
1999	1359931	389837	51886	46330
2000	1360984	409467	52279	47534
2001	1365847	413247	52834	49694
2002	1368001	425732	53949	52794
2003	1369532	454538	55879	54789
2004	1387634	478983	56983	57261
2005	1398650	499694	57925	60337
2006	1407432	498348	58824	60565
2007	1441212	506583	62175	64804
2008	1443652	524965	65966	66302
2009	1448421	534679	67326	68956

2010	1457452	551745	68996	71954
2011	1466541	572211	69800	74300
2012	1483450	599845	71934	78980
2013	1594672	608456	74626	85683
2014	1665322	639858	75056	88438
2015	1702681	666930	78387	89703

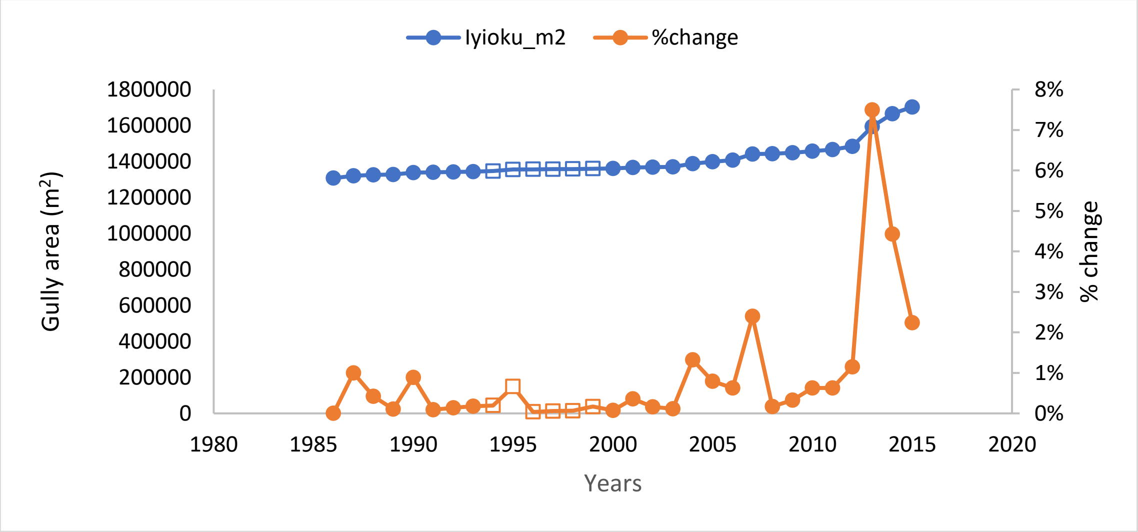


Figure 127: Open source Iyioku Gully area and % change graph showing from 1986 – 2015

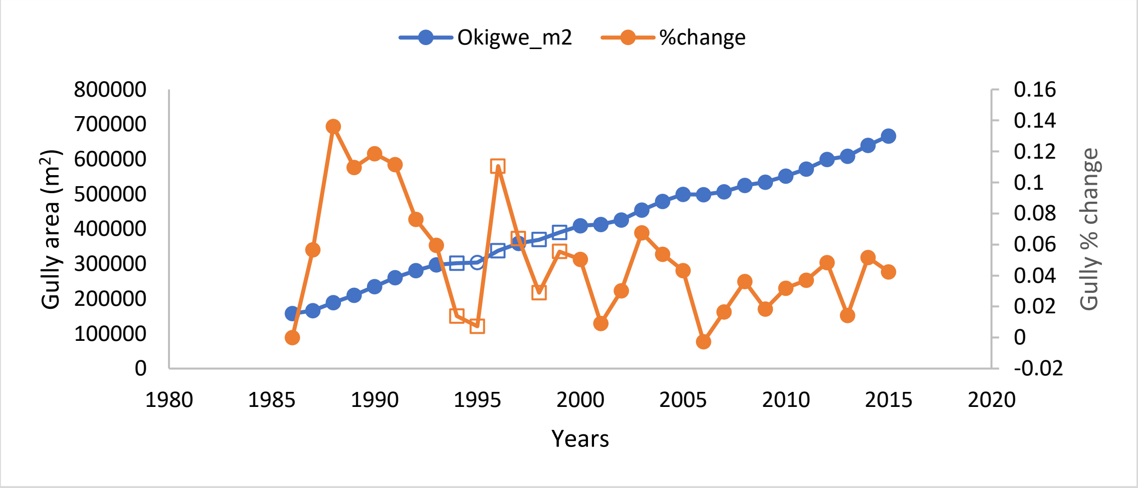


Figure 128: Open source Okigwe Gully area and % change graph showing from 1986 – 2015

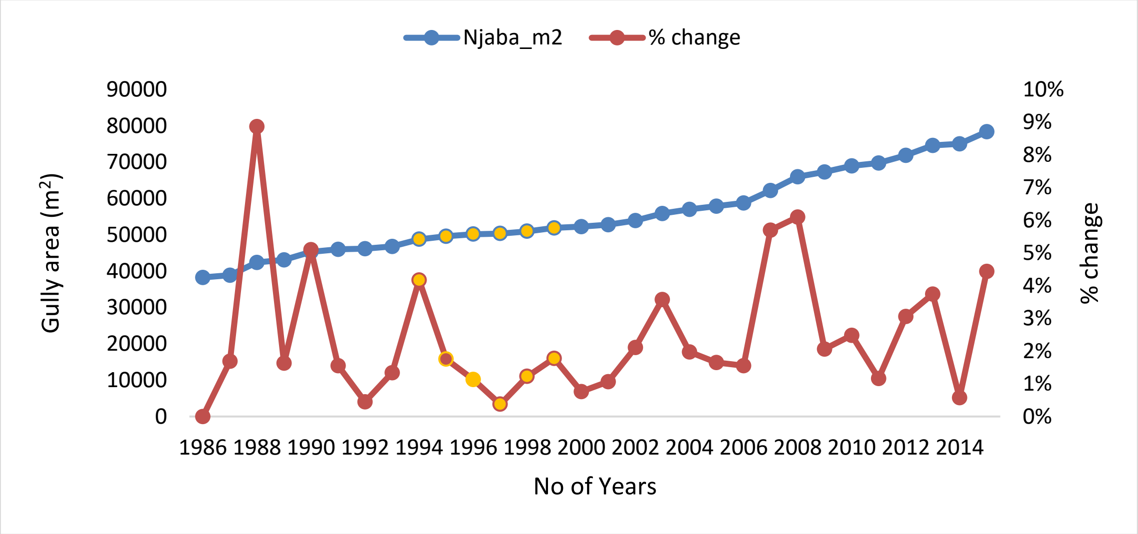


Figure 129: Open source Njaba Gully area and % change graph showing from 1986 – 2015

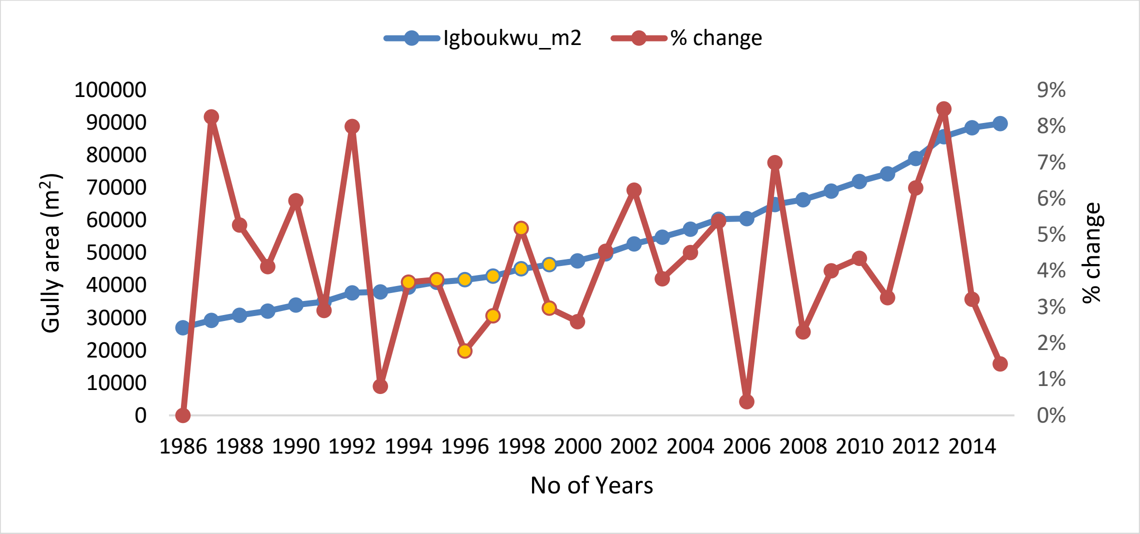


Figure 130: Open source Igboukwu Gully area and % change graph showing from 1986 – 2015

5.8.9.1 Correlation of ArcGIS and Open Source Software Values

The results of ArcGIS and Open source values were correlated to observe relationship. There is no need drawing the differences since each software has its own merits and demerits in data handling and processing. The concern here is to demonstrate how open source software can be used to accomplish the same work done in ArcGIS software so that this work and similar ones can be replicated in countries with low GDP especially Nigeria and other African countries. The reason being that some of these developing countries that cannot have easy access to all these expensive GIS and Remote Sensing software can now be able to use alternative software that can accomplish the same work.

In **Table 62**, the Pearson's correlation of Arc and Open source values from vegetation areas show that Pixel and OBIA vegetation in both Arc and Open source produced a strong positive correlation of .75 and a very strong positive correlation of .98 respectively. From **Table 63,** the Pearson's correlation for Arc Pixel and Open Source Gully/openland class show that it produced a very strong correlation of .96 and .9 respectively. **Table 64** show that the Iyioku Arc and Open Source values produced a correlation of .98 showing a very strong positive correlation. The Okigwe gully Arc and Open Source values produced a correlation of .92 also showing a very strong positive correlation. Also in **Table 65,** Njaba gully values for Arc and Open source produced a very strong positive correlation of .98 and Igboukwu produced a perfect correlation of .99.

The positive correlation of the results has demonstrated that the work can be easily replicated in open source software which will produce similar or near similar result.

Table 62: Correlation of Arc Pixel and OBIA Vegetation area values verses Open source pixel and OBIA vegetation area values

Correlations

		ArcPix_Vege	ArcOBIA Vege	OpenSourcePix_Vege	OpenSource OBIAVeg
ArcPix_Vege	Pearson Correlation	1	.720**	.751**	.732**
	Sig. (2-tailed)		.000	.000	.000
	N	30	30	30	30
ArcOBIA_Vege	Pearson Correlation	.720**	1	.990**	.988**
	Sig. (2-tailed)	.000		.000	.000
	N	30	30	30	30
OpenSourcePix_Vege	Pearson Correlation	.751**	.990**	1	.981**
	Sig. (2-tailed)	.000	.000		.000
	N	30	30	30	30
OpenSourceOBIAVeg	Pearson Correlation	.732**	.988**	.981**	1
	Sig. (2-tailed)	.000	.000	.000	
	N	30	30	30	30

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

Table 63: Correlation of Arc Pixel and OBIA Gully/openland area values versus Open source pixel and OBIA Gully/openland area values

Correlations

		ArcPix_GullyOpenland	ArcOBIA_GullyOpenland	OpenSource_PixGullyOpenland	OpenSource_OBIAGullyOpenland
ArcPix_GullyOpenland	Pearson Correlation	1	.878**	.966**	.955**
	Sig. (2-tailed)		.000	.000	.000
	N	30	30	30	30
ArcOBIA_GullyOpenland	Pearson Correlation	.878**	1	.913**	.909**
	Sig. (2-tailed)	.000		.000	.000
	N	30	30	30	30
OpenSource_PixGullyOpenland	Pearson Correlation	.966**	.913**	1	.968**
	Sig. (2-tailed)	.000	.000		.000
	N	30	30	30	30
OpenSource_OBIAGullyOpenland	Pearson Correlation	.955**	.909**	.968**	1
	Sig. (2-tailed)	.000	.000	.000	
	N	30	30	30	30

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

Table 64: Correlation of Arc Pixel and OBIA Iyioku Gully area values verses Open source pixel and OBIA Iyioku Gully area values And Correlation of Arc Pixel and OBIA Okigwe Gully area values verses Open source pixel and OBIA Okigwe Gully area values

Correlations					
		Arc_IyiokuGully	OpenSource_ IyiokuGully	Arc_ OkigweGully	OpenSource_ OkigweGully
Arc_IyiokuGully	Pearson Correlation	1	.982**	.974**	.924**
	Sig. (2-tailed)		.000	.000	.000
	N	30	30	30	30
OpenSource_ IyiokuGully	Pearson Correlation	.982**	1	.973**	.938**
	Sig. (2-tailed)	.000		.000	.000
	N	30	30	30	30
Arc_ OkigweGully	Pearson Correlation	.974**	.973**	1	.920**
	Sig. (2-tailed)	.000	.000		.000
	N	30	30	30	30
OpenSource_ OkigweGully	Pearson Correlation	.924**	.938**	.920**	1
	Sig. (2-tailed)	.000	.000	.000	
	N	30	30	30	30
**. Correlation is significant at the 0.01 level (2-tailed).					

Table 65: Correlation of Arc Pixel and OBIA Njaba Gully area values verses Open source pixel and OBIA Njaba Gully area values And Correlation of Arc Pixel and OBIA Igboukwu Gully area values verses Open source pixel and OBIA OIgboukwu Gully area values

Correlations					
		Arc_NjabaGully	OpenSource _NjabaGully	Arc_ IgboukwuGully	OpenSource_ IgboukwuGully
Arc_NjabaGully	Pearson Correlation	1	.988**	.993**	.980**
	Sig. (2-tailed)		.000	.000	.000
	N	30	30	30	30
OpenSource_NjabaGully	Pearson Correlation	.988**	1	.994**	.993**
	Sig. (2-tailed)	.000		.000	.000
	N	30	30	30	30
Arc_IgboukwuGully	Pearson Correlation	.993**	.994**	1	.991**
	Sig. (2-tailed)	.000	.000		.000
	N	30	30	30	30
OpenSource_Igboukwu Gully	Pearson Correlation	.980**	.993**	.991**	1
	Sig. (2-tailed)	.000	.000	.000	
	N	30	30	30	30
**. Correlation is significant at the 0.01 level (2-tailed).					

5.9 Open Source Multi-Variate Statistical Analysis of Gully Factors

This section also fulfils part of objective 7 and compare the statistical result obtained from commercial and open source software. In line with positive correlation observed with Arc and open source values, the values obtained in open source were used to perform multi variate statistical analysis. The reason is to know if it will produce the same result as in Arc software. For the purpose of this statistical analysis, other 10 gullies were traced and calculated also gully area change recorded with vegetation Loss of 10km X 10 km around each gully. The same method used in obtaining values from Arc software in statistical analysis were employed for Open Source statistical analysis. The following are the variables:

1. Soil
2. Vegetation loss
3. Slope
4. Gully area
5. Yearly gully change in metre squared per square metre
6. Elevation
7. Gully stream order

5.9.1 Open Source 2014/15 Cluster Analysis of Variables: 2015-VegLoss, 2015- Gully Area, Slope Degrees, Soil, Elevation, Gully Stream and 2014/15- Yearly Gully Change in Metre Squared per Square Metre (Comparison of Arc and Open source software, the Cluster statistical analysis)

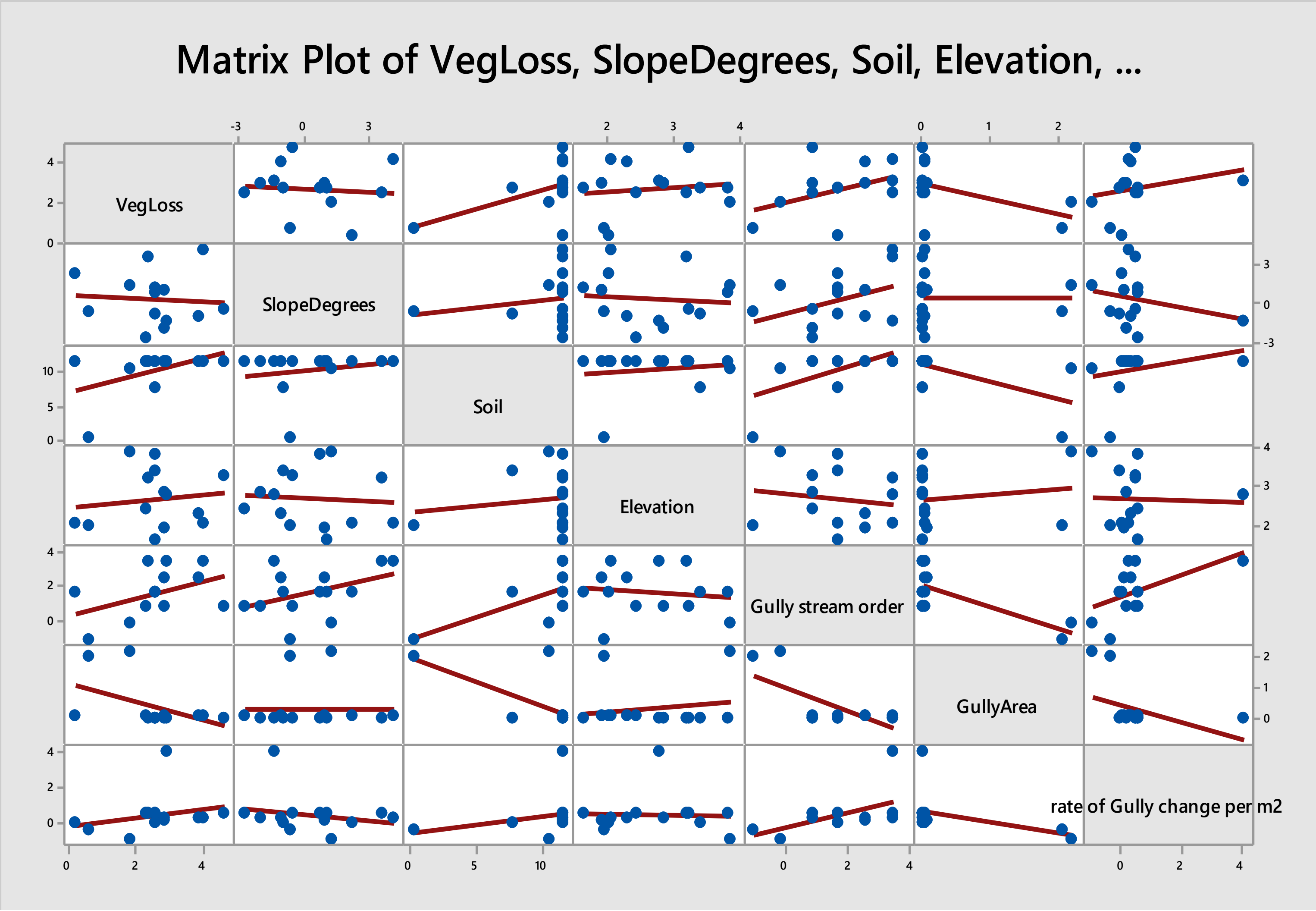


Figure 131: Open Source Matrix Plot of 2014/15-VegLoss, SlopeDegrees, Soil, Elevation, Gully stream order, 2015-Gully area, 2014/2015-yearly gully change in metre squared per square metre (The solid lines represent linear regression). The x,y plots don't seem to show any linear relationships between rate of change and the other variables.

Table 66: Open source 2014/15 Correlation Coefficient Distance, Complete Linkage (complete linkage methods group clusters based upon single pair distances and best suited for the variables of this study. This is because this analysis is looking at the distance of each variable to yearly gully change in metre squared per square metre)

Step	Number of clusters	Similarity level	Distance level	Clusters joined	New cluster	Number of obs. in new cluster
1	6	83.7766	0.32447	4 7	4	2
2	5	76.5325	0.46935	4 5	4	3
3	4	66.6867	0.66627	1 4	1	4
4	3	59.8365	0.80327	1 3	1	5
5	2	43.0426	1.13915	1 6	1	6
6	1	3.5348	1.92930	1 2	1	7

Table 67: Open source 2014/15 Final Partition

Cluster 1	Vegeloss GullyChange Slope Soil GullyStream
Cluster 2	Gully Area
Cluster 3	Elevation

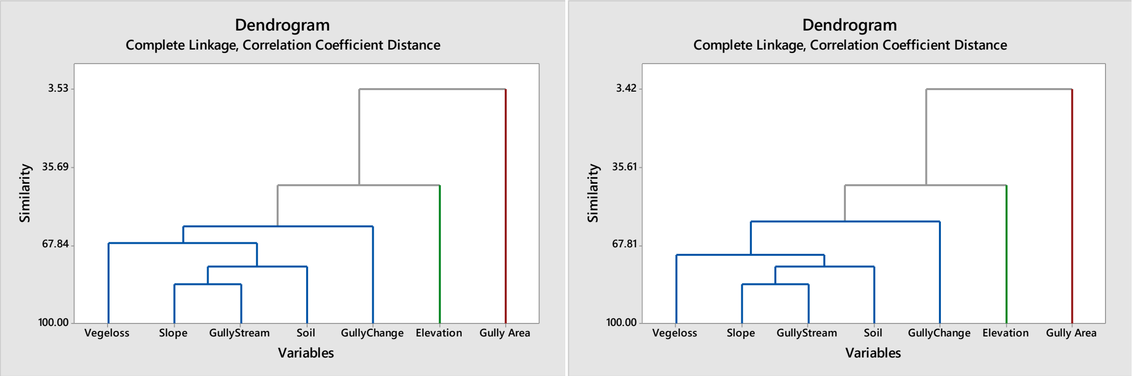


Figure 132: (Left) Open Source Dendrogram of the year 2014/15 with 7 gully variables represented in 3 cluster solution. (Right) ArcGIS equivalent data

A closer look at the Cluster Analysis of 2014/15 arc and open source softwares of the gully variables show that they appear to have near similar result. Compare the result of arc 2014/15 Cluster Analysis **section 5.5.1**

5.9.2 Open Source 2009/10 Cluster Analysis of Variables: 2009/10-VegLoss, 2010-Gully area, SlopeDegrees, Soil, Elevation, Gully stream and 2009/10- yearly gully change in metre squared per square metre.

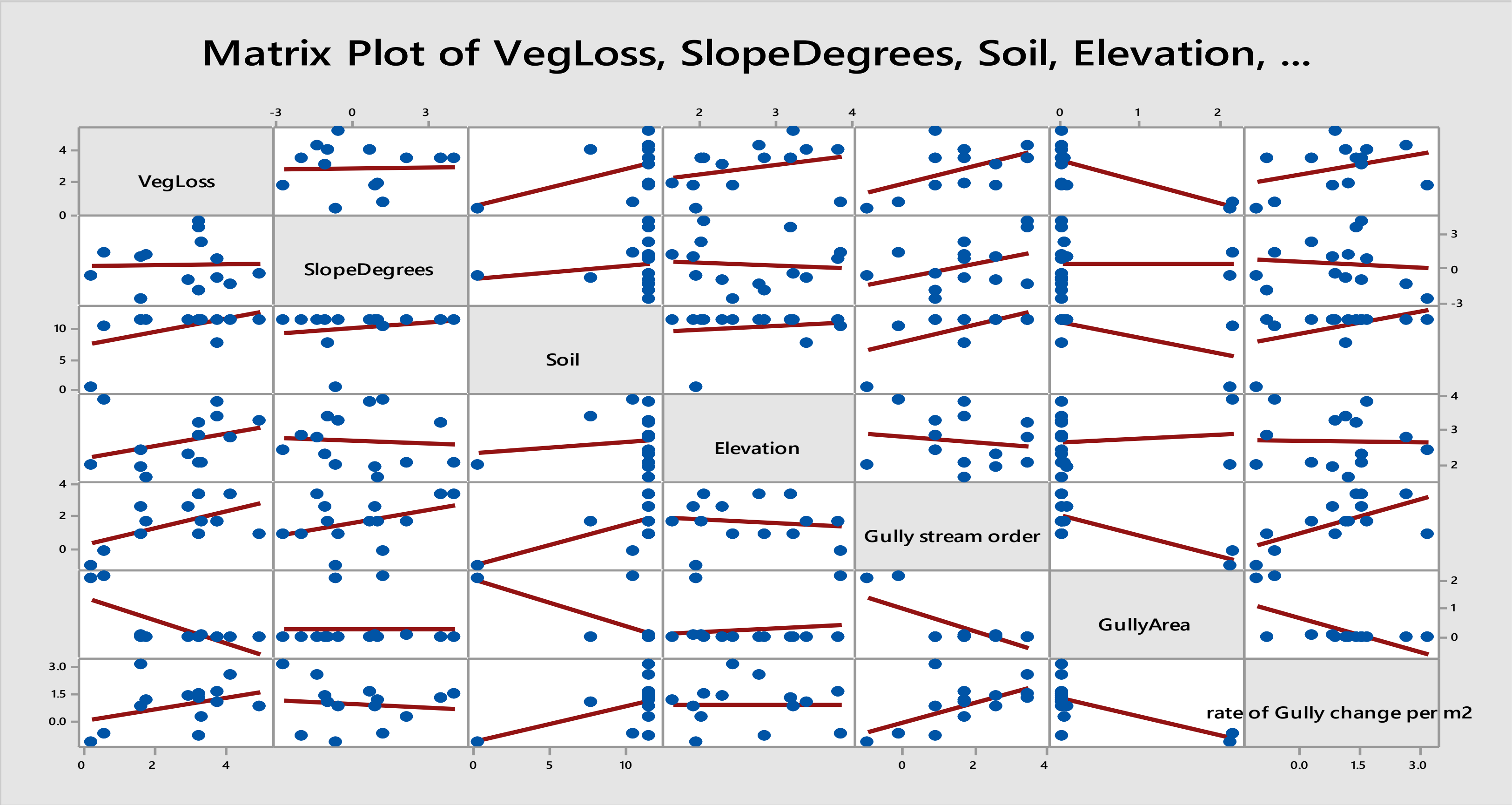


Figure 133: : Open Source 2009/10 Matrix Plot of 2009/10-VegLoss, SlopeDegrees, Soil, Elevation, Gully stream order, 2010-Gully area, 2009/2010-yearly gully change in metre squared per square metre (The solid lines represent linear regression).

Table 68: Open Source 2009/10 Correlation Coefficient Distance, Complete Linkage (complete linkage methods group clusters based upon single pair distances and best suited for the variables of this study. This is because this analysis is looking at the distance of each variable to yearly gully change in metre squared per square metre)

Step	Number of clusters	Similarity level	Distance level	Clusters joined	New Cluster	Number of obs. in new cluster
1	6	83.7766	0.32447	4 7	4	2
2	5	76.5325	0.46935	4 5	4	3
3	4	65.1082	0.69784	1 4	1	4
4	3	55.9845	0.88031	1 3	1	5
5	2	43.6751	1.12650	1 6	1	6
6	1	3.3589	1.93282	1 2	1	7

Table 69: Open Source 2009/10 Final Partition

Cluster 1	VegLoss, Soil, slope, Gully stream order , yearly gully change
Cluster 2	GullyArea
Cluster 3	Elevation

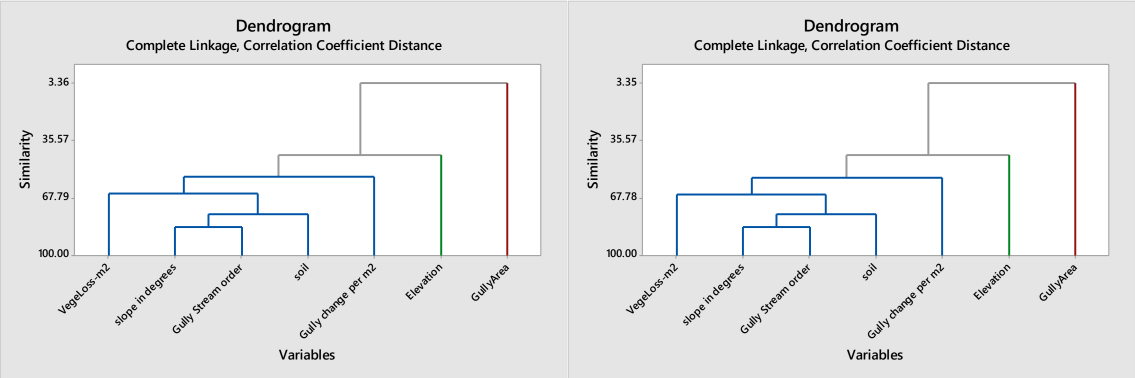


Figure 134: (Left) Open Source 2009/10 Dendrogram of the year 2010 with 7 gully variables represented in 3 cluster solution (Rright) ArcGIS equivalent data.

A closer look at the Cluster Analysis of 2009/10 arc and open source software of the gully variables show that they appear to have similar result. Compare the result of arc 2009/10 Cluster Analysis **section 5.5.1**

5.9.3 Open source 2006/07 Cluster Analysis of Variables: 2007-VegLoss, 2007- Gully Area, Slope Degrees, Soil, Elevation, Gully Stream and 2006/07- Yearly Gully Change in Metre Squared per Square Metre.

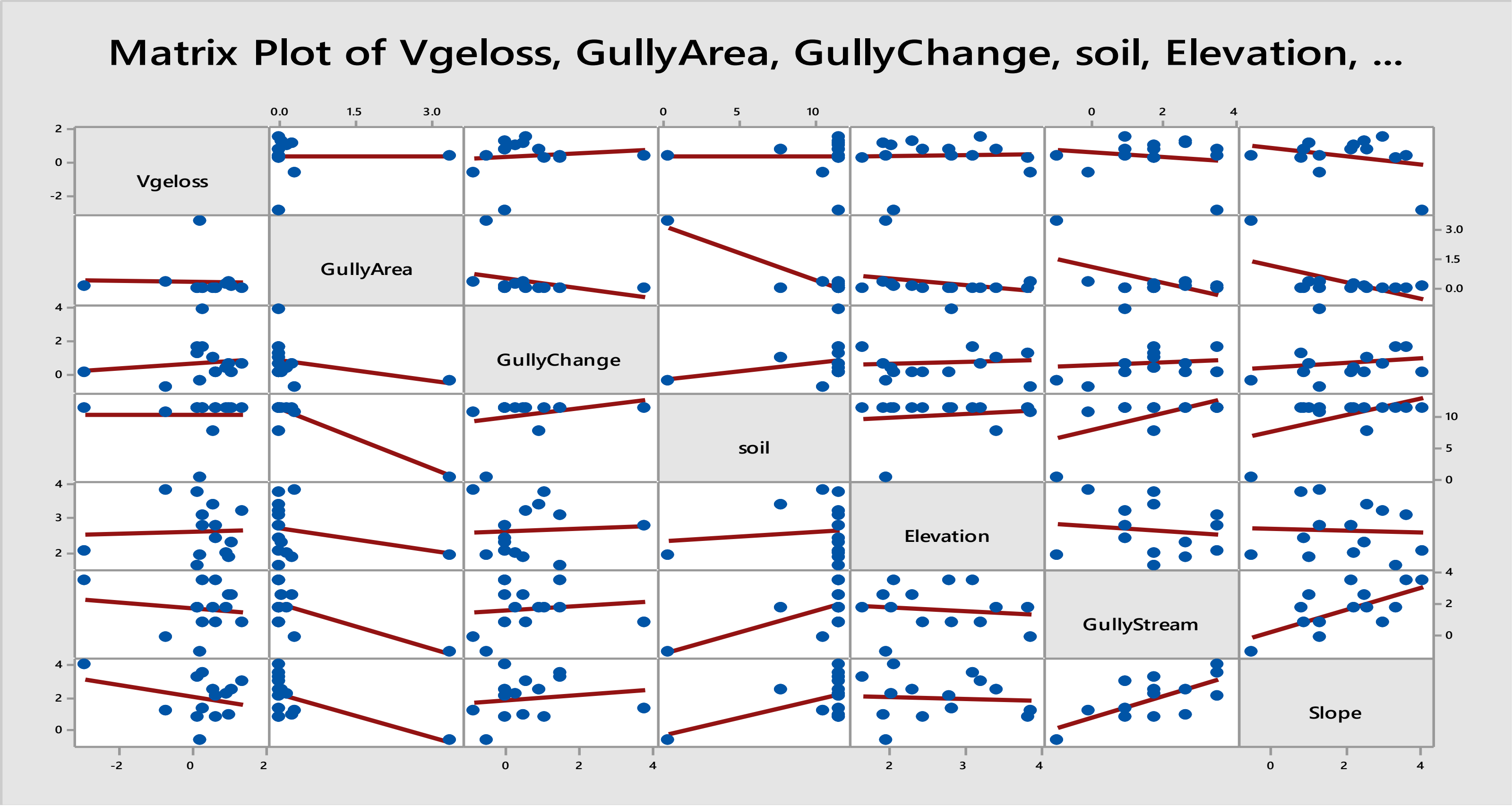


Figure 135: Open Source 2006/07 Matrix Plot of 2006/07-VegLoss, SlopeDegrees, Soil, Elevation, Gully stream order, 2007-Gully area, 2006/2007-yearly gully change in metre squared per square metre (The solid lines represent linear regression).

Table 70: Open source 2006/07 Correlation Coefficient Distance, Complete Linkage (complete linkage methods group clusters based upon single pair distances and best suited for the variables of this study. This is because this analysis is looking at the distance of each variable to yearly gully change in metre squared per square metre)

Step	Number of clusters	Similarity level	Distance level	Clusters joined	New cluster	Number of obs. in new cluster
1	6	83.7766	0.32447	6 7	6	2
2	5	76.5325	0.46935	4 6	4	3
3	4	56.1679	0.87664	1 3	1	2
4	3	52.5941	0.94812	1 5	1	3
5	2	34.9114	1.30177	1 4	1	6
6	1	3.2193	1.93561	1 2	1	7

Table 71:Open Source 2006/07 Final Partition

Cluster 1	Vgeloss GullyChange Elevation
Cluster 2	GullyArea
Cluster 3	soil GullyStream Slope

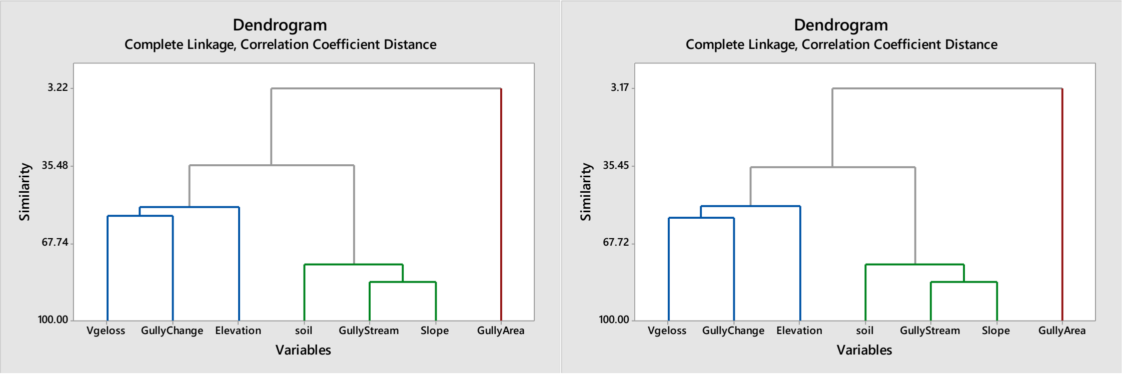


Figure 136: (Left) Dendrogram of the year 2006/07 with 7 gully variables represented in 3 cluster solution. (Right) ArcGIS industry standard equivalent data.

A closer look at the Cluster Analysis of 2006/07 arc and open source software of the gully variables show that they appear to have almost similar result. Compare the result of arc 2006/07 Cluster Analysis **section 5.5.1**

Although vegetation loss and elevation appear to have more relationship with yearly gully change in metre squared per square metre in open source software the same in Arc software,

5.9.4 Open Source 2014/15 Principal Component Analysis (PCA)

In further comparison of Arc and Open source software, the PCA statistical analysis of the 2014/2015 Total Variance Explained from PCA **Table 73 and**, Scree plot of **Figure 139, when compared with arc software 2014/15 total variance explained Table 29 and scree plot Figure 98 appear to have near similar output. For example, the arc variance explained 2014/15 for PC1 is 3.5681 and Open source is 3.5684.** The 2014/15 open source Component Score Coefficient **Table 74 and arcTable 34. Open source loading plot Figure 140. Biplot for open source Figure 142 and arc Figure 104.**

Open Source Total Variance Explained from PCA of 7 variables. This is also shown in a graphical manner using a Scree Plot in Figure 136

Table 72: Open Source 2014/15 Eigenanalysis of the Correlation Matrix

Eigenvalue	3.5684	1.2299	0.8246	0.7109	0.4285	0.1881	0.0494
Proportion	0.510	0.176	0.118	0.102	0.061	0.027	0.007
Cumulative	0.510	0.685	0.803	0.905	0.966	0.993	1.000

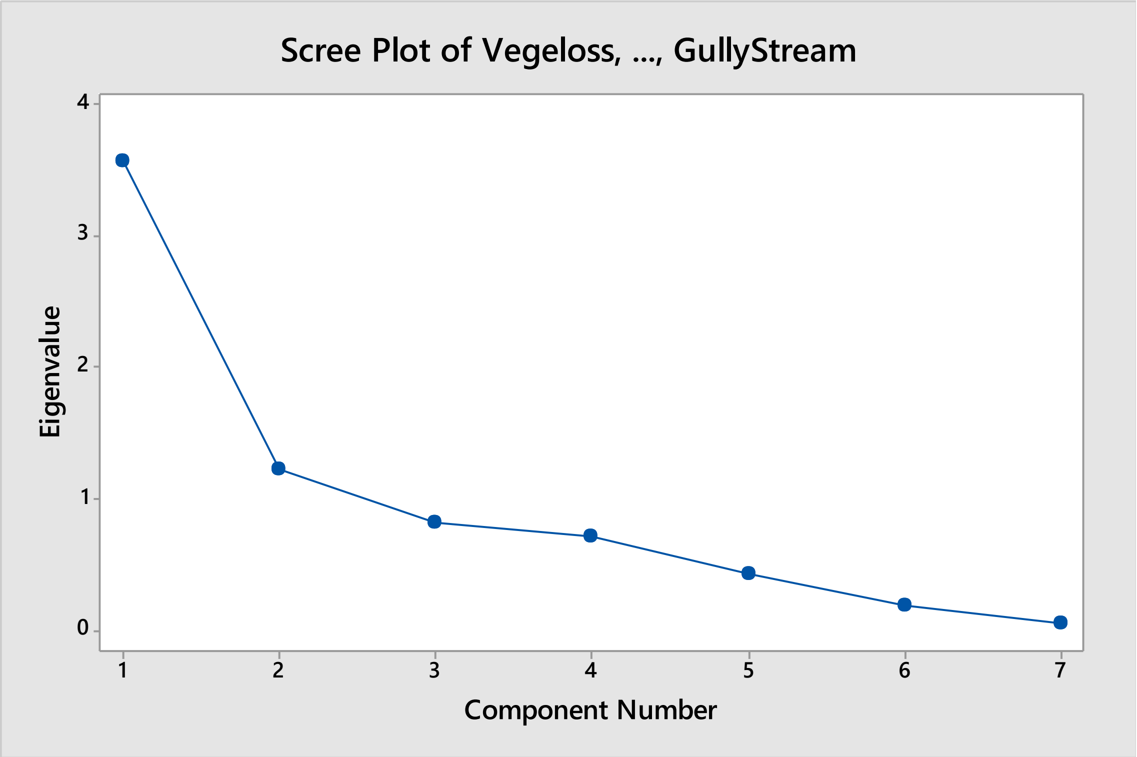


Figure 137:Open Source 2014/15 Scree plot showing the contributions of each of the new principal components; a graphical representation of the principal components of the data.The blue line represents the cumulative variability explained by the increasing number of components considered.

Table 73: Open source 2014/15 Component Score Coefficient Matrix showing the loadings of the 2 components and variables

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Vegeloss	0.348	-0.206	0.105	0.788	-0.330	-0.308	0.005
Gully Area	-0.479	0.220	-0.028	0.323	0.209	-0.107	-0.750
GullyChange	0.278	0.321	-0.812	0.213	0.027	0.339	-0.002
Slope	0.417	0.116	0.497	0.181	0.405	0.591	-0.144
Soil	0.459	-0.125	-0.017	-0.417	-0.447	-0.005	-0.632
Elevation	0.055	-0.818	-0.287	0.002	0.479	0.002	-0.130
GullyStream	0.430	0.330	-0.018	-0.147	0.504	-0.656	-0.006

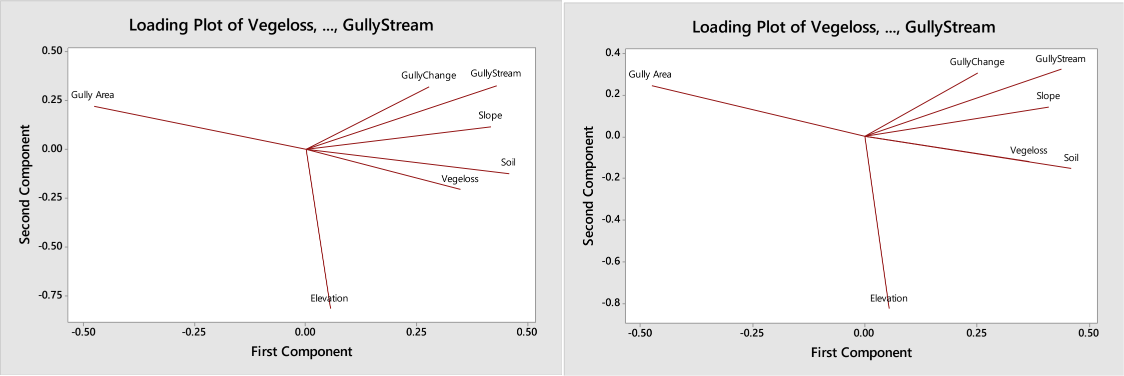


Figure 138: 2014/15 PCA loading plot of variables showing variability and relationship in the 2 most important components (F1 and F2). (Left) Open Source, (Right) ArcGIS sourced data

5.9.5 Figure 137:Open Source 2014/15 PCA Loading Plot of Variables Showing Variability and Relationship in the 2 most Important Components (F1 and F2).

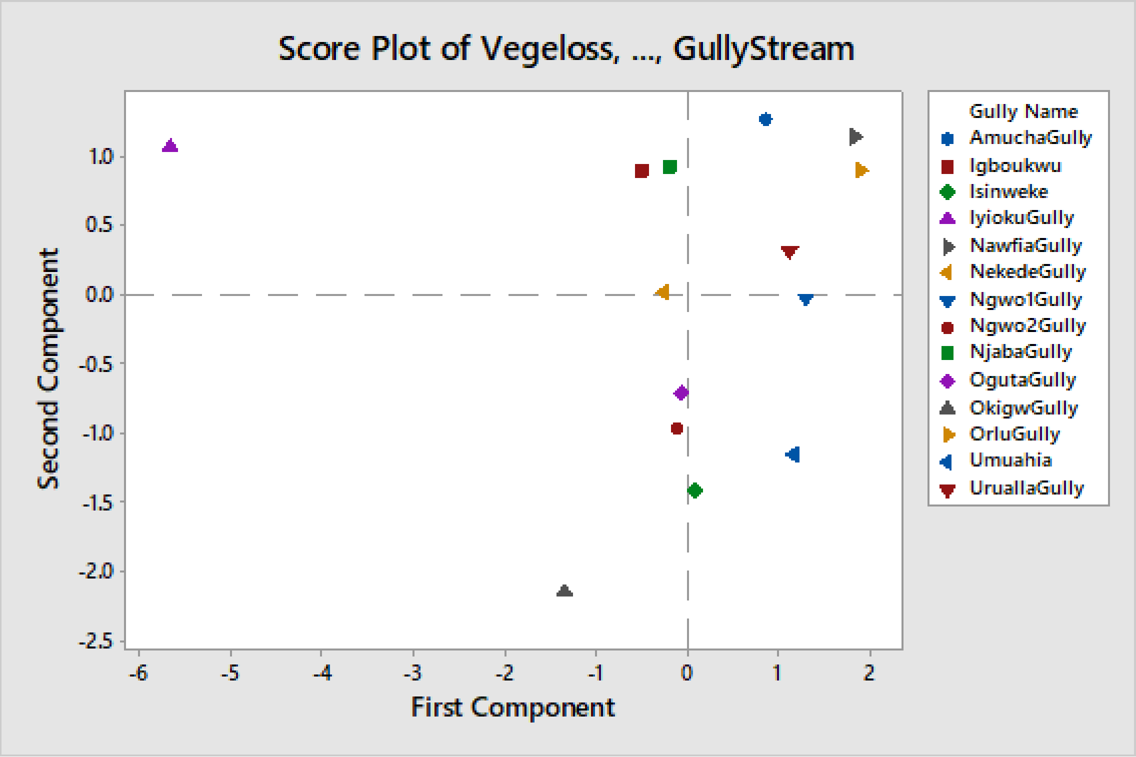


Figure 139: Open Source 2014/15 Score plot of the 7 variables with the 14 gullies

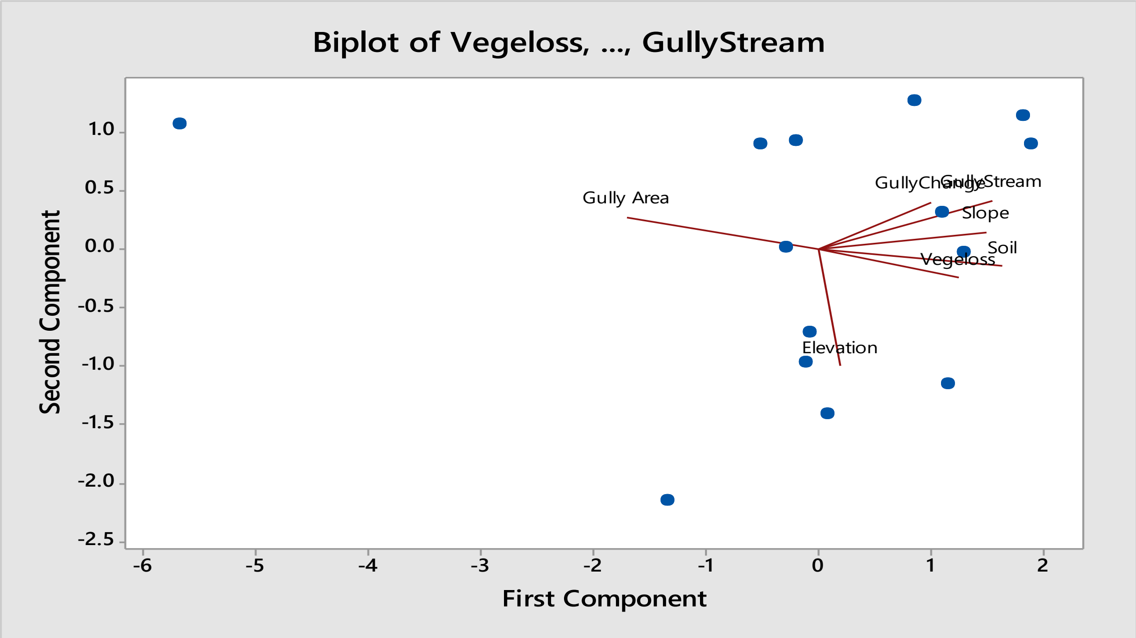


Figure 140: Open Source 2014/15 Biplot of vegetation with 7 variables and 14 gullies

5.9.6 Open Source 2009/2010 PCA

Total Variance Explained from PCA of 7 variables shown for 7 components.
Also, shown graphically through the Scree Plot).

comparison of 2009/2010 Open source and arc software, the PCA statistical analysis of the 2009/2010 Total Variance Explained from PCA **Table 74 and**, Scree plot of **Figure 143, when comared with arc software 2009/10 total variance explained Table 35 and scree plot Figure 106 appear to have near similar output. For example, the arc variance explained 2009/10 for PC1 is 3.5099 and Open source is 3.4821.** The 2009/10 open source **Component Score Coefficient Matrix Table 75 and arcTable 36**, PCA open source and Arc 2009/10 loading plot of variables **Figure 144. Biplot for open source Figure 146 and arc Figure 109.**

Table 74: Open Source 2009/2010 Eigenanalysis of the Correlation Matrix

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Eigenvalue	3.4821	1.2205	0.8391	0.6478	0.4743	0.2986	0.0376
Proportion	0.497	0.174	0.120	0.093	0.068	0.043	0.005
Cumulative	0.497	0.672	0.792	0.884	0.952	0.995	1.000

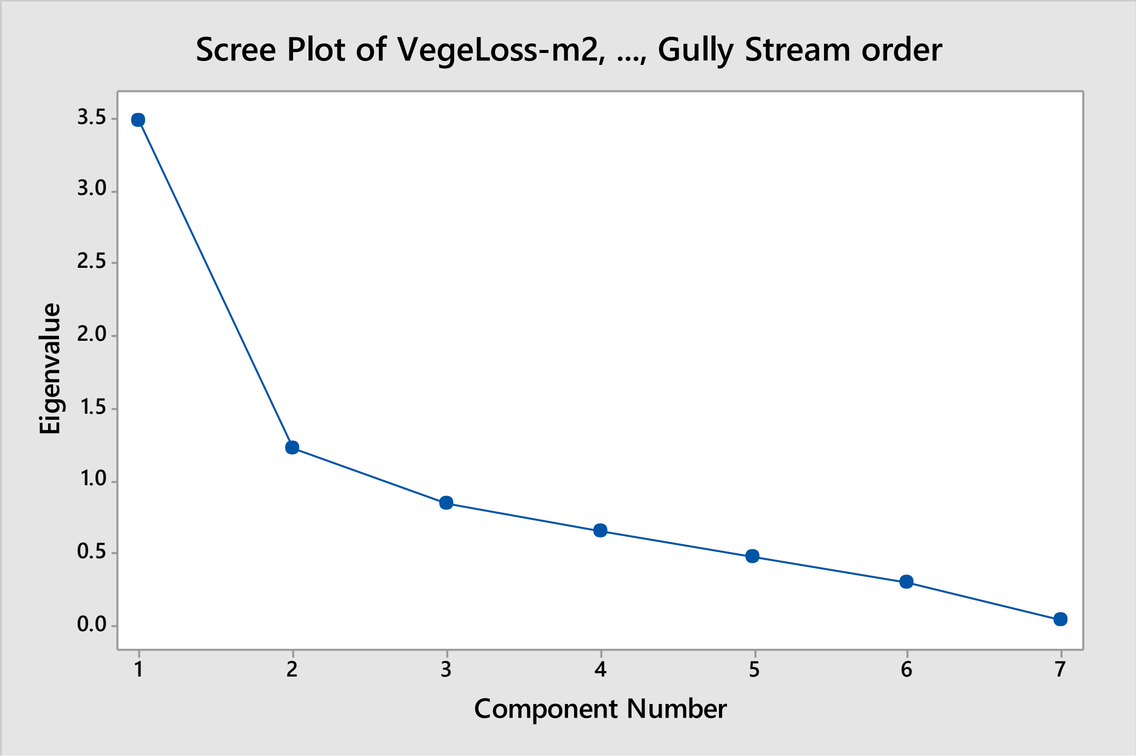


Figure 141: Open Source 2009/2010 Scree plot showing the contributions of each of the new principal components a graphical representation of the principal components of the data.

The blue line represents the cumulative variability explained by the increasing number of components considered.

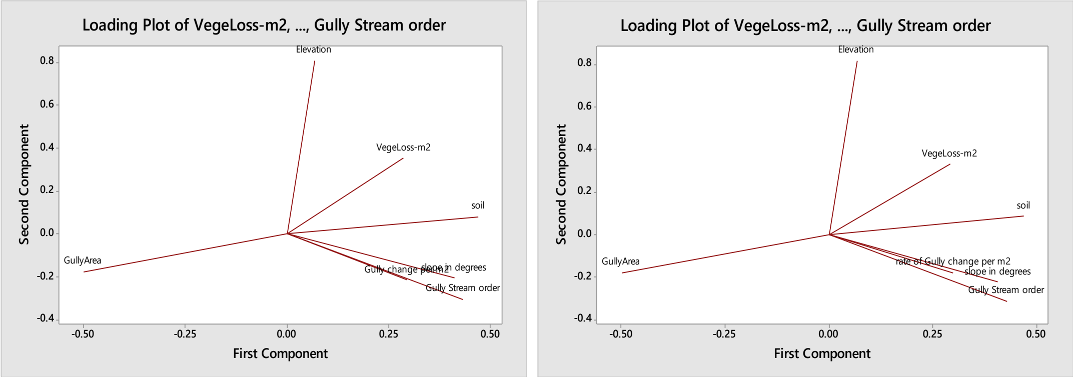


Figure 142: Open Source 2009/2010 PCA loading plot of variables showing variability and relationship in the 2 most important components (F1 and F2 (Left) Open source (Right) Arc GIS sourced data.

Table 75: Open Source 2009/2010 Component Score Coefficient Matrix showing the loadings of the components and variables

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7
VegeLoss-m2	0.286	0.351	0.539	0.701	-0.066	-0.006	0.093
GullyArea	-0.501	-0.178	0.091	0.147	0.285	-0.128	0.768
Gully change	0.294	-0.216	-0.712	0.546	0.194	0.138	0.072
slope in degrees	0.411	-0.209	0.306	-0.257	0.557	0.551	0.118
soil	0.470	0.079	-0.119	-0.273	-0.558	0.053	0.608
Elevation	0.067	0.809	-0.271	-0.200	0.437	-0.154	0.114
Gully Stream order	0.432	-0.307	0.114	-0.091	0.252	-0.796	-0.012

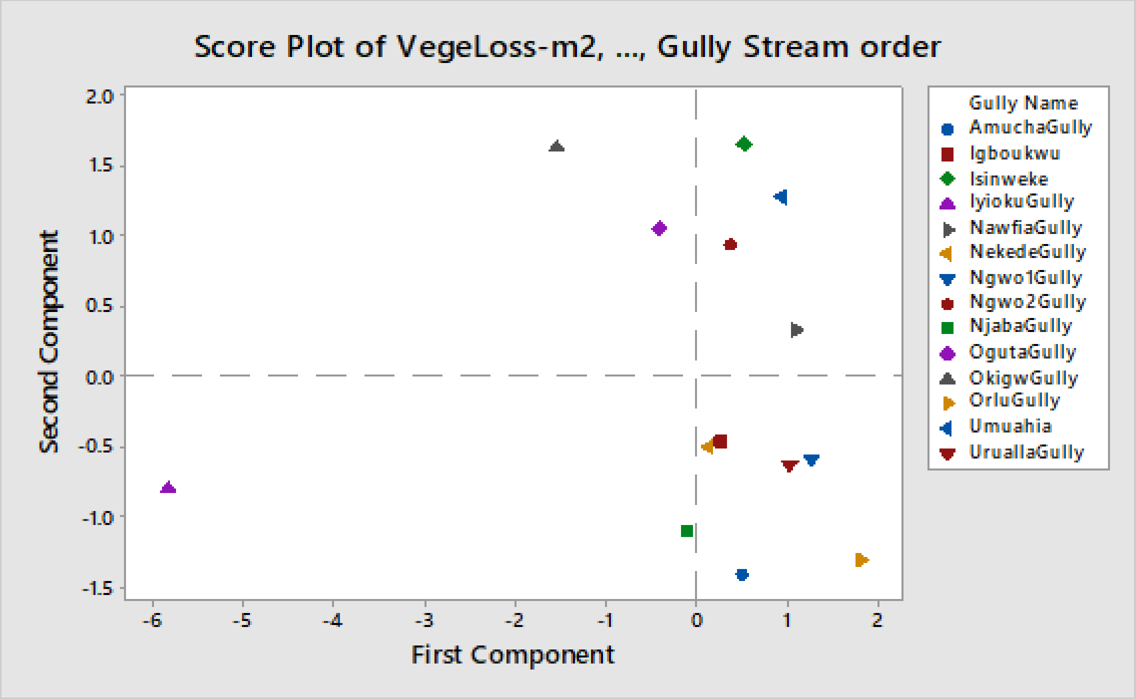


Figure 143: Open Source 2009/2010 Score plot of the 7 variables with the 14 gullies

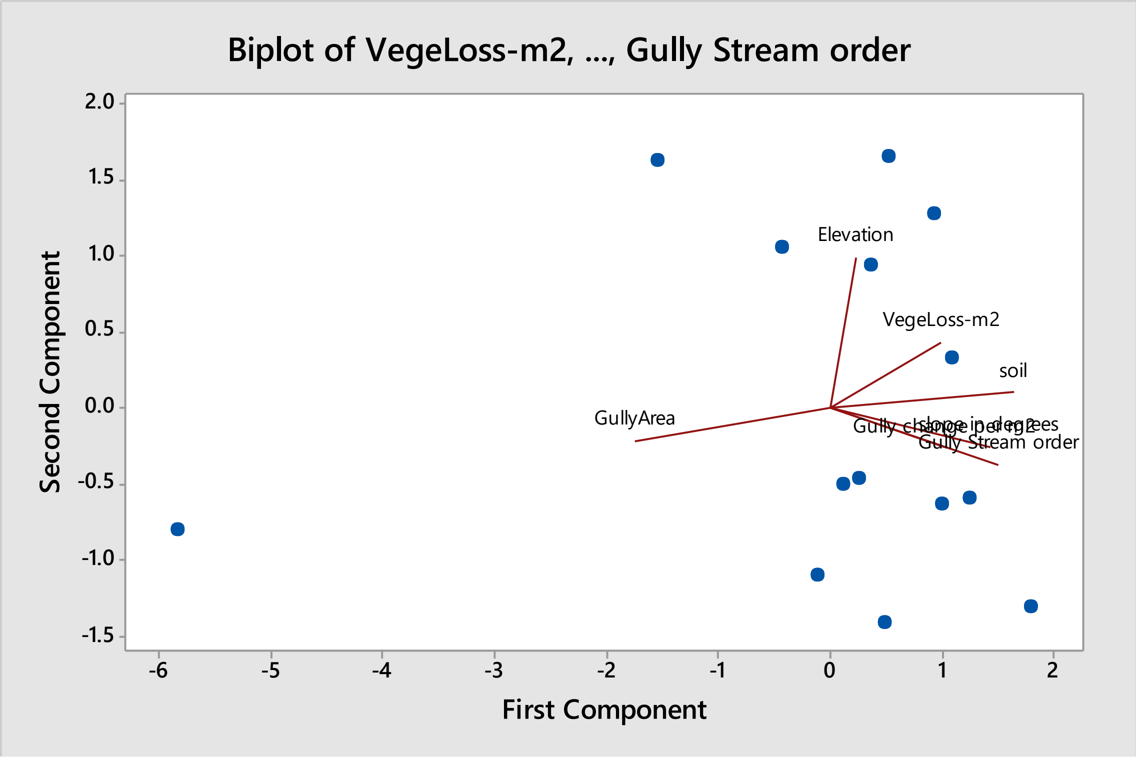


Figure 144: Open Source 2009/2010 Biplot of vegetation with 7 variables and 14 gullies

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5.9.7 Open Source 2006/2007 PCA

Total Variance Explained from PCA of 7 variables shown for 7 components. Also, shown graphically through the Scree Plot

comparison of 2006/2007 Open source and arc software, the PCA statistical analysis of the 2006/2007 Total Variance Explained from PCA **Table 76 and**, Scree plot of **Figure 147, when comared with arc software 2006/07 total variance explained Table 37 and scree plot Figure 111 appear to have near similar output. For example, the arc variance explained 2006/07 for PC1 is 3.1065 and Open source is 3.1176.** The 2006/07 open source **Component Score Coefficient Matrix Table 77 and arcTable 38**, PCA open source 2006/07 loading plot of variables **Figure 148 and for arc. Biplot for open source Figure 150 and arc Figure 114.**

Table 76: Open Source 2007/2007 Eigenanalysis of the Correlation Matrix

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Eigenvalue	3.1176	1.3635	0.9857	0.7888	0.4062	0.2967	0.0416
Proportion	0.445	0.195	0.141	0.113	0.058	0.042	0.006
Cumulative	0.445	0.640	0.781	0.894	0.952	0.994	1.000

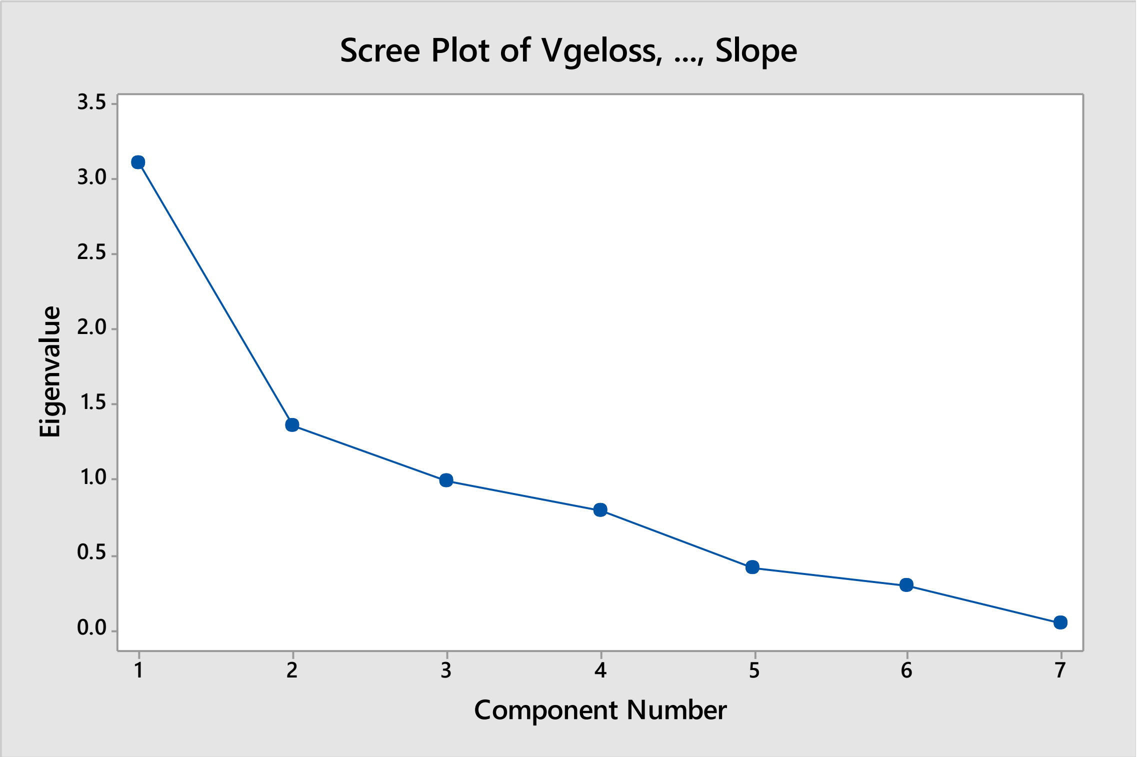

Figure 145: Open Source 2006/2007 Scree plot showing the contributions of each of the new principal components: a graphical representation of the principal components of the data. The blue line represents the cumulative variability explained by the increasing number of components

Table 77: Open Source 2006/2007 Component Score Coefficient Matrix showing the loadings of the components and variables

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Vgeloss	-0.086	-0.582	-0.488	0.544	0.326	-0.103	0.050
GullyArea	-0.527	0.214	-0.079	-0.115	0.242	0.137	0.761
GullyChange	0.205	-0.403	-0.392	-0.788	0.090	0.106	0.048
soil	0.507	-0.161	0.012	0.171	-0.546	-0.100	0.616
Elevation	0.055	-0.518	0.763	-0.035	0.322	0.161	0.126
GullyStream	0.457	0.261	-0.137	0.192	0.296	0.761	0.028
Slope	0.450	0.302	0.025	-0.054	0.581	-0.587	0.142

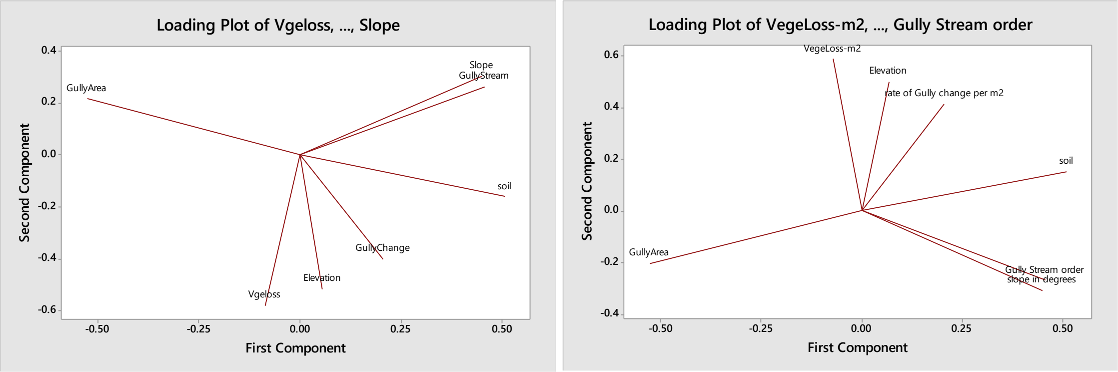

Figure 146: Open Source 2006/2007 PCA loading plot of variables showing variability and relationship in the 2 most important components (F1 and F2). (Left) Open source, (Right) Arc GIS sourced data.

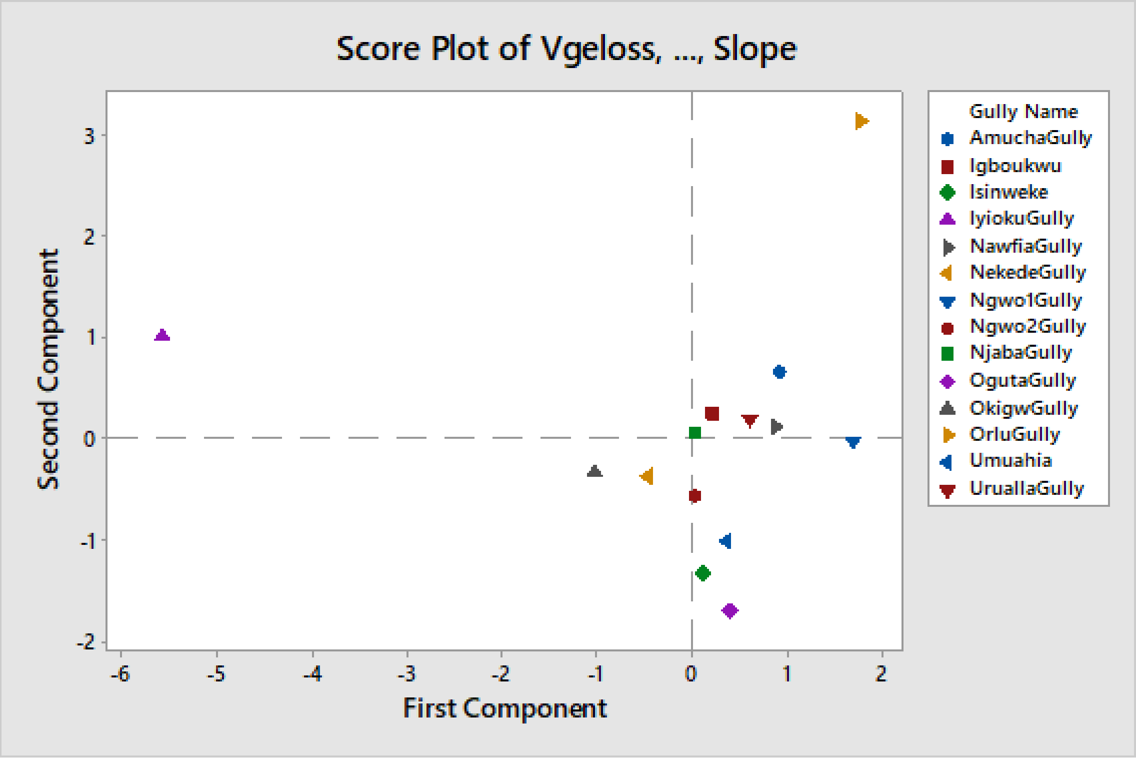

Figure 147: Open Source 2006/2007 Score plot of the 7 variables with the 14 gullies

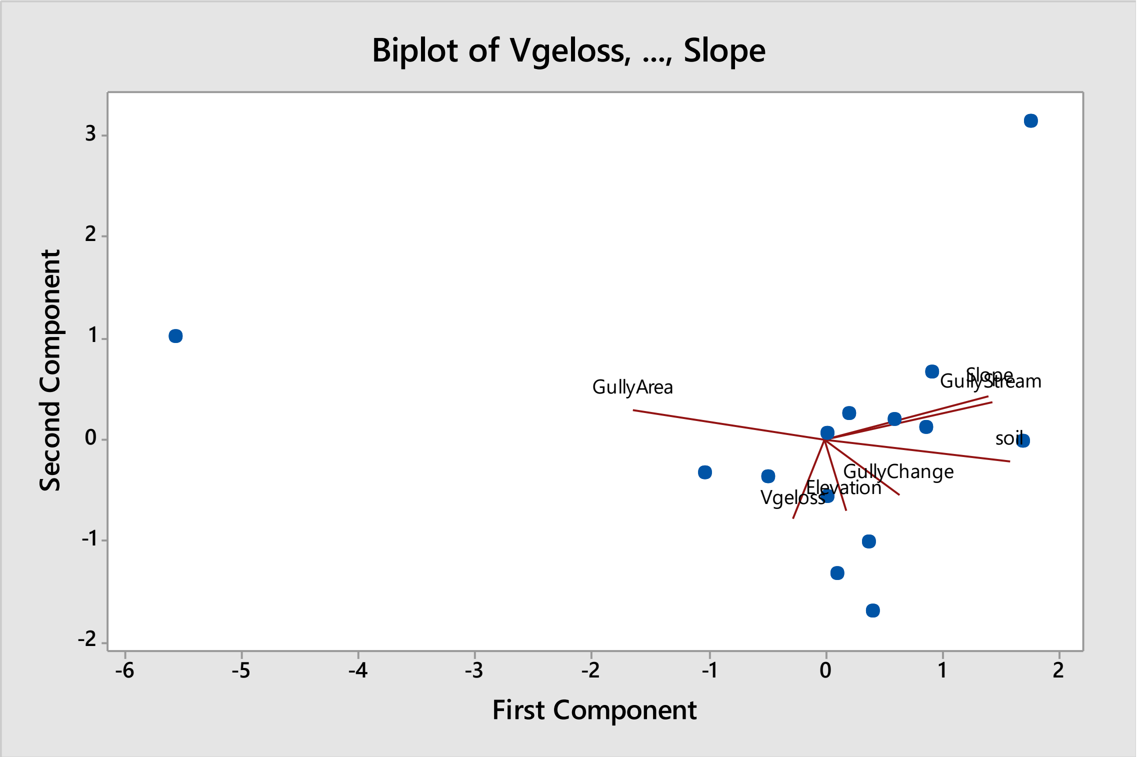

Figure 148: Open Source 2006/2007 Biplot of vegetation with 7 variables and 14 gullies

5.9.8 Open Source Multiple Linear Regression

The process in Arc software was repeated here by using the dependent variable (yearly gully change in metre squared per square metre) and the 6 independent variables , they are vegetation loss, slope, soil, elevation, gully stream order and gully area.

5.9.8.1 Open Source 2014/2015 Multiple Linear Regression Analysis

To aid the Multiple Linear Regression, the correlation table of the 6 independent variables to predict the yearly gully change in metre squared per square metre are entered for Open source and Arc software in **Table 78 and Table 41** respectively, the ANOVA tables outlining the performance of the regression are shown in 80 and 43 respectively. The measure of variance of the variables is shown in **Table 81 and Table 44 respectively**, and the Coefficients of the variables showing significance are outlined in **Table 82 and Table 45 respectively.** **All of the presented results** and other tables show that all analyses exhibit near similarity in result between open source and Arc software. A result of the variables' values showing near similarity.

Table 78: Open Source 2014/2015 Dependent and independent variables entered for (MLR)

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	GullyStream, Elevation, Vegeloss, Soil, Slope, GullyArea[b]	.	Enter

a. Dependent Variable: GulyChange

b. All requested variables entered.

Table 79: Open Source 2014/2015 Correlation Table of the 6 independent variables to yearly gully change in metre squared per square metre

Correlations

		Vegeloss	Gully Area	Gully Change	Slope	Soil	Elevation	Gully Stream
Vegeloss	Pearson Correlation	1	-.495	.289	.541*	.429	.185	.334
	Sig. (2-tailed)		.072	.315	.046	.126	.527	.244
	N	14	14	14	14	14	14	14
GullyArea	Pearson Correlation	-.495	1	-.325	-.620*	-.929**	-.261	-.620*
	Sig. (2-tailed)	.072		.257	.018	.000	.368	.018
	N	14	14	14	14	14	14	14
GullyChange	Pearson Correlation	.289	-.325	1	.197	.349	-.070	.511
	Sig. (2-tailed)	.315	.257		.500	.222	.812	.062
	N	14	14	14	14	14	14	14
Slope	Pearson Correlation	.541*	-.620*	.197	1	.531	-.067	.676**
	Sig. (2-tailed)	.046	.018	.500		.051	.820	.008
	N	14	14	14	14	14	14	14
Soil	Pearson Correlation	.429	-.929**	.349	.531	1	.132	.602*
	Sig. (2-tailed)	.126	.000	.222	.051		.653	.023
	N	14	14	14	14	14	14	14
Elevation	Pearson Correlation	.185	-.261	-.070	-.067	.132	1	-.139
	Sig. (2-tailed)	.527	.368	.812	.820	.653		.635
	N	14	14	14	14	14	14	14
GullyStream	Pearson Correlation	.334	-.620*	.511	.676**	.602*	-.139	1
	Sig. (2-tailed)	.244	.018	.062	.008	.023	.635	
	N	14	14	14	14	14	14	14

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

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

Table 80: Open Source 2014/2015 Anova Table (test using alpha = 0.05)

ANOVA[a]						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3.740	6	.623	.677	.675[b]
	Residual	6.446	7	.921		
	Total	10.186	13			
a. Dependent Variable: GulyChange						
b. Predictors: (Constant), GullyStream, Elevation, Vegeloss, Soil, Slope, GullyArea						

Table 81: Open Source 2014/2015 Measure of variance of the variables entered in Multiple linear regression

Model Summary[b]				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.606[a]	.367	-.175	.95958965
a. Predictors: (Constant), GullyStream, Elevation, Vegeloss, Soil, Slope, GullyArea				
b. Dependent Variable: GulyChange				

Table 82: Open Source 2014/2015 Coefficients of the variables showing significance in Multiple linear regression

Coefficients[a]						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.199	3.867		-.051	.960
	Vegeloss	.221	.280	.297	.787	.457
	GullyArea	.001	1.018	.001	.001	.999
	Slope	-.314	.340	-.458	-.923	.387
	Soil	.020	.254	.072	.080	.938
	Elevation	-.086	.444	-.072	-.194	.852
	GullyStream	.432	.298	.668	1.452	.190
a. Dependent Variable: GulyChange						

5.9.8.2 Open Source 2009/2010 Multiple Linear Regression Analysis

To aid the Multiple Linear Regression, the ANOVA tables outlining the performance of the regression are shown in 85 and 47 respectively. The measure of variance of the variables is shown in Table 84 and Table 49 respectively, and the Coefficients of the variables showing significance are outlined in Table 86 and Table 50 respectively. All of the presented results and other tables show that all analyses exhibit near similarity in result between open source and Arc software. A result of the variables' values showing near similarity

Table 83: Open Source 2009/2010 Dependent and independent variables entered for (MLR)

Variables Entered/Removed[a]			
Model	Variables Entered	Variables Removed	Method
1	GullyStream, Elevation, Vegeloss, Soil, Slope, GullyArea[b]	.	Enter
a. Dependent Variable: GulyChange			
b. All requested variables entered.			

Table 84: Open Source 2009/2010 Measure of variance of the variables entered in Multiple linear regression

Model Summary[b]				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.539[a]	.291	-.317	1.37321952
a. Predictors: (Constant), GullyStream, Elevation, Vegeloss, Soil, Slope, GullyArea				
b. Dependent Variable: GulyChange				

Table 85: Open Source 2009/2010 Anova Table (test using alpha = 0.05)

ANOVA[a]						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	5.416	6	.903	.479	.806[b]
	Residual	13.200	7	1.886		
	Total	18.616	13			
a. Dependent Variable: GulyChange						
b. Predictors: (Constant), GullyStream, Elevation, Vegeloss, Soil, Slope, GullyArea						

Table 86: Open Source 2009/2010 Coefficients of the variables showing significance in Multiple linear regression

Coefficients[a]						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	4.894	6.014		.814	.443
	Vegeloss	-.165	.361	-.174	-.458	.661
	GullyArea	-1.508	1.625	-1.117	-.928	.384
	Slope	-.201	.444	-.217	-.451	.665
	Soil	-.236	.389	-.614	-.605	.564
	Elevation	-.286	.622	-.178	-.461	.659
	GullyStream	.230	.424	.264	.543	.604
a. Dependent Variable: GulyChange						

5.9.8.3 Open Source Multiple Linear Regression Analysis (2006/2007)

Again to aid the Multiple Linear Regression, the ANOVA tables outlining the performance of the regression are shown in **Tables 89 and 52** respectively. The measure of variance of the variables is shown in **Table 88 and Table 54** respectively, and the Coefficients of the variables showing significance are outlined in **Table 90 and Table 55** respectively. All of the presented results and other tables show that all analyses exhibit near similarity in result between open source and Arc software. A result of the variables' values showing near similarity

Table 87: Open Source 2006/2007 Dependent and independent variables entered for (MLR)

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	GullyStream, Soil, Vegeloss, Slope, Elevation, GullyArea[b]	.	Enter

a. Dependent Variable: GulyChange

b. All requested variables entered.

Table 88: Open Source 2006/2007 Measure of variance of the variables entered in Multiple linear regression

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.399[a]	.159	-.562	1.44470819

a. Predictors: (Constant), GullyStream, Soil, Vegeloss, Slope, Elevation, GullyArea

b. Dependent Variable: GulyChange

Table 89: Open Source 2006/2007: Anova Table (test using alpha = 0.05)

ANOVA[a]						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	2.761	6	.460	.220	.958[b]
	Residual	14.610	7	2.087		
	Total	17.371	13			
a. Dependent Variable: GulyChange						
b. Predictors: (Constant), GullyStream, Soil, Vegeloss, Slope, Elevation, GullyArea						

Table 90: Open Source 2006/2007 Coefficients of the variables showing significance in Multiple linear regression

Coefficients[a]						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	3.382	6.114		.553	.597
	Vegeloss	.081	.415	.075	.196	.850
	GullyArea	-1.131	1.644	-.873	-.688	.513
	Slope	-.146	.403	-.393	-.361	.729
	Soil	-.215	.663	-.137	-.324	.756
	Elevation	-.131	.448	-.156	-.293	.778
	GullyStream	-.052	.501	-.058	-.103	.921
a. Dependent Variable: GulyChange						

6 Discussion of the Results

In this section the results will be discussed with reference to the aim and objectives with theories and expectations derived from the literature. It will begin by analyzing the anthropological activities through Land-cover classification and topographical influences exacted on gully development as procured from the analyses undertaken before exploring the main body of results in greater detail. Where appropriate the discussion will refer back to the results section and literature review.

6.1 Land Cover Changes Influenced by Anthropological Activities

Correlation analyses examining the relationship between vegetation area and the occurrence of Gully/open-land development were examined in the results section using Pearson's, and where necessary Spearman's, correlation coefficients **Table 18**. The analysis was conducted for both the OBIA and Pixel based classification methodologies incorporated in this study within a broader analysis of land cover change in the study area. In terms of the correlation between vegetation area and gully/openland development, Pixel based classification produced a correlation of $r = -0.9$ ($p<0.05$). A similar strength of correlation was exhibited for OBIA with $r = -0.9$ ($p<0.05$) with both results indicating a very strong and significant negative correlation between the amount of vegetated area and Gully/open-land development over the study period 1986-2015. Although such a strong and apparent correlation is evident and fundamentally expected, what cannot be conclusively determined from the analysis is whether the vegetation loss had a causal effect on gully development. Based on the correlation levels and from referring to studies such as Egboka (1993); Nyom (2005); Posser and Slade (1994); Madu et al. (2006); and Max (1998) the causal effect is highly probable. These referenced studies from different time periods and regions agreed that the removal of vegetation begins a detrimental series of events which affect soil quality and stability which then directly result in gully development.

The vegetation land cover reduction exhibited on the regional scale in this study, across approximately 57,758km2, is predominantly enacted through anthropological activities, **Table 12 and 13**, with anthropogenic landcovers inversely related with vegetation cover. Similar correlation analyses undertaken with the other landuse classes showed that the resulting correlation between Vegetated area and Urban-land increase were r= -0.5 and r= -0.9 ($P<0.05$) for Pixel and OBIA classifications respectively, showing reasonably strong negative associations. The increasing level of urban area exhibits very strong correlation with a decreasing area of vegetation particularly for the OBIA classification approach. Values of r= -0.9 and r= -0.2 ($P<0.05$) for pixel and OBIA classification respectively show a very strong negative correlation and a weak negative correlation respectively between Agricultural land area and vegetated area showing similar advances for these classes as vegetated area reduced. The largely differing correlation coefficients associated with the agricultural landuse could be as a result of the methodology OBIA method uses in classification through grouping similar pixels of agricultural areas into vegetation areas or vise versa (Blaschke 2014). Okpara (2004) has reported that some cities such as Onitsha and Nnewi, Owerri and Orlu, Enugu and Nite Mile in southeast Nigeria have formed conurbations because of population pressure, resulting in a loss of rich rainforest vegetation. Nigeria itself has the 9th largest urban population in the world therefore pressures on the land in habitable areas can be extreme (Leila et al. 2014). This urban expansion is therefore a likely reason why urban areas have continuously increased while vegetation is reducing as a consequence. The urban expansion also has the added dimension of being largely unregulated and this is believed to be where significant drivers for gully erosion are arising. Igbozurike (2000) notes that about 600 buildings that are erected in Owerri, Awka, Aba and Onitsha as a consequence of vegetation removal do not possess the required planning permissions. This unregulated expansion is therefore a contributor to environmental issues, for example blocking natural water runoff courses and channels. This can lead to severe land degradation and gully erosion. This was discovered by Okocha, (2008) that some gully erosion going on at Okigwe, Umuahia, Onitsha and Enugu urban centres in southeast Nigeria resulted from buildings being built across topographic contours, runoff channels and areas prone to gully devastation. Therefore, the problem is not the population but the relationship to the environment, as pointed out by Clarke (1992).

According to multivariate PCA statistical analysis (**Figures 102 and 107**), the analysis reveals that more vegetation loss is associated with smaller gully areas. Essentially this is where the more rapid gully area changes occur. The large gullies have already lost a lot of vegetation, meaning that they are fully developed. (The observation shows that big gullies mean less vegetation loss. This assumes that once the gully is big, there is actually very little further vegetation loss). This could be perceived to be the reason for gully development in the study area as pointed out by many studies like Onyekwere (2001), Ijeoma and Okey (2005), Ayanlade and Drake (2015). More significantly, and understandably, the yearly gully change in metre squared per square metre is positively correlated with the loss of vegetation, further evidence of acting as a driver for gully development. Equally, Cluster Analysis recognises a similar relationship between vegetation loss, rate of gully change per sq. metre. This supports the views of Okpara (2004) and Igbozurike (2000)and also supports the correlation between vegetation loss and gully area development earlier discussed in Table 16. The evidence supports the theory that a reduction of vegetation area results in gully/open-land development.

6.2 Local and Regional Analysis of Land-cover in Relation to Gully Development

Within the study region, according to the tested classification methods, **Table 12** and **Table 13**, the level of vegetation area has reduced during the study period from 90% (Pixel) and 83% (OBIA) in 1986 to 35% (Pixel) and 42% (OBIA) in 2015. These percentages are taken from a total area of 57,758.034km^2. Correlating the year on year regional changes in landcover with the changing individual gully sizes, shows that the area of each gully and hence its change in this metric is negatively correlated with vegetation area in the region. From the analysis of all

14 surveyed gullies independently with the landscape on a local scale, (10km by 10km centred on gully), they were generally shown to exhibit a very strong negative correlation between vegetation area and gully/openland area **Table 21**. This was shown in all cases for both pixel and OBIA vegetation classes except for Oguta where the gully displayed strong positive correlation. The correlations were r= 0.798 (pixel) and (OBIA) r= 0.808. Based on the correlation, the study area has consistently shown a reduction in areas of vegetation resulting in increasing levels of gully/openland as denoted by a negative correlation on both the regional and local scale.

These examples largely vindicate the use of both classification methods as a quality control. The strong negative correlation reported means that vegetation, or more precisely the removal of vegetation is very likely contributing to gully development in a direct or indirect manner (Kosmas et al. 1997). At this stage there are several other variables to consider but the evidence to support this statement is apparent and supported by David et al. (1999), Egboka (1993) and Okey (2005), among others. Those that don't exhibit a very strong negative correlation are known to have had been subject to anthropogenic interventions in one way or the other. The dynamics, reported by the correlation analysis of the gullies of Oguta potentially relate to the reducing size of the gullies through management rather than any large increases in vegetation. It is evident from available data that the size of Oguta started to reduce by 2010. Visual evidence and anecdotal accounts from field-work at the gully site show that the communities have diverted the main runoff to Orash river through a constructed channel. This has had the effect of reducing gully erosion but also of stimulating vegetation growth in areas surrounding the gully. As an example of other intervention work, according to Okeke et al (2012) during the reconstruction of Enugu – Onitsha road in year 2012, the contractors used soil to fill some parts of the Nawfia gully site which prevented the main runoff from feeding the gully. This does not mean that the gully is no longer active as the correlation still exists with the vegetation loss but the level of development has reduced. The Ngwo2 gully is known to be contained by the local community. It was reported by Columbus (2012) that the Ngwo community, by the year 2012, enforced a cordon around the gully area with its citizens advised not to farm within 200m around the gully site or to cut trees. Failure to adhere to this results in community fines. The approach would appear to be successful based on the reduction of gully area sizes from 5943m^2 in 2012 to 58842m^2, 5708m^2 and 5600m^2 for years 2013, 2014 and 2015 respectively (Columbus 2012).

6.3 Vegetation Loss as a Precursor to Gully Development

Vegetation loss was evident across the study region as identified by this study Tables 12 and 13. This appears to follow a global trend with gully development responding to vegetation losses similar to those posed by Posser and Slade (1994); and Ahmed and Dinye (2012), in both southern Australia and in Kumasi, Ghana, respectively. In all these cases reduced vegetation cover made the area susceptible to widespread rapid gully formation. Based on the land cover classification analyses the steady reduction in vegetation clearly revealed a significant correlation with increases in open land and gully development. The large scale study by Keenana et al. (2015) observed that forest area expansion is being enacted in Europe, North America, the Caribbean, East Asia, and Western-Central Asia, but continues to decline in Central America, South America, South and Southeast Asia and all regions in Africa. It is pointed out by Igwe (2005) that in South East Nigeria gullies mostly develop on soil on which vegetal growth has been disturbed. This is evidenced on the correlation of gully area sizes and vegetation area which shows very strong correlation **Tables 20 and 21**. Looking at PCA of year 2014/15, and 2009/2010, vegetation loss appears to have a good variance explained by the principle component of 37% (PC1), and 29% (PC1) for the respective years. The percent variance of vegetation loss explained is almost similar to that for yearly gully change in metre squared per square metre in the corresponding years of 25%, and 31%, could help to drive home the importance of vegetation loss in gully development, although for 2006/2007 these similarities weren’t as apparent. The results correspond with those of Onyekwere (2001); Ijeoma and Okey (2005); that used different methodology of interview and site measurement to observe that vegetation loss was a big factor in gully area development in southeast Nigeria. For each year, the gully area variable is correlated with high vegetation loss associated more with smaller gullies which fits the model of vegetation loss acting as an initial driver rather than the key variable driving advanced behaviour.

6.4 Topographical Influences on Gully Development

Topography has a strong influence on gully development. Several studies have identified topography as the main link to gully development. Poesen et al. (2003), Marquisee (2010), Boardman (2006), Bochet (2004) and Igbokwe (2008) observed that topographical influence was the prime reason for gully development in different locations. Some of the topographical factors include the contribution to runoff as the amount and intensity of rainfall combines with these. In southeast Nigeria, rainfall data is high because it is influenced by tropical monsoon climate which generates over 1000mm of monthly rainfall every year during rainy season (March - November). The slope of land, properties of soil, and the nature and extent of ground cover are all deemed essential contributors to gully formation as reported in Sharhrivar and Christopher (2012), Valentin (2005), and Abegunde et al. (2006). In southeast Nigeria, many works such as Ofomata (2001), found that there is a positive relationship between relief and gully erosion leading to more pronounced and aggressive gully erosion in areas with valley topography than areas with flat land. This is expected due to the physics of the scenario. Ofomata pointed out that in areas like Agulu-Nanka, Njaba, Nekede-Owerri, Iyioku, Okigwe, Afikpo, Ohafia, and Umuahia, the gullies can be traced to the natural slope of the topography but the occurrence of gullies must be influenced by more than just this, otherwise gullies would form on all steep topography. The result of this study tends to agree with Ofomata on the importance of slope by showing that the studied gullies are located at the base of slopes or hills. For example the slope degree of Iyioku, Okigwe, Umuahia and Nekede are 15^0, 11^0, 10^0 and 10^0 respectively. with the gullies evidently developing at the base of the slope because it is the area where runoff converges to form the gully head before it develops. PCA and Cluster analysis conducted here shows there is high variance and clustering between the actual magnitude of slope and the proportional yearly gully change in metre squared per square metre, indicating that the gully specific metrics are largely independent of the slope. This study therefore indicates the importance of slope but only to the extent that it exists for a gully to form. This is further supported by the existence of the slope and other variables clustering well with yearly gully change in metre squared per square metre for each year considered using hierarchical clustering, see Figure **91** for example.

6.4.1 Nature of Gully Development on Slope

One of the objectives of this study is to generate Digital Elevation Models (DEM) to detect changes and calculate gully dimensions (including slope) of focused gully sites. The South East Nigeria study area is characterized by gentle to steep slopes with extreme slopes also found in certain areas where 20^0 inclines are exhibited, see for example **Figure 50**. Slope areas less than 20^0 are seen in gentle slope and flat areas including river courses, flood plains and hill top areas. Areas classified to have slope of 10^0 and greater, are expected to favour erosion activities based on (Igbokwe 2008). The theory suggests correctly that the greater kinetic energy is gained at the plane with the highest slope angles but the data presented here suggests that this is not as important a driver as theorised. The revelation from this study shows that most of the gullies develop at the base of the slope for example Iyioku and Njaba gullies with slope areas of 15^0 and 9^0 respectively have their upper part of the slope ahead of them with areas ranging from 35^0 to 40^0 at 30 metre resolution. The energy increases down the slope as they converge from lower stream order to higher stream orders at the slope base while carrying eroded materials from deep incisions made at those points. Slope has an effect on run-off and drainage therefore having a profound influence on the moisture regime of the soil. Studies such as Poesen et al. (2003); Teme (2001) and Bennard (2012) have observed that slope generates the runoff that causes gully erosion. These studies were of the opinion that valley topography is also an underlying factor in gully generation, with steeper and longer slopes providing the higher erosion risk. This theory is not debated here but it is strongly proposed that other factors need to be in place before such erosion can occur; the prime driver proposed here being the loss of vegetation. In South-East Nigeria, Ofomata (2001); Iwu (2012); Abdulfatai et al. (2014); Ekanade et al. (2008); Nwilo et al. (2011); and Chikwe (2012) all agreed that, most developed gullies can be traced to the natural slope of the topography with slope inclinations ascertained to be greater than 8^o encouraging gully erosion. This theory fits more seamlessly with the results exhibited here where all gullies were seen to occur on slopes of at least 5^0.

95% of the gully erosion sites examined in south-east Nigeria, as part of this study, develop down the hill side areas, determined initially from field visits and through the overlaying of gully points on calculated slope maps, Figure **50**. Gully sites such as Iyioku, Okigwe, Njaba, Umuahia, Ngwo1 and Ngwo2 show that they have developed on slope areas greater than 5^0 at 30m resolution. The slope analysis has shown that gullies in the study area, amongst other gully factors, anchor their development on the nature of the slope, revealing that when every other contributing factor is in place such as vegetation loss, gully stream order and unconslodated soil, the slope provides the ideal conditions to trigger gully development. Without this characteristic the level of erosion required to form gullies is unlikely to occur. Although not ground breaking information the multivariate analysis allows the importance of the magnitude of slope to be put in context.

6.4.2 Curvature as an Aspect of Slope in Gully Development

Slope curvatures were determined in conjunction with slope magnitudes. The curvatures of the study area ranged from -5 plan, defining convexity; to high values of 6 plan characterizing concavity **Figure 53**. The relationship between gullies and plan curvatures in south-east Nigeria shows that gully erosion processes commonly occur on concave slopes. Studies by Gobin revealed that

60% of the gullies in southeast Nigeria occur on concave slopes (Gobin et al. 1998) as can be found in Iyioku, Okigwe, Isinweke, Njaba, Ngwo1, and Umuahia, gully sites Figure 52. In terrain analysis, hill and moderate relief can produce curvatures that vary from -0.5 to 0.5; while for mountain, steep, rugged extreme relief, the values can vary between -4 and 4 (Environmental Systems Research Institute 2011). The nature of the landscape can in part be determined through analysis of these curvatures with negative values typically representing gullies and river courses while positive values are more representative of uneroded landscapes (Igwe 1999). This analysis shows that the nature of the topography is in part responsible for gully development in the study area. In the study area for this work the values range between -5 and 6 which signifies a hilly relief Figure 52, therefore, the surface of the area that is receiving high runoff from hilly areas could be the reason for gully development. The high value of 6 shows that the surface is upwardly concave at more cells (a cell is the area covered on the ground and represented by a single pixel) which contributes to generate accelerated flow and theoretically influence gully development. This helps to explain the development of gullies in the area in combination with other identified factors. This finding is supported by Beshah (2003); Bewke (2003) and Igwe (2012), where it is observed that the slope geometry of concave hill sides can often contribute significantly to soil loss and gully development. Mat et al. (2009) suggested that Gullies in Okigwe Local Government Area of Imo-State, southeast Nigeria, developed through association with particular slope shapes. That such shapes can be determined accurately from Digital Elevation Models of the area with concave formations in general resulting in more severe gullying. This was observed and concurred in this study. Among other gullies, Okigwe gully developed on concave slope to encourage severe gullying and result in high gully area rate of change. In all the 14 surveyed gullies in the study area, 11 are located on concave while 3 are located on convex slopes evidencing the high proportion.

6.4.3 Influence of Aspect (slope direction) on Gully Development

The Aspect map produced for the South East Nigeria region is dominated by slopes facing N (337.5 - 360) to NW (292.5 – 337.5) **Figure 52** and evident via the histogram. The gullies are not necessarily conforming to this dominance. The South slopes are intermittently the drier and wetter landscape due to the greater exposure to the sun and being inundated by high rainfall due to the Tropical Maritime Air mass moving up from the southern part of Nigeria (Oladipupo 2003). The southern facing slopes are subject to both extremes in the study area. A consequence of this extreme alteration of soild condition is a loss of soil (Ohlmacher 2007 and Godwin 2013). Nine of the studied gullies in the study area are developing towards the south facing slopes while the remaining 5 are developing on North facing slopes. This is expected due to the north slopes being exposed to the more drying winds of the Harmattan. Values of aspect map around -1 indicate flat surfaces **Figure 52**. These flat areas are areas where floods, areas liable to flooding and where rivers are located. Slopes experience faster geomorphic evolution because of high rainfall received from Tropical Maritime Air Mass as reported in Igwe (2012). Cevik and Topal (2003) and Pulice et. al; (2009) report that the aspect of a slope can indirectly influence gully erosion processes, controlling the exposition to several climate conditions (duration of sunlight exposure, precipitation intensity and moisture retention). Although the studied gullies are located in numerous aspect locations they remain dominated by those on south facing slopes where the climatic extremes are more severe.

6.5 Gully Extent and Rates of Change Over Identified Life Spans

The studied gullies have shown increases in area with time unless intervention has taken place. As examples the Iyioku and Njaba gullies have increased their area sizes from a level in 1986 of 1316860m^2, and 38286m^2 to 2015 1701881m^2, 114387m^2 respectively (Table 91). For Ngwo2 and Urualla from 2006 sizes of 2829m^2, and 0m^2 to 2015 levels of 5600m^2 , and 43570m^2 respectively (Table

91). Anthony (2011) has reported, in work conducted on gully erosion of southeast Nigeria, that the Orlu gully increased from the year 2008 with area size of 18542m^2 to year 2009 with an area size of 21338m^2.

Cluster analysis was used to look at Gully area size and yearly gully change in metre squared per square metre for the 14 studied gullies to investigate the possibility of gullies clustering according to these characteristics. For example are yearly gully change in metre squared per square metre of gully size associated with the absolute size of the gully. For instance; Iyioku and Okigwe have similar characteristics in terms of gully area and at yearly gully change in metre squared per square metre. This can be found in 2015 gully areas and 2014/2015 yearly gully change in metre squared per square metre of 1701881m^2 and 0.05m^2yr^{-1} for each unit area and 666930m^2 and 0.04m^2yr^{-1} for each unit area respectively (**see Table 91 section 6.7.2**). In a similar fashion Urualla and Orlu gullies show similar characteristics, with (43569.9m^2, 0.07m^2yr^{-1}) and Orlu (47297m^2 - 0.05m^2yr^{-1}) respectively showing almost similar characteristics and magnitudes in area sizes and yearly gully change. The observation here tends to suggest that as gullies get old the more likely the yearly gully change in metre squared per square metre will reduce with younger gullies tending to have higher yearly gully change in metre squared per square metre as a percentage of size, but not in all gullies as can be seen in Oguta gully. The Oguta gully is younger than Iyioku but it continued to have some negative yearly gully change in metre squared per square metre. Also, Okigwe gully that is older, tends to have mostly positive yearly gully change in metre squared per square metre throughout the study period. This observation was as well recorded by Njoku, (2012) in the study of rate of gully change in Ohafia gully and Nkporo gully sites southeast Nigeria where Ohafia, which is older, had a reduced rate of change while Nkporo, which is younger, had a higher and faster rate of gully change irrespective of the gully area sizes.

Some factors can reduce or accelerate the yearly gully change irrespective of the gully age and gully size. For example Columbus (2012) observed that Ngwo people have been controlling Ngwo2 gully. This study observed that this could be responsible for a reduction in the yearly gully change with negative proportional values reported of -0.01 in 2013 and -0.02 in 2015. This intervention is likely a reason why some gullies with large area sizes will cluster or have similar characteristics in terms of proportional yearly gully change with smaller gullies. For example Orlu gully with a vastly larger area size of 47297.2m^2 in 2015 and proportional yearly gully change of 0.05 and Oguta with area size of 7228.41m^2 and yearly proportional gully change of 0.05 possess the same rate of change and development characteristics The existence of a level of gully control measures at Orlu gully, as reported by Njaba council (2009), is an example where the theory of reduced rates for large gullies falls down. This is because the intervention is likely reducing the development to a lower level shared by the smaller gully. Examples like this are useful in determining the impact of intervention but are less useful in terms of establishing the drivers behind the erosion and gully development adding an unpredictable level of variability. A full understanding of this behaviour could only be achieved by monitoring entirely naturally developing gullies but allowing those that are affected indirectly by anthropogenic activity.

6.6 The Detection and Link of Deforestation and Gully Erosion Rate with Radar Statellite Data in Southeast Nigeria

The existence of forest removal and degradation in the study area has been recognised by many studies, for example Igwe, (2005) was of the opinion that the continuous removal of forest in southeast Nigeria was the reason why gully erosion is rampant. Onyekwere (2001) maintained that Nkporo gully in southeast Nigeria developed in 2010 as a result of excessive logging and wood fetching which exposed the bare ground. In line with these studies above, this study identified large scale and continuous forest removal in the study area. **Table 11** reveals, using Synthetic Aperture Radar, the level of deforestation apparent from the three time periods analysed. By evaluating the differences between the paired years of 2008-2007, 2009-2007 and 2010-2007 the radar images reveal an increased forest removal rate of 1% with each passing year. The overlay of gully points on the extracted deforestation areas show that gullies are located where forest has been evidently disturbed. This corroborates the findings in land cover classification of the study area, which shows a more general corresponding vegetation loss from the beginning of the study period to the end. Tables **12 and 13** evidence this data which equally reveals strong correlation between gully openland and vegetation loss Table **18**. Although the work presented in this section has not directly or quantitatively linked the rate of forest deforestation and degradation with the rate of gully development in the immediate proximity of the gully, it does successfully support the trends observed in both the regional and local analysis of landcover change and gully erosion rates.

6.7 Soil and Geological Influence in Gully Development

Many researchers such as (Ofomata 1985; Onwumerobi 2002; Igwe 2005) have observed that gully areas in southeast Nigeria have been developing due to the soil type and characteristics. In southeast Nigeria, gullies occur more in areas where soils are unconsolidated, friable and with deep weathering in comparison to areas with recent alluvial and high clay content. The study region in general is dominated by unconsolidated infertile soils like ferralsols. According to Igwe (2012); Odemerho and Sada (2002); and Ofomata (2009) they all grouped soils of southeast Nigeria as the main zones where gully erosion occurs. From **Figure 11**, the studied gullies occur in areas with fluvisols, Nitosols and Ferralic-Arenosols. These soils' deposits are deeply weathered making them more vulnerable to erosion through run off (Onwumerobi, 2002). From the Cluster Analysis exercise of the years 2014/2015, 2009/2010 and 2006/2007, soil class is one of the gully variables that clustered closely with rate of gully change per sq. metre. Figures **91, 93 and 95** show these years respectively. In Principal Component Analysis, the Soil variable appeared strongly with high variance explained by PC1 in all the 3 years under review, see **Table 39**, and importantly related well to yearly gully change in metre squared per square metre which maintains the focus of the analysis. For example in 2014/2015 PC1 when incorporating all 7 key variables explained 46% of soil variability and 25% of yearly gully change in metre squared per square metre. This was closer still in 2009/2010 with 47% and 30% respectively. In each year the eigenvalue of PC1 was much more significant than the other components. Soil class has equally shown an inverse realtionship to gully area with higher soil class, indicating a strong relationship to gullies see Figures 99, 104 and 109. With the gully area expected to be significantly related to the soil type and time to be much more of a significant variable. Some other studies such as Jenny (2007) and Zoun (2007) agree with the observation of this study that gullies form on particular soil classes. Using different methodologies such as ground measurement and soil testing techniques these studies observed, geologically, that the gullies at Njaba, Urualla, and Nawfia are located on False-bedded sandstone, coastal plain sands which are under Asu River group and the Bende-Ameki sands under Eze-Aku formations Figure 14. Onwumerobi (2009) pointed out that these are all sandy formations which have more gullies than their shale formation counterparts. The importance of soil cover identified in this research, and geology in these referenced works, reinforce the requirement and importance of locational properties such as the geological foundation. Onwumerobi (2009) indicated that areas of high susceptibility to gully erosion correspond to geological regions of weak unconsolidated sandy formations like the Tertiary recent sediments and Cretaceous sediments, while least susceptible areas are within the consolidated Tertiary sediments **Figure 14.** An assertion supported by Egboka et al. (1990); Kenneth (2002); and Ofomata (1998).

In contrast to this, studies such as Nduji et al. (2008); Nwankwo (2010); Chukwu and Okeke (2012); Chigbu et al. (2011); Aigbedion, and Iyay (2007) maintained that nature, (to include geology and soil composition),was there before man came to explore and exploit it. They agree that without man’s interference, gullies in the area will not develop. It was stressed in Ofomata (1998) that the main contributing factor causing soil erosion is not society; rather, the physical factors. Soil and geology type again presenting ideal conditions for gully erosion to proliferate. Again showing the complex nature of gully erosion and the numerous independent drivers across several locations.

6.7.1 The Implication of Gully Variables in the Study Area

As earlier discussed, the study area has shown that there is a steady increase in gully/openland corresponding with vegetation loss. This finding was supported directly **Table 12** and **13** and by the significant correlations shown in **Table 18** . As vegetation of the study area continues to deplete, the gully/openland continues to grow. Although this only explicitly shows that the forest is being removed without conversion to a different land use it indirectly suggests that the removal of vegetation is encouraging gully development of the study area with new gullies forming on this disturbed land. Through more focussed anlaysis it also shows directly that the removal of vegetation regionally and within a more local perimeter is correlated with the increasing size of the studied gullies. Also linked are the increases in urban development and agriculture, all correlating with the increasing gully area of each individual gully (see Tables **20** and **21**). The correlations, although not suggesting causation, strongly support the idea that these land changes occur in conjunction with natural factors like slope, soil, geology and rainfall pattern which are considered the key natural variables. These variables are believed to combine to cause widespread gully development in the study area.

The statistical analyses have shown that from Cluster Analysis, analysing the year 2014/15 vegetation loss, soil, slope and gully stream order appear to cluster closely with yearly gully change in metre squared per square metre **Figure 91**. Also, for 2009/10 the same variables cluster closely with yearly gully change in metre squared per square metre than others **Figure 93**. Equally, in 2006/07 Vegetation loss and Elevation cluster with yearly gully change in metre squared per square metre more than others **Figure 95**. These results, as with other analyses, suggest that there is no one variable that contributes solely to influence gully development in the study area. This finding is further supported by the lack of any stand out variable in the principal component Analysis for each year studied as evidenced in **Table 39** for years 2014/15, 2009/10 and 2006/07. From observing Biplots showing the variables and the 14 gullies (**Figure 104, Figure 109 and Figure 114**), all 14 gullies appear to depend on a number of different variable combinations, although in the 2006/7 data there are larger constituent clusters of gullies being developed. The idea that multiple variables may influence gullies in different ways presents a view contrary to those supported by Posser and Slade (1994); Ahmed and Dinye (2012); Onyekwere (2011); and Ijeoma and Okey (2005) who affirm that vegetation loss is the main gully factor upon which gully development rests. Although, this study identified vegetation loss as an important variable it is in conjunction with other ideal conditions that cause the gully development in this study region and insufficient evidence is found to fully support these statements in this context.

Without the vegetation loss, the influence of unconsolidated and deeply weathered soil that make a way for gully incision and widening, and slope and gully stream order for runoff to be transported may be diminished. As previously discussed, all the 14 analysed gullies are located on slopes exceeding 5^0 incline and are found on grouped soils of southeast Nigeria, which are mainly ferralic-Arenosols, Fluvisols-Gleysols, Feralsols - Nitosols soils which are all zones where gully formation mainly occurs.

In terms of predicting rate of change and therefore yearly gully change in metre squared per square metre, using the examined variables, Multiple Linear Regression (MLR) analysis was employed to use the independent variables to predict yearly gully change in metre squared per square metre. The MLR models revealed that none of the variables were considered significant predictors of yearly gully change in metre squared per square metre in 2014/15, 2009/10 and 2006/2007 when all variables were used simultaneously within the regression. In **Table 44, 49 and 54** the significance of each independent variable is ranked for each of the three test years. It is worth keeping in mind that these are the significance of predictive power rather than the driving factors behind gully area increases or yearly gully change in metre squared per square metre specifically, and even more specifically they relate to the significance within the chosen independent variable combination. Vegetation loss in each case was ranked 4 or 5 for each year. Using the 6 dependent variables the R^2 values were reported as 0.145, 0.301, and 0.325 for 2006/07, 2009/10, and 2014/15 respectively. This was confirmed through Stepwise regression which did not as well improve th R^2. The low significance of each regression analysis is largely due to the lack of linearity observed between the yearly gully change in metre squared per square metre variable and the other independent variables, as an example see Table 105. For each regression an assessment was made as to how the regression met the four assumptions of linearity, residual bias, residual normality, and residual homoscedasticity.

In support of that discussed above, this regression study summarizes that there is no single variable identified as fundamentally controling the proportional yearly gully change, particularly from a linear perspective. The results of studying the influence of the 6 variables on gully development highlight gully erosion in southeast Nigeria being linked to topography, environmental variables, and anthropogenic activities. Again this forms a disagreement with theories and results presented by Ofomata (1998),Onyekwere (2001); and Ijeoma and Okey 2005. Their argument is largely built around the concept that gully erosion is solely influenced by either physical factors or Anthropogenic activities. Ofomata (1998) stated that the main contributing factor causing gully erosion in southeast Nigeria is not society; rather, the physical factors, Ofomata is of the strong opinion that no matter the contribution to gully erosion initiation, if the physical causes do not support its formation, gullies will not develop. Ofomata stated that gully erosion formations in south-east Nigeria result from physical causes, linked to soil type, slope and topography. Also this study questions Onyekwere (2001);and Ijeoma and Okey (2005) which emphasised society's activities in modifying the environment, in particular vegetation loss, as the main cause of gully erosion development in southeast Nigeria. But the results of this study agree with the work of Ezezika et al. (2011), Uche et al. (2006), Godsun (2007) and Chuk (2010). They all agreed that gully formation in south-east Nigeria is initiated by the poor geological and topographical nature of the area, but that the severity is complicated by societal contributions which makes the prediction of future growth using historical time series data very complex.

6.7.2 Long Term Gully Analysis, Extent and Rates of Change

Long term gullies are here defined as those gullies that have been developing prior to 1986 and have had some recognition by government, or environmental agencies in addition to some measure of study being carried out by researchers. The **Table 91** below reveals that the gullies have been in existence since before 1986 and as such the Landsat remote sensing record is unable to fully account for gully development for the full life cycles.

Table 91: Area covered in m2 by Iyioku, Okigwe, Njaba and Igboukwu Gullies from 1986-2015 (Years in red = linearly interpolated)

Years	Iyioku (m^2)	Okigwe_(m^2)	Njaba_(m^2)	Igboukwu_(m^2)
1986	1316860	157543	38286	27008
1987	1319890	166453	39635	30697
1988	1323453	189123	45289	33049
1989	1328842	209856	49279	36049
1990	1331644	234762	54279	38049
1991	1330812	260967	57582	39634
1992	1331674	280849	59990	41729
1993	1334004	297563	62406	43034
1994	1336634	301693	64160	44434
1995	1338543	303870	65413	45614
1996	1340042	337453	66875	46639
1997	1340784	358977	68562	47784
1998	1345643	369345	70179	48995
1999	1350931	389837	72586	50330
2000	1343984	409467	74679	52834
2001	1348847	413247	72934	52694
2002	1353001	425732	75649	52794
2003	1366532	454538	78679	54654
2004	1387634	478983	79883	56261
2005	1397650	499694	87025	58337
2006	1407632	498348	90424	60565
2007	1455212	506583	96375	62904
2008	1453652	524965	98866	65304
2009	1449421	534679	101426	68956

2010	1447452	551745	110196	70956
2011	1446541	572211	112200	74300
2012	1483450	599845	118134	77980
2013	1504673	608456	119924	79683
2014	1618323	639858	112056	81437
2015	1701881	666930	114387	81703

6.7.2.1 Iyioku and Okigwe Mature Gullies 1986-2015

From **Table 91** the two gully sites of Iyioku and Okigwe are shown to have developed prior to 1986 which marks the earliest extent of this study. The work of Nduji (2008) supports this. By the year 1990, some communities around and along Iyioku gully site, started independently to divert the run-off to catch-pits while giving farmers orders not to farm around the gully site. The evidence can be observed in 1991 when occupying an area of 1330812m^2, the gully receded along a negative trend of area changes of -832m^{2}yr^{-1} which presented as a temporary respite from erosion. The Iyioku gully which had an area of 1316860m^2 in 1986 exhibited aproportionately large estimated area change of 3030m^{2}yr^{-1} in 1986 – 1987 and developed to a size of 1701881m^2 by 2015. By 2015 the year on year area rate of change was a much higher than absolute area change of 83558m^{2}yr^{-1}. A proportionate change was also exhibited between 2013/2014 but from observing the long term trend of **Figure 62** the positive correlation betwen time and gully area is still evident although fluctuations in the proportionate area change continue. The containment from the communities, their positive mitigating actions, is believed to have resulted in the general fluctuations in the area rate of change which is as a result of unharmonized method of mitigation of the gully by those communities (Nduji 2008). The Iyioku gully is known to traverse 10 communities, with no harmonized agreement existing regarding the containment strategy (Nwaigwe et al. 2009). Some communities actively seek to control, while some do not. Generally the response is guided by the immediate threat to livelihoods. This is potentially why there is inconsistency in its rate of area change over the study period regardless of mitigation strategies implemented.

The Okigwe gully site **Figure 63** began to threaten infrastructure including buildings, roads, electricity poles and water pipes by 1988 (Igbokwe, 1995). At this stage the gully covered 189123m^2 The threat to public infrastructure attracted state ministry of Environment and other agencies to intervene by 2000 and 2005 with cut and fill methods incorporated during the dry season to avoid run off. In addition aggressive tree planting in and around the gully site took place during rainy season. This method was in agreement with the Food and Agricultural Organisation recommendation that gullies with very little water flow can be stabilized by filling and shaping, that is, if the surface water is diverted, and livestock and fire are kept out (FAO 2015). The year 2001 experienced a proportional area of change drop from 19630 m^{2}yr^{-1} to 3780m^{2}yr^{-1} and 2006 with area change of 20711m^{2}yr^{-1} to -1346m^{2}yr^{-1} . This gully has remained incessant in area size. The gully, which had an area of 157543m^2 in 1986 and experienced area change of 8910m^{2}yr^{-1} in 1986 – 1987, was calculated to have an area of 425732m^2 in 2002 and to have reduced to an area of change of 12485m^{2}yr^{-1} by 2002. By 2015, it had developed to an area of 666930m^2 but the area change increased to 27072m^{2}yr^{-1} between the years 2014 and 2015. The control measures could be the reason the gully started to reduce in size briefly in 2005/2006 with much less reduced area change evident more generally in 2001. What is not clear is why the area change fluctuated significantly. In 2014, an area of 639858m^2 is calculated and an area rate of change of 31402m^2 between 2013 and 2014, between 2014- 2015 the gully recorded a slowdown in absolute areal growth, seen in**Table 91**. This slowdown could be attributed to the measures which by now had started to stabilize and contain the gully development resulting in proportionate changes of <<4%. According to Okereke, (2013), the intervention of the Federal Ministry of Environment and Abia State Ministry of Environment is largely responsible for this successful control. The mitigation methods used were interventions like tree planting in and around the site, relocating people living around the gully site, and prohibiting people from cutting trees, hunting, and farming within 200 metres proximity. David, (2010) in his work “Poverty Leads to

Environmental Degradation" reported that some of the government interventions could not work properly because the communities defy government orders to farm, fetch firewood and hunt around the gully sites but the observed slowdown in erosion brings a level of validity and success to some of the mitigation strategies.

6.7.2.2 Njaba and Igboukwu Young Gullies 1986 – 2015

In contrast to the older Iyioku and Okigwe gully sites, the Njaba (**Figure 64**) and Igboukwu (**Figure 65**) gullies are younger. The area size of Njaba in 1986 at the start of the study period was 38286m^2 with an area change of 1348m^{2}yr^{-1} estimated in 1986 – 1987 representing <4% proportional change. The gully continues to grow in size today, aided in its expansion by illegal sand mining along the site as observed from eye witness evidence during field-work. Ukachi (2014), reported that illegal sand mining has been continuing since 1988 in the area and that the Njaba local government has been intervening to stop sand extraction in vulnerable areas since 2000. This study would suggest from the rapid increase in the area rate of change that this extraction activity precedes 1988. The area rate of erosion is exacerbated by sand miners defying public orders and, in some cases, security agents who have been employed to guard sites(Okorie, 2010) thus putting immediate economic gain above long term sustainability. The inconsistency in the control of the sand miners is a likely reason why by the year 2000, an area size of 74679m^2 is calculated for the Njaba gully but a area rate of change of -2226m^{2}yr-^{1} is exhibited between 2000- 2001 resulting in an area size of 72934m^2 in 2001. Evidence that mitigation strategies have been effective and that not only controls but also refilling has taken place. In 2013-2014 a further significant reduction in gully area is seen of 112056 m^2 with an area rate of change of -7868 m^{2}yr^{-1} but by 2015, the area size of 114387m^2 has reported a positive area change once again of 2331 m^{2}yr^{-1} **Table 91 and Figure 64.** As stated earlier, the negative and positive area changes of this gully reflect the inability of Njaba Local Government and the communities to consistently prevent sand mining and other interference with the gully (Ukachi 2014).

The Igboukwu gully, seen in **Table 91 and Figure 65,** is located at the northern part of the Njaba gully. In 1986 the area size was 27008m^2 with the highest area rate of change of 3689 m^{2}yr^{-1} occurring between 1986-1987 and likely continuing a rapid increase in size evident prior to this year. By 1988 the area size was calculated to have grown to 33048m^2 with a further area rate of change of 2353 m^{2}yr^{-1} between 1988 and 1989 to produce an area size of 36049m^2 and subsequent area rate of change of 3000 m^{2}yr^{-1} from 1989-1990. The area change was found to have dropped to as low as 266m^{2}yr^{-1} between 2014-2015 but with an area in 2015 calculated of 81703m^2. The reduced rate of change is a result of the implementation of runoff control in the area, constructed along the main runoff line (Patrick 2013). According to Patrick, gully bunds, catch-pits and runoff ponds were constructed along the major channels to reduce the influence of runoff to further control the expansion of the gully site. This mitigation strategy was in agreement with the recommendations of gully prevention and control laid out by Igbozurike (1989).

6.7.3 Medium Term Gully Analysis, Extent and Rates of Change

These are gullies that are younger when compared with the 4 gullies discussed above. Some of the gullies defined as medium term have formed post 1986 and could not be detected with Landsat due to its low resolution of 30m compared with Google Earth images covered in most of the study area. 2 – 3m resolution satellites are available over some selected gully sites. The inability of Landsat satellite images to detect these gullies can also be linked to ground feature cover like forest and structures (buildings).

6.7.3.1 The Newly Developed10 Gullies 2006-2015

The 10 gullies are detected by Google Earth images from the year 2006 when high resolution Google Earth images were introduced in some areas in the study area. As can be seen in the **Table 92** below, some gullies like Isinweke, Oguta and Ngwo2 could have developed earlier than 2006 but because of non-availability of high resolution Google Earth imagery, the research could not detect it from the available open source images prior to this date.

Table 92: Area covered in m2 by the 10 Gullies from 2006-2015

No of Years	Orlu_ m^2	Isinweke m^2	Amucha_ m^2	Nekede_ m^2	Ngwo2_ m^2	Oguta _m^2	Umuahia_ m^2	Urualla_ m^2	Ngwo1_ m^2	Nawfia_ m^2
2006	0	3837	0	15131	2829	2315	812	0	2112	0
2007	10945	4446	2588	22756	3209	4435	872	18170	2051	0
2008	16004	4971	3077	35876	3107	6356	1084	20532	2766.32	0
2009	20843	5190	3798	38765	3561	7823	1289	25665	3135.2	0
2010	24567	6209	4809	40765	4024	7198	1407	30235	3674.32	0
2011	30034	6843	5395	45850	4906	6121	1524	30842	4042	2334
2012	36934	7867	5980	50876	5943	6592	1860	34268	4807.34	13529
2013	40456	8210	6988	54896	5884	6209	2244	38342	6087	13812
2014	44749	9014	7866	58893	5708	6912	2503	40678	10234	14062
2015	47297	10186	8954	59652	5600	7228	2785	43570	10734	36120

Several of the featured gullies are growing with little or no mitigation/controls in place. A prime example is found in Orlu gully **section 5.4 Figure 66** showing an area size in 2006 of 0m^2. As with the majority of studied gullies, the most recent data marks the largest area size, recorded in 2015, when it recorded an area size of 47297m^2 with area rate of change of 2548m^2yr^{-1} between 2014 and 2015. The gully development has been shown to be positive and gradual in terms of absolute area increases but as a proportion the area rate of change has been gradually declining with the lowest proportional increase shown in 2014/2015. Although this gully was not being actively controlled by the community over the study period, the negative trend is likely a consequence of the natural revegetation taking place in some parts of the gully as a response to diverted runoff deposits. The sediments deposited along the gully area help control the runoff and encourage revegetation on some affected areas.

The Isinweke gully that has area size of 3837m^2 in 2006 and recorded the highest area rate of change of 1024m^{2}yr^{-1} in the year 2011/2012 is shown in **section 5.4 Figure 67**. This gully has been growing in size but with a fluctuating proportional area rate of change over the years. The lowest area rate of area change was recorded of 343m^{2}yr^{-1} in 2012/2013. The accepted reason, taken from Eke (2014), is that control measures were adopted by a family whose house was threatened by the gully. These control measures involved divertion of runoff and tree and grass planting. As of 2015 the gully has continued to develop to an area size of 1172m^2 which could be that the gully overwhelmed the control measures although the linear development in terms of size increases largely remains consistent throughout the study period.

The Amucha gully shown in **section 5.4**, **Figure 68** is only detectable post 2006. The highest area rate of change is seen between 2014/2015 at 1088m^{2}yr^{-1} but doesn’t represent the largest propotional change which is associated with 2009/10. Prior to 2015, the area change has been gradual with a generally linear relationship exhibited between time and area. At this gully site a notable event occurred with the closure of the track road in 2007 that crossed the gully to farmland used by the Amucha and Umuezike community . The road could have been an instigator of the gully erosion with the effects only visible post road closure. The increase in proportional erosion rises to a maximum of approximately 27% in 2009/10 before substantially reducing in the following years. Later, the farmers reopened the road in 2012/2013 (Njaba council, 2014)leading to a more variable area rate of change. For example, in 2010/2011 and 2011/2012 the gully was recording area changes of 586m^{2}yr^{-1} and 585m^{2}yr^{-1} respectively and rose to 1007m^{2}yr^{-1} area change by 2012/2013 marking a 17% proportional increase. In a similar way to Orlu gully the large proportional increases were seen in the early years of development before reducing to a variable but much lower area rate of change. Interestingly it is the absolute area change that remains the more consistent over the study period.

Nekede gully **section 5.4 Figure 69** follows almost the same trend as the Amucha gully. Okoro et al. (2011) report that the MCC sand Mine Company is largely responsible for the gully development and contribute to the gully increase in size, from the year 2008 with area size of 35876m^2 and area change between 2008/2009 of 2889m^{2}yr^{-1} . The gully has increased in area size consistently over the study period even following intervention from Imo state government to stop the illegal sand mine in 2008. This measure did not cause drastic reduction as the gully continued to grow in area that by 2013/2014 it had increased to area change of 3997^{2}yr^{-1}, adding toan area of 58893m^2 in 2014, but shows a slow growth in 2015 with area size of 59652m^2, with area rate of change for 2014/15 of 759m^{2}yr^{-1} less than what is obtained through out the study period.

The Ngwo1 **section 5.4 Figure 70** was estimated to have an area size of 2112m^2 and area change of -61m^{2}yr^{-1} by 2006/2007 but the gully continued to grow in area size. The highest area change was reported in 2012/2013 of 1280m^{2}y^{r-1} with area size of 6087m^2 but in between 2007 and 2015 the gully has continued to increase in size with the similar trend in high proportional area rate of change at the early stage of development and generally linear increase in absolute size with time. There is no reported intervention at this site within the timeframe of the study.

Urualla gully **section 5.4 Figure 71** again exhibits similar trends. The highest area change of 5133m^{2}yr^{-1} is recorded in 2008/2009. According to Levi et al. (2013) the communities had been trying to contain the gully since 2011, but to no avail. The main runoff was later diverted to a more stable area through a channel in 2013 although, a neighboring community then channeled runoff to the area once again in the same year 2013. The gully, in a similar way to the majority of other gullies has experience a linear increase in size while exhibiting the variable proportional increases between 2006 to 2015 with the peak proportional change exhibited in 2013.

The Ngwo2 **section 5.4 Figure 73**, and Oguta **section 5.4 Figure 74** have a different trend to the majority of other gullies studied. As well as these the Nawfia gully is characterized by different behaviour in regards to area rate of change and size. The Nawfia gully **section 5.4 Figure 72** did not develop until 2011, the community reported that its development followed a road construction in 2010 close to the gully site (Okonkwo 2014). From 2011 to 2012 it exhibited an area rate of change of 11195m^{2}yr^{-1} to an area size of 13529m^2 in 2012. Active efforts were made by the community to contain its development but all to no avail (Okonkwo 2014). Following these mitigation events an increase in size was still recorded in 2015 due to the Nawfia road reconstruction in 2014, which required a rerooting of runoff back to the original site.

The Ngwo2 gully according to Ngwo people developed prior to 2006. The Ngwo community and the other adjourning communities close to the gully have been containing it through cut and fill of some arears close to roads and houses (Columbus, 2012). This agrees with the Food and Agricultural Organisation's recommendation to handle gullies as also adopted at the Okigwe gully site. That was the reason why the gully has been reporting slow and negative area change since 2012. Between2006 and 2007 the gully area size was 2829m^2 rising to 3209m^2 due to an area change of 380m^{2}yr^{-1}. The gully reduced in area between 2007 and 2008 with -103m^{2}yr^{-1}.The largest area change of 1037m^{2}yr^{-1} was exhibited between 2011 and 2012 with the gully measuring 5943m^2. The mitigation methods were employed from 2012. At which point proportional changes were vastly reduced with sub 1% increases and even decreases in size were recorded. The relationship between the area and time deviates from the more consistent linear trend seen at other sites.

Oguta gully, according to Oguta Local Council (Eke 2014) developed when oil companies were moving their machines for crude oil exploration and exploitation. Before 2006 the gully was being contained by the community, local council and individuals. In 2006-2007, the area size was 2315m^2 and 4435m^2 and the gully has an area change of 2120m^{2}yr^{-1}. The gully increased in size until 2009 from which point changes were negligible or negative, with the 2009 gully size not being exceeded for the remainder of the study period**.** The mitigation strategies used here were cut and fill with grass planting which was employed in 2009 with immediate benefit (Eke 2014). The strategy truly contained the gully from this point on with the 2009 levels not exceeded for the remainder of the study period except 2014 and 2015 where there is marginal increase in area change..

The Umuahia gully returns to the more typical trend of the linear increase in gully size with respect to the year. With a strong correlation shown between these variables. In 2006 and 2007 the gully has an area of 812m^2 and 872m^2 respectively with an area change of a minimal 60m^{2}yr^{-1}.Typical to the development of the younger gullies in this study, the early development is characterized by large per centage changes peaking at approximately 24% for this particular gully. Although the gully is growing proportionally very quickly the gully has been adequately contained by the road contractors working at Enugu – Port Harcourt road who have prevented the gully from rapidly developing from a small to large scale feature. The contractors used soil to fill some parts of the gully to aid their working conditions and has encouraged vegetation to grow in those areas not experiencing high runoff (Okeke et al 2012). The containment was not deliberate and the benefits are not easily visible as a constant increase in gully size is still visible in **Figure 75**, although the proportional increase in gully rate of change has fluctuated with the main reductions in rate visible between 2008 and 2011..

6.8 Morphological Differences of Gully Cross Profiles

The cross profiles of the gullies were included to show the current gully morphology. From the analysis of the cross profiles **Figures 40 – 46 section 4.7.2** of the 14 focussed upon gullies, morphological differences are evident. The gullies like Nawfia, Urualla, Orlu, Nekede, Amucha and Umuahia have likely reached a more consolidated part of the rock as revealed in **Figures 42 (a), 42 (b), 43 (b), 44 (b), 46 (a) and 46 (b)** where the gully beds are seen to have flat or crescent shape. As a result of this, they are restricted in the way they incise more into the rock but concurrently they use the sediments from the up-slope to deposit down-slope, helping to create the flat bottom. Gullies like Iyioku, Okigwe, Igboukwu, Njaba, Isinweke, Oguta, Ngwo1 and Ngwo2 **Figures 40 (a), 40 (b), 41 (b), 41 (a), 43 (a), 44 (a), 46 (a) and 46 (b)** have a valley-bottom shape. This suggests that even though some of the gullies mentioned are old, they remain active in some areas and located on higher slopes. The structure of the gully also shows that the soil is unconsolidated. Again gullies like Iyioku, Okigwe, Njaba, Umuahia, Isinweke, Orlu, Oguta, Nekede, Ngwo1, and Ngwo2 all have hanging-gullies. This reveals that the run-off is meeting consolidated and unconsolidated rocks on their path. The cross profile of the gullies has revealed the diversity and different shapes of the gullies which shows that the gullies have different time of formation and exacerbates their differing natures.

6.8.1 Rainfall Data and its Relationship with Gullies

According to Igboka (2011) and Mbella (2011), the run-off of the study area depends on rainfall pattern, slope and surface cover. The results of this study have shown that there must be gully erosion factors as without rainfall run-off, gullies will not develop in the study area. This is supported by the rainfall pattern and gully area % change of the gullies. The percent change seems to be high when there are high rainfall patterns in the annual record. For example, in the year 2012 the mean annual rainfall was 3794mm. Gullies like Iyioku, Okigwe, Njaba and Igboukwu experienced a positive % area change of 2.5%, 1%, 5% and 5% respectively in this time period.

The gully area proportional change and the rainfall data graph **Figures 76 – 89 section 5.4.1** show that years where the rainfall pattern are high were years some gullies recorded postive level of area percent change. The Iyioku gully area change and rainfall pattern **Figures 75, section 5.4.1** reveals that the years 1988, 1992, 2005, 2012, 2013, 2014 and 2015 consistently show high rate of percent change which corresponds to high annual rainfall (runoff) for these years which are 2008mm, 2500mm, 2807mm, 3794mm, 2871mm, 2857mm and 3604mm respectively. In some of the gullies that did not follow this pattern such as Oguta and Ngwo2, communities, government and agencies have typically intervened to offset the expected meteorologically influenced percent change. Examples of the mitigation effects which have offset the meteorological effects can be found in the reduction of percent area change recorded in high rainfall years of Igboukwu, Nekede, and Ngwo2 all in 2015 and Nawfia in 2014. Rainfall is required for gullies to develop in the study area, with the expectation that the problem lies on the intensity, duration and amount. As more fine resolution rainfall data could not be sourced this study was unable to explore this theory further. Looking at the mean annual rainfall data of the study area, they appear to be greater than 1000mm which is enough to initialise gully development (Igboka 2011). According to Igbozurike (1989), southeast Nigeria is a rain forest zone with over 1000mm mean annual rainfall data reported every year. Igbozurike is of the opinion that since the area has high rainfall data, which is natural and almost the same every year, emphasis should be more on other gully factors which encourage runoff to devastate the area with the rainfall driver assumed a relative constant in the region. Equally, Igbozurike pointed out that the runoff is almost the same every year in southeast Nigeria and that the yearly gully change is not necessarily from the runoff but other gully factors on ground such as slope, forest removal, and soil. From this study, even though some of the area change is adduced to some control measures, it tries to support Igbozurike's assertion, examples can be found in gullies like Njaba and Igboukwu which showed reductions in gully area change despite high rainfall pattern in 2013 and 2014. Conversely, some of the results obtained in this study did not support Igbozurike's assertion. Gullies like Iyioku, Urualla, Ngwo1, Amucha and Nawfia recorded high levels of area percent change when highest rainfall data was recorded in 2012 showing that there remains some influence in the rainfall variation.

6.8.2 Implications Vegetation Loss in Gully Development

One of the key headline findings in this work is that in the study region vegetation removal has a strong influence on gully development. This is primarily shown from remote sensing approaches and land cover classification. The overlay analysis of gully points on the forest degradation and deforestation maps reveal that they commonly develop on areas where vegetation is removed. The clear suggestion is that it could be acting as a driver as observed by Igwe (2005); Onyekwere (2001); Ijeoma and Okey (2005) which contribute to the formation and development of gullies in the study area but with further influence exacted by studied physical and environmental variables. .

6.8.3 Comparing the Performance of Classification Methods

The two classification methods (Pixel and OBIA), used for land-cover analyses in this study, were incorporated to provide a comparison of methods and to provide additional confidence in findings. According to Gao and Mas (2006) pixel based image analysis largely neglects the spatial photo-interpretive elements such as texture, context, and shape while in OBIA there are shape and texture features of the objects available which can be used to differentiate land cover classes with similar spectral information. Furthermore, OBIA works on (homogeneous) objects produced through image segmentation allowing more elements to be used in the classification. As an object is a group of pixels, object characteristics such as mean value, standard deviation, ratio, and other descriptive statistics can be calculated, and used to differentiate land cover classes with similar spectral information. This extra information gives OBIA the potential to produce land cover thematic maps with higher accuracies than those produced using traditional pixel-based method (Gao and Mas 2006). This is reflected when comparing the accuracies of the two approaches in section 4.3.1 for the year 2013. These accuracies are 90% and 92% for pixel and OBIA respectively. The percentages of landcover classification are well represented in **Tables 12 and 13 section 5.3.** The performance of OBIA classification is deemed better than the pixel approach by examining 100 points at random to validate the landuse/landcover classifications assigned. Due to this higher accuracy it is suggested that the OBIA approach is more suited to the classification of the Landsat imagery for the purpose of this study but this may be a site specific result and therefore caution should be taken when choosing the appropriate methodology.

6.8.4 Open Source as an Alternative and Comparison to Licensed Software Approaches.

Having carried out the analysis in both Arc and Open Source software, the values obtained from both show a high positive correlation in performance. Most importantly,the outcomes from using the proprietary, and industry standard,Arc software suite and the Open Source alternatives are highly similar.

The comparative analysis has shown that the low cost approach is workable and that it allows poor GDP countries like Nigeria to access the necessary tools. It is the lower GDP countries that are most limited by such barriers posed by licence fees and also typically the locations that would benefit the most from such capacity building. A simple study in 2003 (Ghosh, 2003) showed that in Nigeria the cost of purchasing such licensed software as Windows XP would cost 21 times the GDP per capita in comparison to UK equivalent of 0.28, and as a result software piracy is vastly above the global norm, 71% compared to a UK level of 25% (Ghosh, 2003). The message that software companies provide is one that places an overwhelming need to purchase high profile, branded products. Obtaining such software is then often illegal while the opportunity to use open source alternatives is largely overlooked and not effectively promoted. In Nigeria, powerful GIS Desktop software, like those used in the core of this study, such as ArcGIS, Erdas Imagine, eCognition and ENVI are not readily available due to the expense. In some organisations, institutions, and agencies where licenses of some of these GIS software have been obtained, it is either they are partially acquired, not fully licensed or only valid when used for specific assignments. Specifically in Nigeria, some of the organisations that are engaging with licensed GIS and remote sensing software include; Abuja Geographic Information System (AGIS), Lagos Geographic Information Science, (LGIS), National Centre for Remote Sensing (NCRS) Jos, University of Benin and University of Ilorin. It is observed that since the evolution of open source software, a lot of Remote Sensing and GIS work conducted in Nigeria at the higher academic and governmental level is moving to open source platforms and this study confirms the suitability of this transition for the monitoring of gullies. Some examples of the

Open Source software include System for Automated Geoscientific Analyses (SAGA GIS), Geographic Resources Analysis Support System (GRASS), Integrated Land and Water Information System (ILWIS), and Quantum GIS (QGIS). Some of the studies conducted with open source software in Nigeria include Ezeomedo et al. (2013) in Mapping and Analysis of Land Use and Land Cover for a Sustainable Development, Okereke et al. (2012) in Mapping Gully Erosion Using Remote Sensing Technique: A Case Study of Okigwe Area, Southeastern Nigeria and Igbokwe et al. (2008) in Mapping and Monitoring of the Impact of Gully Erosion in Southeastern Nigeria with Satellite Remote Sensing and Geographic Information System among others.

In the reduction of disaster risks in developing countries, emphasis and capacity are needed in the area of free open source GIS and Remote sensing (Teeuw 2012). This is to allow the high cost of desktop GIS and Remote Sensing software to be surmountable in providing solutions to their environmental problems. It is with the ideal of presenting an informative comparison within a specific case study that the use of open source approaches are examined as part of this study.

All the processes undertaken in this study are repeatable using solely open source GIS and remote sensing software as investigated in **Section 5.8**. The main differences determined between open source and licensed GIS observed in this study were that the open source GIS software required much more time to process large datasets (observed by the author). Licensed GIS software like ArcGIS, ENVI, Erdas Imagine processed the same image over much smaller time periods. These shorter processing periods were also accompanied by much more simple work flows, with the open source GIS software requiring many manipulations, plugins and buttons to process.

Having observed the advantages of open source GIS software in this study, there are several generic advantages that can be listed here- It is (a) easily accessible to beginners and start up companies alike. If you're starting a small project, a private venture, or even a project within a large company or working within academia, there is the opportunity to freely experiment with technology. (b) There are active communities which offer support- The software environment is adaptable with user modifications encouraged to suit individual needs. If there is a need to convert a software component to a different infrastructure, technology or environment, a free sandbox is available for development purposes. This allows priceless experience with cutting-edge technologies without the financial risks involved with trying new pricy products. The open source environment allows extensive configurability, which means that one can fine-tune the product to exact required needs. For niche demands, hiring a software developer to change the product will be considerably cheaper than paying a software company for changing the product. (c) In general open source platforms offer a plethora of web-oriented tools: mapping, tiles, databases, webservers, web framework and web authoring tools. Potentially allowing users to construct individual and bespoke GIS environments.

The more general disadvantages of the open source approach relate to the number of options available and the difficulties in determining the validity or suitability of different projects. This can also present additional time cost due to that required to ascertain validity. In a very general sense the user interfaces are considered less “user friendly”. The inferiority in GUI design is often the result of developers being more proficient with command line structures and delivering the essential functionality rather than devoting developing time to the aesthetics. The problem then is that counterintuitive interfaces could be used which are less accessible to the user. Open source software options may also present less of a complete package with users required to examine and experiment with several different products to achieve their goals. A small classification project such as conducted in this study could require the use of 2 or 3 different software approaches. The proprietary alternatives offer several advantages which arrive with the fee. The interactive support offered can be hugely advantageous to keep projects on track and to schedule, and the industry standard marques which some software have acquired mean that partners commercially and academically will require data accessible using these means and in compatible formats.

The above advantages of the two approaches to GIS and remote sensing data handling have been presented in a very general way but the real discussion must centre around the application of open source products to the efficient and effective mapping, monitoring, and analysis of natural hazards, particularly focussed on gullies. The comparison conducted in this thesis is centred around the replication of results obtained using the proprietary software and through a classification validation using 100 land use/cover points.

To authenticate and and provide open source software match to licenced GIS/Remote sensing software, all the work carried out in this study with licenced GIS/Remote Sensing software and open source software provided a very strong correlation. For example the correlation between vegetation area in both Arc and open source software produced a very strong correlation in both pixel and OBIA classification of 0.75 and 0.98 respectively. The openland class of Arc and Open software produced a very strong correlation of 0.96 and 0.9 for pixel and OBIA classification respectively. Again, these very high positive correlation were replicated in all the gully values done with Arc and open software. Most importantly, the statistical analysis from Cluster and PCA of the Arc and Open source methods produced almost identical result. For example in Arc dendrogram for 2014/15, 2009/10 and 2006/07 **Figures 134, 136 and 138,** have similarity in all the years with Open source. The same similar results were produced for example in 2014/15, 2009/10 and 2009/2010 Total Variance Explained from PCA**.** The work done in open source software has helped to authenticate and give more credence to the Arc software work used in this study.

6.8.5 The Fulfilment of this Research Study

This study has used Landsat, SAR, DEM, Google Earth images, Rainfall data, soil and geology maps to monitor and quantify gully erosion and development over time, thereby identifying the impact and incorporating analysis of environmental factors and land use change, fulfilling the aim in **section 1.3**. The fulfilment of the aim has answered the objectives of this study which are; 1) To use remote sensing data (Landsat and ALOS PALSAR) to determine change in land-cover through Pixel based and Object Based Image Analysis (OBIA) classification over a maximum 30-year period (1986 – 2015) in SE Nigeria. The classification methods for this purpose will be compared and contrasted; 2) To vectorise and quantify gully extent and rates of change of gully sites over identified life spans. Gullies chosen using remote sensing data according to associated severity and level of management; 3) To generate Digital Elevation Models (DEM) to detect changes and calculate gully dimensions of focused gully sites (to observe how slope, nature of slope, aspect and gully stream order influence gully development); 4) To map dynamics of deforestation and forest degradation in southeast forests using radar satellite data and identify, if any, links between gully erosion rate and vegetation removal; 5) To employing the use of soil and geology maps of the study area to determine the prevalent types of soil and sediment, and identify relationships with those sites yielding more rapid gully erosion and associated meteorological data; 6) To identify the feasibility of establishing an open source methodology, comparing with commercial one to incorporate those living in low GDP countries like Nigeria.

7 Summary, Conclusion and Recommendations

7.1 Conclusion

Determining Causes of Gully Erosion and Associated Rates of Change in South-East Nigeria, using a Remote Sensing and GIS Methodology, was conceived out of the numerous gully developments, inaccessibility to some and the helplessness of the communities in finding solutions to the rampant problem in southeast Nigeria. The field work was carried out in southeast Nigeria and the rest of the developmental research was carried out at the University of Brighton. The research work analysed the topography, the land-cover satellite images for a period of 30 years as well as detailed interpretation of 14 gully sites from the study area. This long period of data collection and analysis provided enough information on what has been happening in the past and the anthropogenic activities that are responsible for gully development. The 14 gullies studied in detail, were traced and tracked from 1986 – 2015 for the older gullies and for 2006 – 2015 for the younger (30Yrs and 10Yrs period respectively). This was primarily to observe their relationship with landcover and topography of the study area.

It was observed from the analysis that as the vegetation of the study area continues to reduce, open lands and gullies continue to develop while new gullies are expected to form. The open land development that was tied to vegetation loss could be responsible for the gully development as can be found from the location of gully points overlaid on classified satellite images. In general, the tracking and tracing of the 14 gully sites showed that their occurrence and development positively correlated with vegetation removal for the 30 years' period. Exceptions were found in some year(s) when gullies were being tackled by communities, ministries and agencies to reduce or stop development. The topographical analysis of the study revealed that gullies develop mainly on slope with angle of 5^0 and above, continuous removal of vegetation, soil (deeply weathered, unconsolidated sandy sediments and friable soils) and on high stream order of 1

– 4 stream order. Even though the topography of the area is a moderate one, it acts to help the gullies to develop in unconsolidated friable soils which are deeply weathered. The unconsolidated and deeply weathered soil enables gully incision and widening.

Three types of multivariate statistical analysis were utilised to assess and explore the gully factors extracted from the landcover and topographical analysis of the study area with limited success at determining generic driving factors to explain gully behaviour in the region. Cluster analysis, PCA and Multiple Regression were used both on data derived from proprietary and open source software with very similar results. These tests were applied to the data as a means to predict the gully factors similarity, characteristics and relationship to incipient gully generation, development and yearly proportional area gully change. . The novel application of this methodology to this setting allows a low cost GIS and Remote Sensing methodology that can be used for monitoring and quantifying gully erosion and development over time. The geospatial location of the study is appropriate as a low cost methodology is required to help such areas. The research has determined the change in land-cover classification over a maximum 30-year period and quantification of gully extent, rates of change and rate of yearly gully change in metre squared per square metre of gully sites over identified life spans in a very successful manner which will allow site specific rather than generic trends to be identified. This study has detected changes in gully dimensions in association with Digital Elevation Models (DEM) and Mapped dynamics of deforestation and forest degradation in southeast Nigeria forests using radar satellite data and has successfully identified links between gully erosion rate and vegetation removal on the local and regional scale. This work has been conducted with the aims and the objectives earlier stated clear in mind with a key outcome being the success of the open source approach producing similar results to the more illustrious and proprietary counterparts. The significance of this being that this work can be replicated in low GDP countries with similar environmental problems.

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It can be concluded that there is no single variable responsible across the region for gully formation and generation in the study area. All the identified gully variables combine to cause gully development and consistent with the literature they are shown to be driven by different variables in different locations. What is not disputed in this study is the importance of each of the variables examined on gully formation and subsequent growth with each tested variable identified from robust literature analysis and shown statistically to contribute to gully formation with the exception of elevation. By examining and establishing a list of driver variables required for gully formation, this thesis can be used to alert those concerned with gully erosion of the risk factors and drivers of this destructive phenomenon. Most importantly it has provided an accessible route to achieve this. Following the identified causes of gullies in the study area which has shown the ability of using remote sensing and GIS to monitor gully development, mitigation measures can now be put in place to prevent further gully development and be able to control already developed ones on a local and regional level and through civilian or governmental pathways.

7.2 Recommendations

When it comes to the development of the gullies there is an overwhelming sense that the relationship is a strong linear interaction between time and areal size but the proportional change, the rate of change, is less easy to predict and less easy to model. This is largely due to the changing environments and drivers associated with each individual gully that can’t be suitably generalised across the region. Since this study has identified that gully development is due to a combination of physical and anthropogenic causes, as shown through the recommendations of Cluster Analysis, PCA and MLRA, it disagrees with the arguments made by many in the literature who have looked at individual, isolated cases and have tried to generalise. For exampleOfomata (1998) and Onyekwere (2001); Ijeoma and Okey (2005) that the causes of gully erosion in southeast Nigeria is predominantly one or the other. The work produced here then supports Ezezika et al. (2011), Uche et al. (2006), Godsun (2007) and Chuk (2010) that support the more mixed influences.

As a result of the findings of this study, 3 key recommendations are offered to help in future to mitigate gully formation, generation and development in southeast Nigeria and potentially in any region having similar environmental problems.

1. Retention and infiltration of surface water should be provided in areas where runoff is high to avoid high runoff which erodes the soil from upland. Therefore, since slope, gradient and elevation is natural and cannot be changed, the retention and infiltration of runoff will be very important.

2. Proper land-management practices must be employed to prevent forest fires and illegal wood logging, and to avoid openlands development which can evidently lead to gully development. If the vegetal covers are allowed, it may lead to soil stabilisation, rainfall runoff retention and also control the already developed gullies but may not curb their progress entirely.

3. Control of urbanlands (road construction, building structures and mining) which can reduce the effect on soil and vegetation removal to avoid gully development. Since urban development is tied on the use and removal of physical environment and mining which helps to create openlands, it can be reduced and controlled, which will reduce the level of gully formation and development.

7.2.1 Limitations and Future Work

7.2.2 Limitations

In the course of this research work, the study encountered a lot of limitations; amongst them are a lack of high resolution and freely available satellite images that cover the study period of the study area to aid observation of small and hidden gullies and equally make more precise land-cover classifications. Again, there is high dense forest covering several gullies, which were observed during field work but cannot be seen in the satellite images. Free open source Geographic Information System and Remote Sensing software take longer period of time to process large areas like the study area of this research work. Although not statistically verified in this work it reports the experiences of the author. Very importantly, studied gullies are large and deep that ground tape measurements were impossible because of incessant gully wall cave-in and some communities living around some of the gully sites do not allow people to have unrestricted walk/work around the gullies. More precise ground validation would have enhanced this work if safely possible. Manual tracing of gully edges with GIS software is very cumbersome, rigorous and takes time. In carring out the digitization process, there are some errors associated in manual tracing of gully edges, which comes from either tracing part of areas not included in the gully or missing some parts of the gully. Future research into machine learning approaches to detect and outline these features in the data would be a very useful development to improve this monitoring approach but would require knowledge and training beyond the capability of the average community and therefore moves away from the aims of this thesis. Some errors also can be found in landcover classification as can be observed in Vegetation and Agriculture classes. Most of the Agricultural class have the same spectral value with vegetation, example is rubber or palm plantations and is a consequence of limitations in the classification algorithms and training data. High resolution satellite images are very costly, especially for a very large area like the study area of this research. Even if one acquires some high resolution images, it is not possible to acquire any of those high resolution images ranging from the period of this study 1986 -2015 (30 years' period).

7.2.3 Future Work

1. Future work could find out if there is an optimum slope for gully erosion to take place.

2. Produce risk maps using the prominence of the studied variables to predict where gullies may possibly form in the future with the use of remote sensing and

GIS techniques and statistical approaches such as logistic regression to offer probabilities. Linear approaches are not sufficient.

3. Governments and Agencies should sponsor additional and ongoing work in this area and to aid research into the potential of high resolution satellite image constellation that if possible covers the same study period of the study area but over daily time periods.

4. An in-depth study of the various anthropogenic contributions to gully development, for example to find out if the building structures are constructed along or across the contour lines of the study area to know why the runoff has been devastating as to cause these open gorges (gullies).

6. A societal investigation at the community level to ascertain more robustly the impacts on the social and economic climate of the study areas.

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Appendix 1 – Landsat and its Description

The MSS and TM bands were selected by Landsat to maximise capabilities for detecting and monitoring different types of Earth resources. For example, MSS band 1 (equivalent to TM band 2) can detect the visible green reflectance of vegetation, and band 2 of MSS (equivalent to TM band 3) is designed for detecting chlorophyll absorption in vegetation. MSS bands 3 and 4 (equivalent to TM band 4) are ideal for near-IR (NIR) reflectance peaks in healthy green vegetation and for detecting water-land boundaries (Hung and Wu 2005). TM band 1 can penetrate water for bathymetric mapping along coastal areas and is useful for soil-vegetation differentiation and for distinguishing forest types (Ji et al. 2009). The two mid-infrared red bands on the TM (bands 5 and 7) are useful for vegetation and soil moisture studies, and discriminating between rock and mineral types. The thermal-infrared band on the TM (band 6) is designed to assist in thermal mapping and for soil moisture and vegetation studies as can be seen in **Table 3** (Short 2011). Landsat 8 data has more bands than Landsat 7, to create the Red Green Blue (RGB) composites, the combination differs from Landsat 7; for example, bands 4, 3, 2 are used to create a colour infrared image with Landsat 7. However, to create Colour Infrared Image (CIR) with Landsat 8 data, bands 5, 4, 3 are used. Table 3 and 4 help to guide where the bands fall in other to create Landsat 7 and 8 composite and other data combinations.

Table 93: Landsat 4-5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) (United State Geological Survey 2015)

Band	Wavelength	Useful for mapping
Band 1 - blue	0.45 - 0.52	Bathymetric mapping, distinguishing soil from vegetation and deciduous from coniferous vegetation
Band 2 - green	0.52 - 0.60	Emphasizes peak vegetation, which is useful for assessing plant vigour
Band 3 - red	0.63 - 0.69	Discriminates vegetation slopes
Band 4 - Near Infrared	0.77 - 0.90	Emphasizes biomass content and shorelines
Band 5 - Short-wave Infrared	1.55 - 1.75	Discriminates moisture content of soil and vegetation; penetrates thin clouds
Band 6 - Thermal Infrared	10.40 - 12.50	Thermal mapping and estimated soil moisture
Band 7 - Short-wave Infrared	2.09 - 2.35	Hydrothermally altered rocks associated with mineral deposits
Band 8 - Panchromatic (Landsat 7 only)	0.52 - 0.90	15-meter resolution, sharper image definition

Table 94: Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) (United State Geological Survey 2015)

Band	Wavelength	Useful for mapping
Band 1 – coastal aerosol	0.43 - 0.45	coastal and aerosol studies
Band 2 – blue	0.45 - 0.51	Bathymetric mapping, distinguishing soil from vegetation and deciduous from coniferous vegetation
Band 3 - green	0.53 - 0.59	Emphasizes peak vegetation, which is useful for assessing plant vigour
Band 4 - red	0.64 - 0.67	Discriminates vegetation slopes
Band 5 - Near Infrared (NIR)	0.85-0.88	Emphasizes biomass content and shorelines
Band 6 - Short-wave Infrared (SWIR) 1	1.57 - 1.65	Discriminates moisture content of soil and vegetation; penetrates thin clouds
Band 7 - Short-wave Infrared (SWIR) 2	2.11 - 2.29	Improved moisture content of soil and vegetation and thin cloud penetration
Band 8 - Panchromatic	0.50 - 0.68	15-meter resolution, sharper image definition
Band 9 – Cirrus	1.36 - 1.38	Improved detection of cirrus cloud contamination
Band 10 – TIRS 1	10.60 – 11.19	100-meter resolution, thermal mapping and estimated soil moisture
Band 11 – TIRS 2	11.5 - 12.51	100-meter resolution, Improved thermal mapping and estimated soil moisture

Appendix II –Other Displayed Vectorised Gullies on the Contour (contour interval in metres)

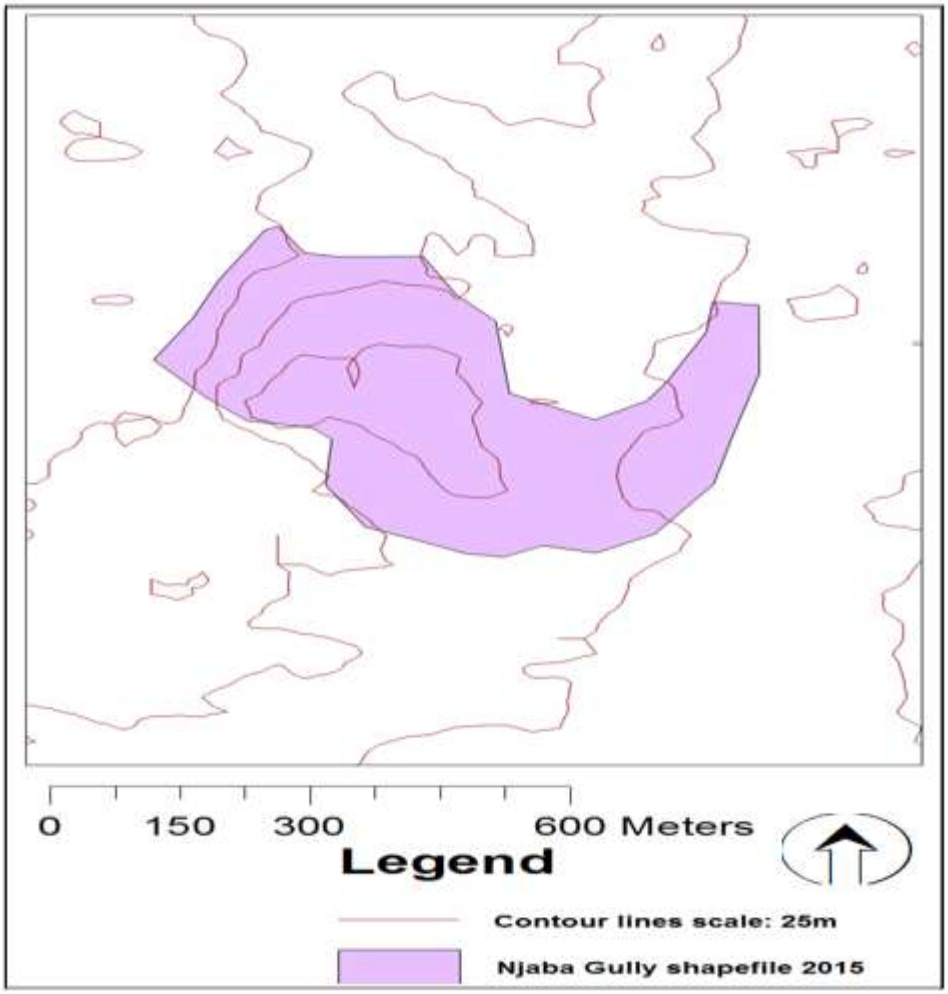

Figure 149: Displayed Njaba vectorised gully of year 2015 on the contour map of the study area with contour interval of 25m

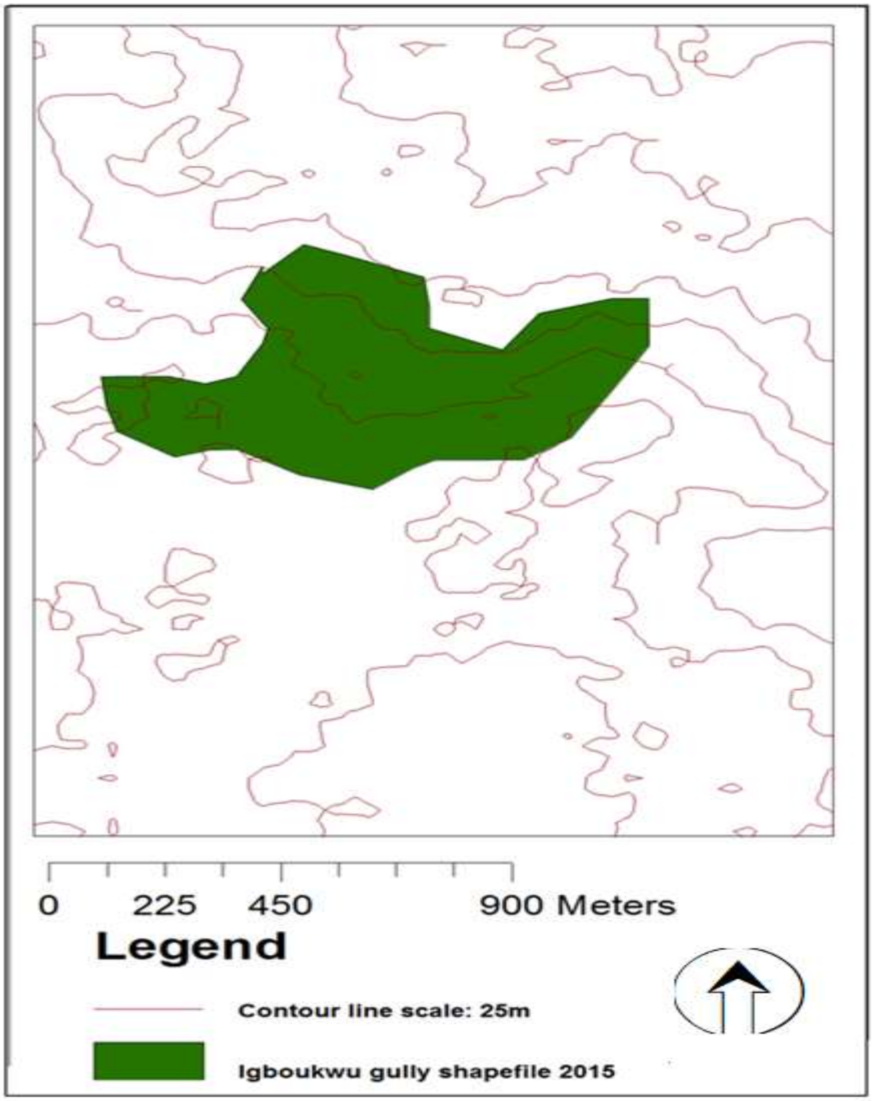

Figure 150: Displayed Igboukwu vectorised gully of year 2015 on the contour map of the study area with contour interval of 25m

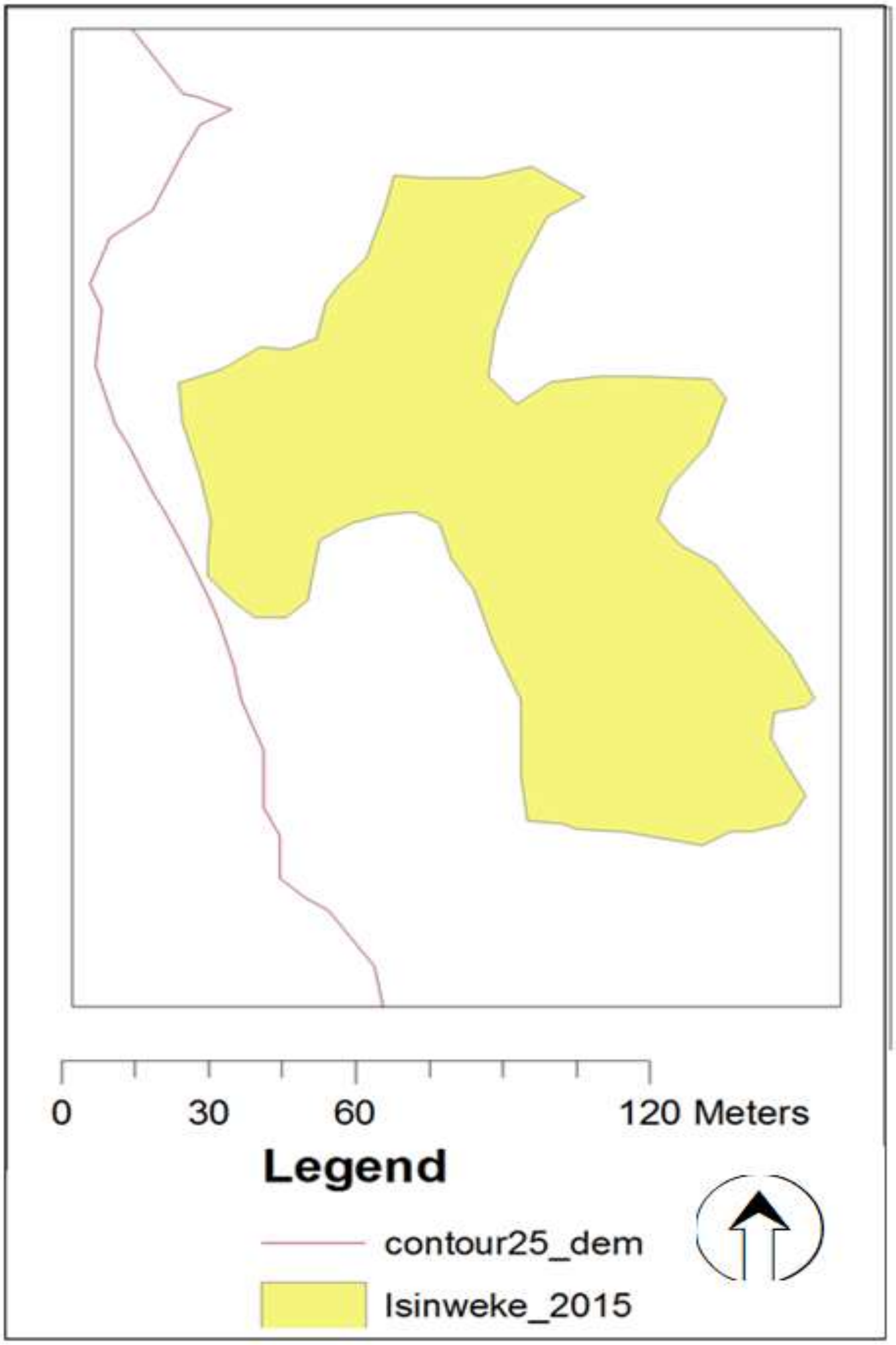

Figure 151: Displayed Isinweke vectorised gully of year 2015 on the contour map of the study area with contour interval of 25m

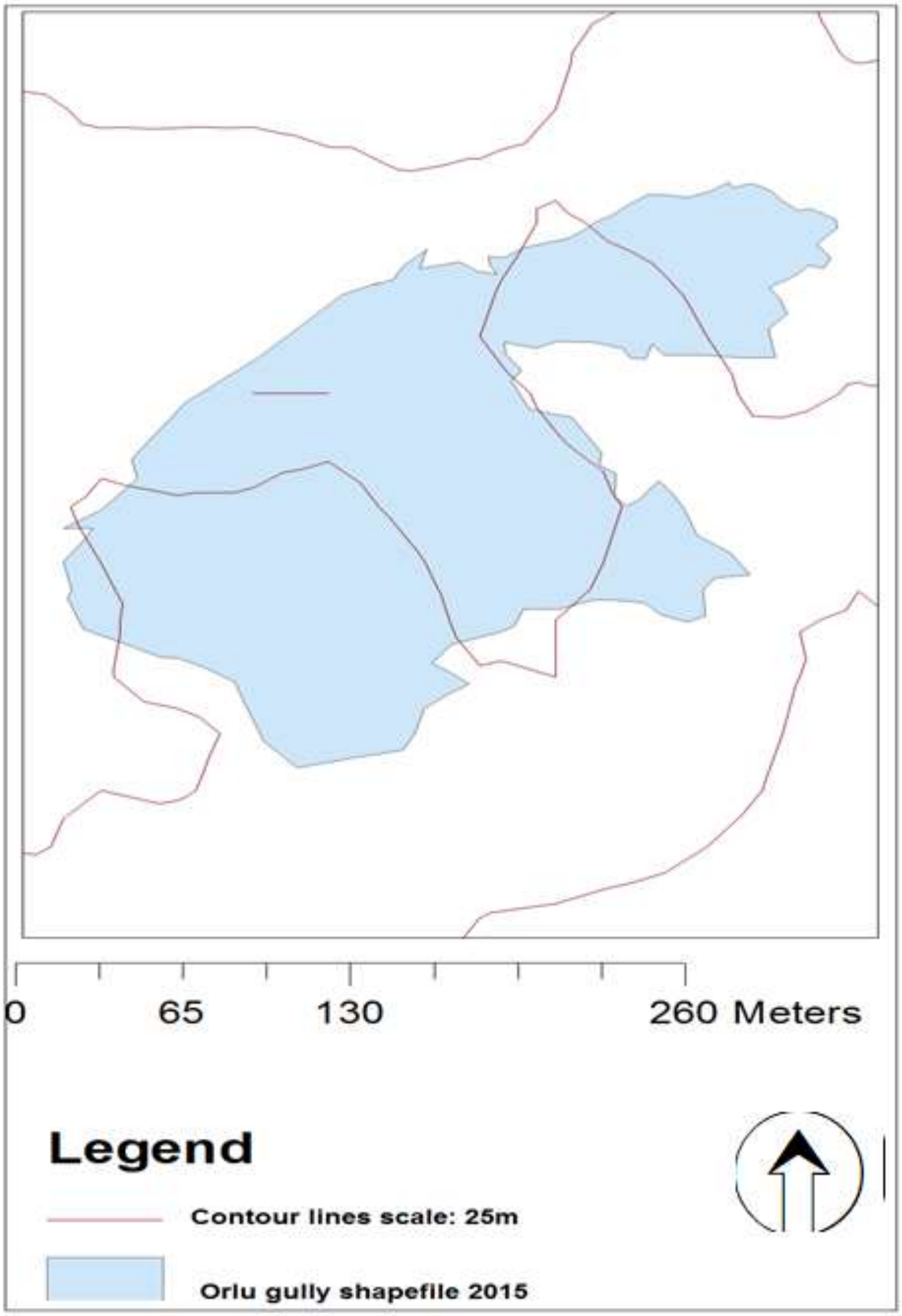

Figure 152: Displayed Orlu vectorised gully of year 2015 on the contour map of the study area with contour interval of 25m

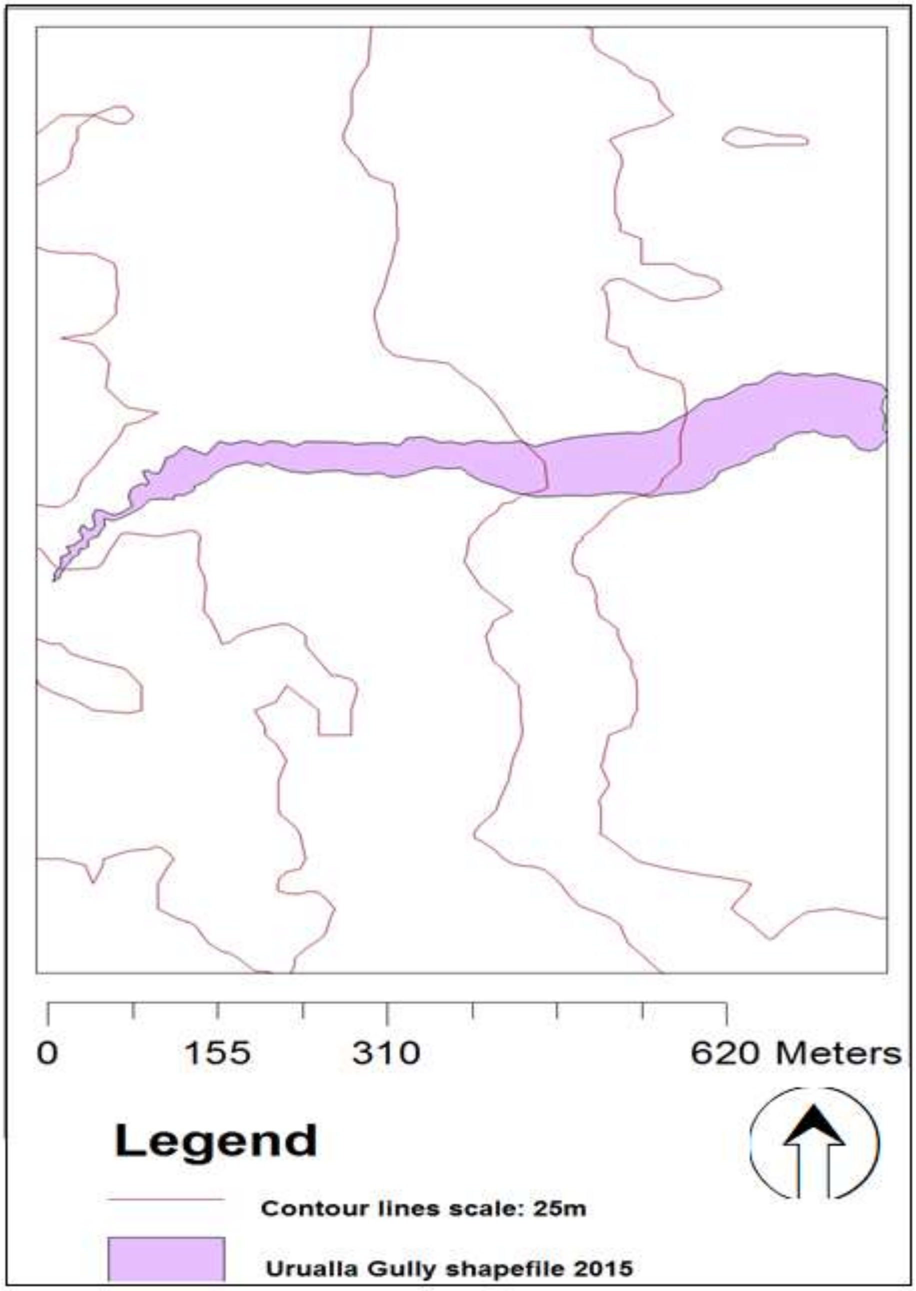

Figure 153: : Displayed Urualla vectorised gully of year 2015 on the contour map of the study area with contour interval of 25m

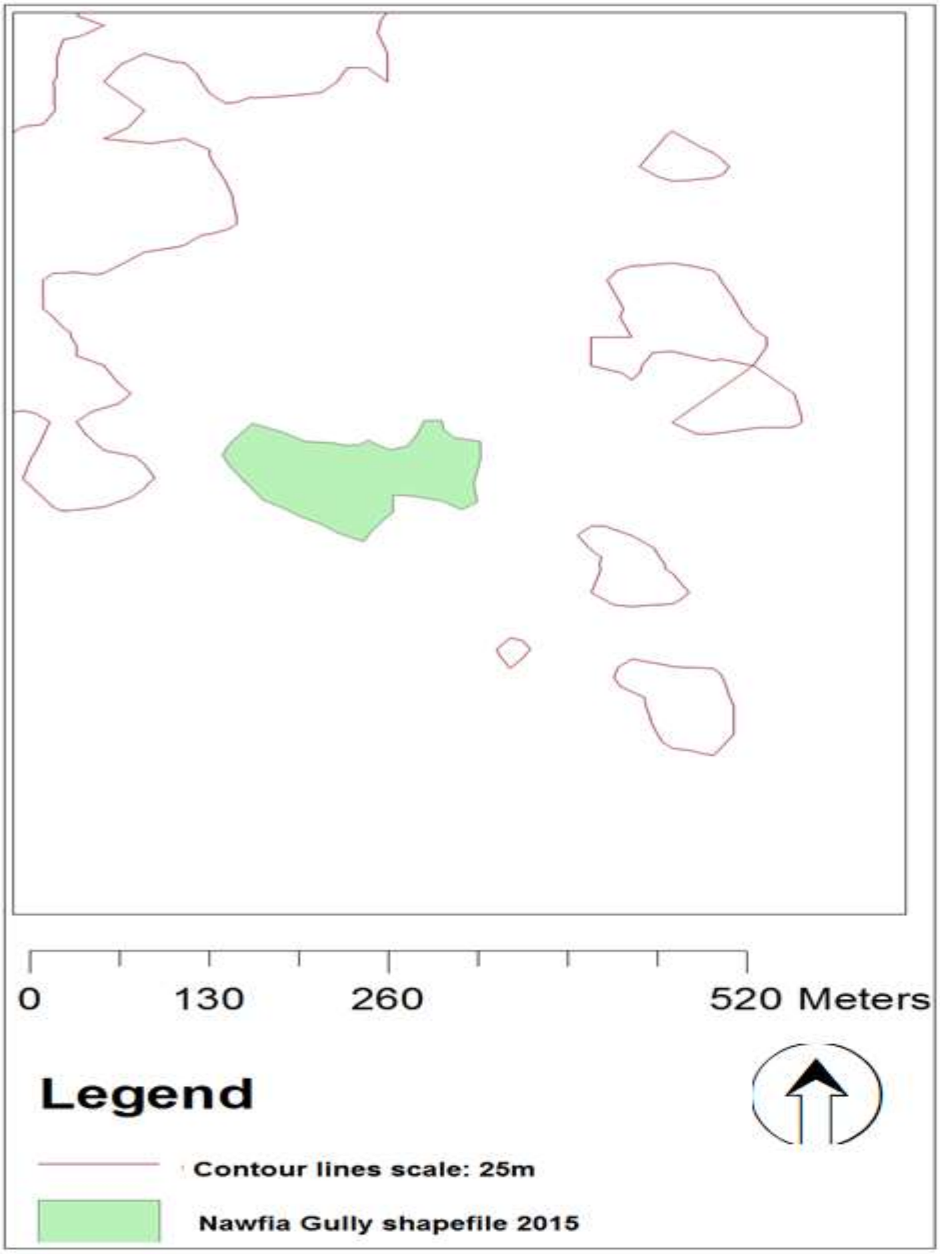

Figure 154: Displayed Nawfia vectorised gully of year 2015 on the contour map of the study area with contour interval of 25m

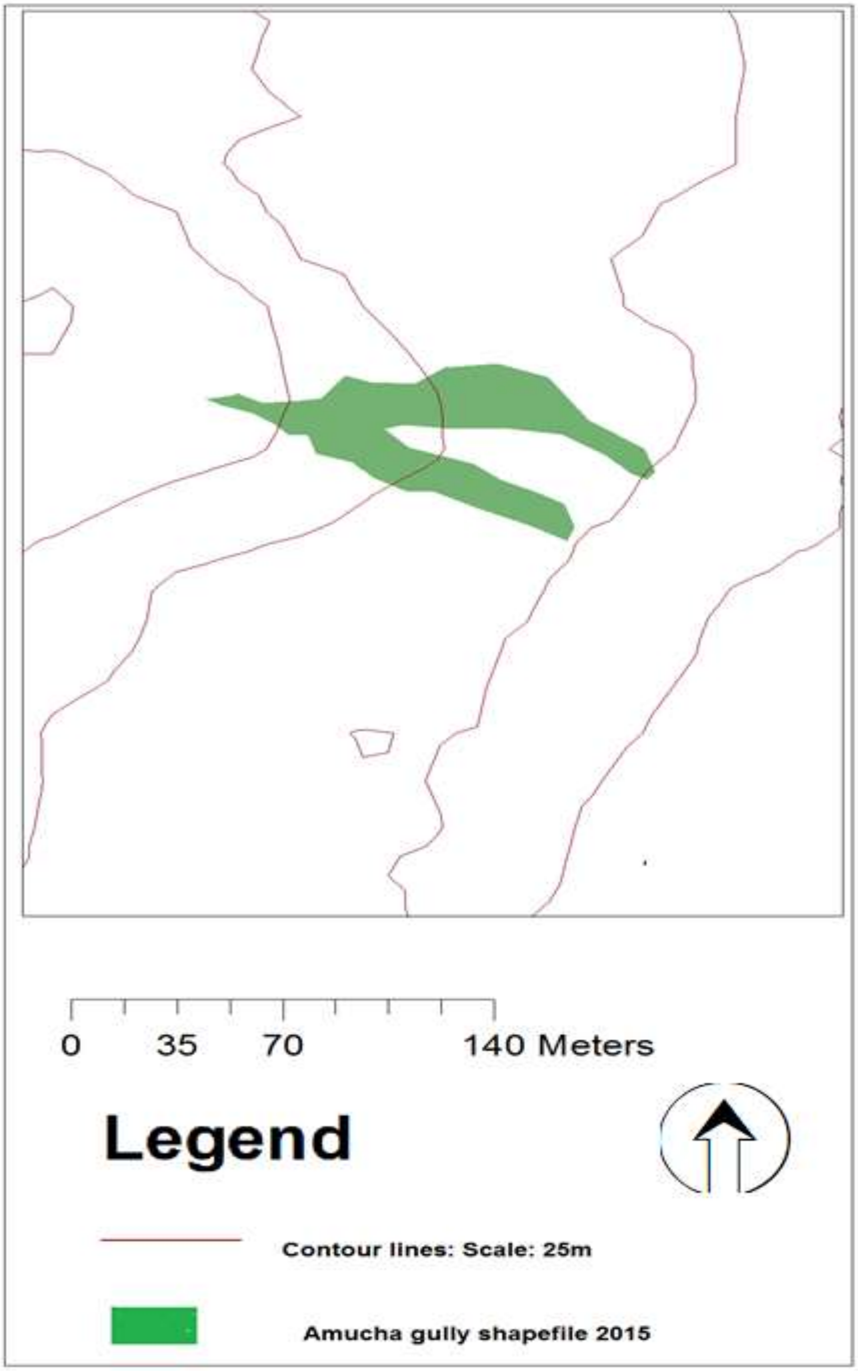

Figure 155: Displayed Amucha vectorised gully of year 2015 on the contour map of the study area with contour interval of 25m

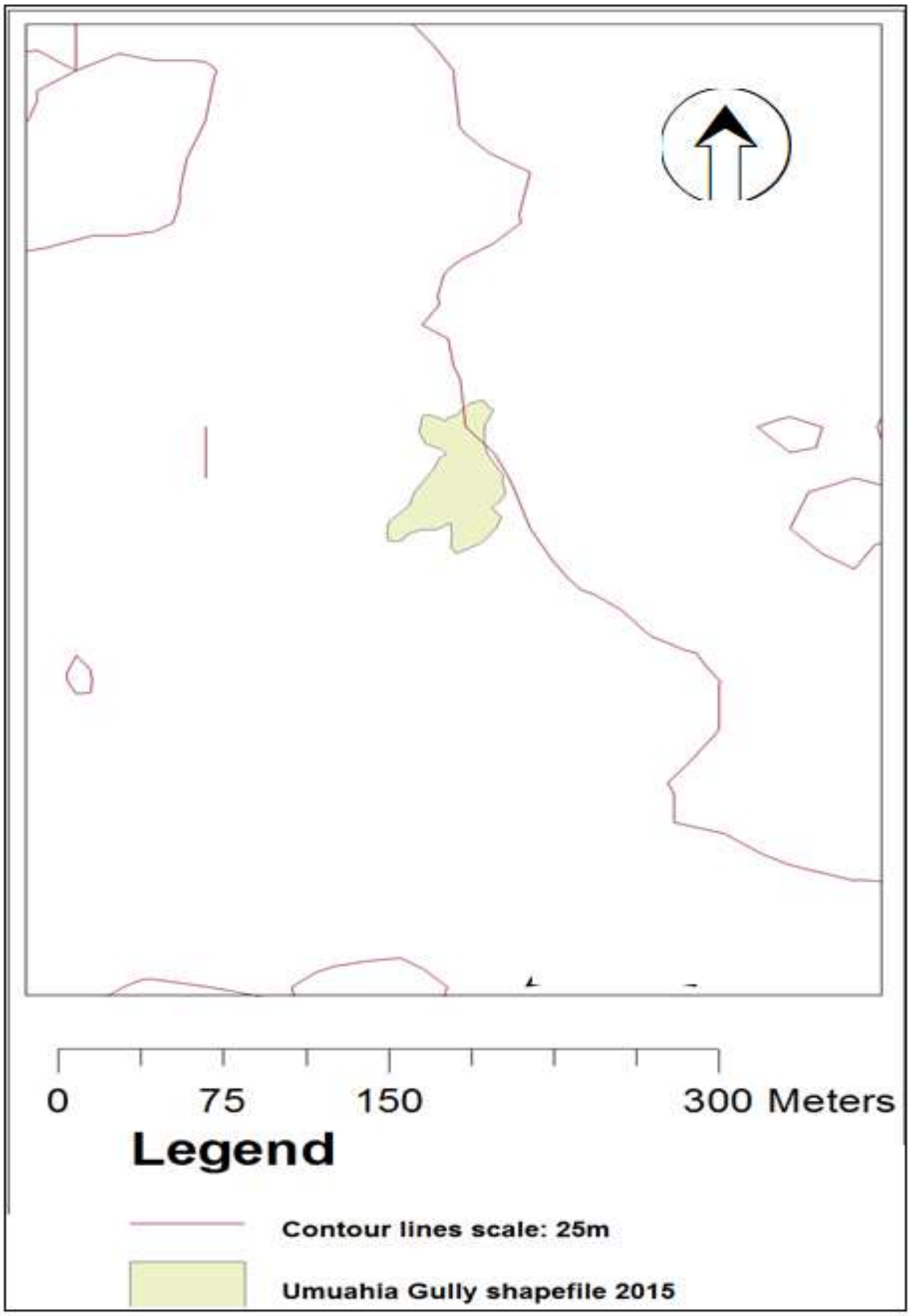

Figure 156: Displayed Umuahia vectorised gully of year 2015 on the contour map of the study area with contour interval of 25m

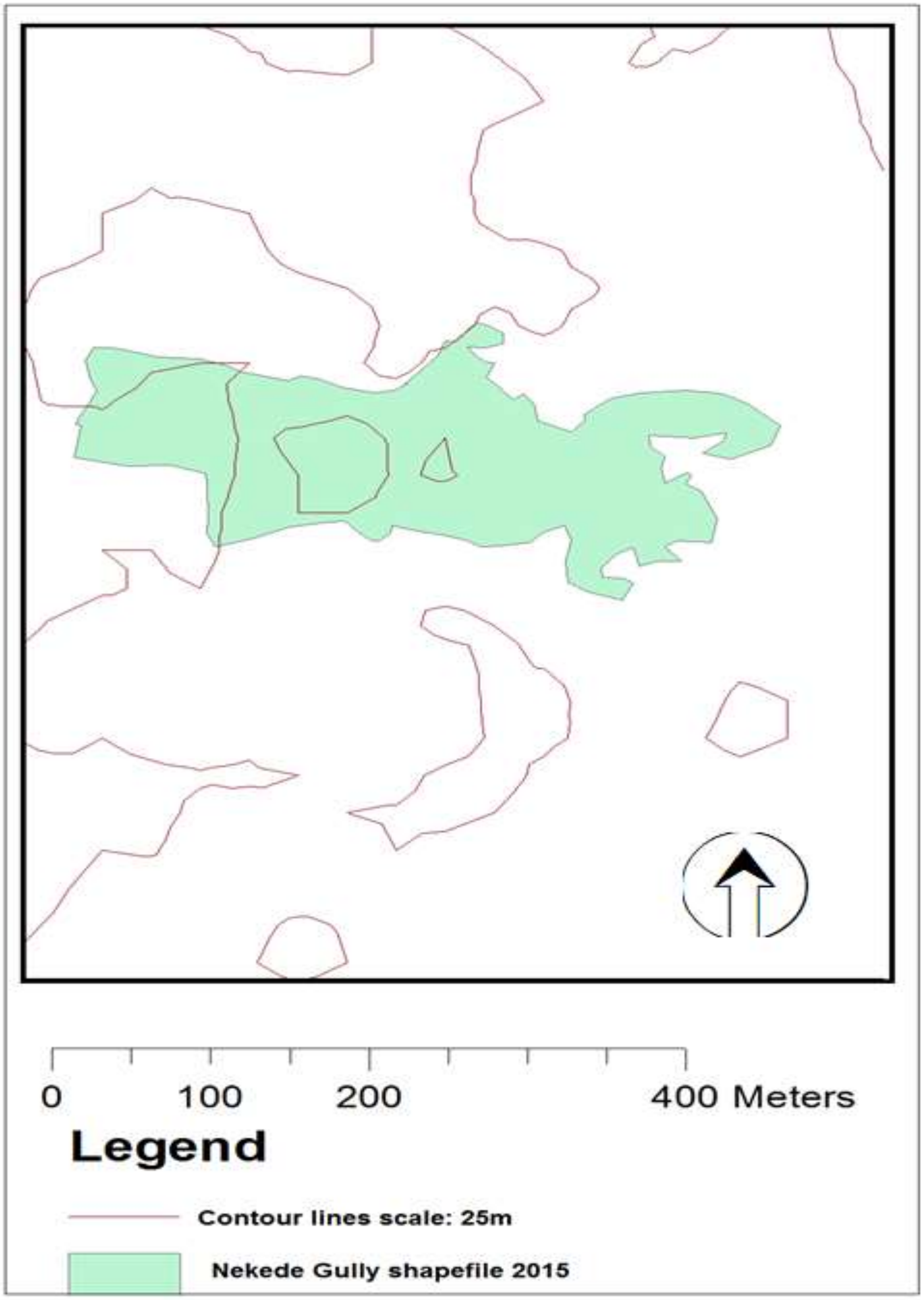

Figure 157: Displayed Nekede vectorised gully of year 2015 on the contour map of the study area with contour interval of 25m

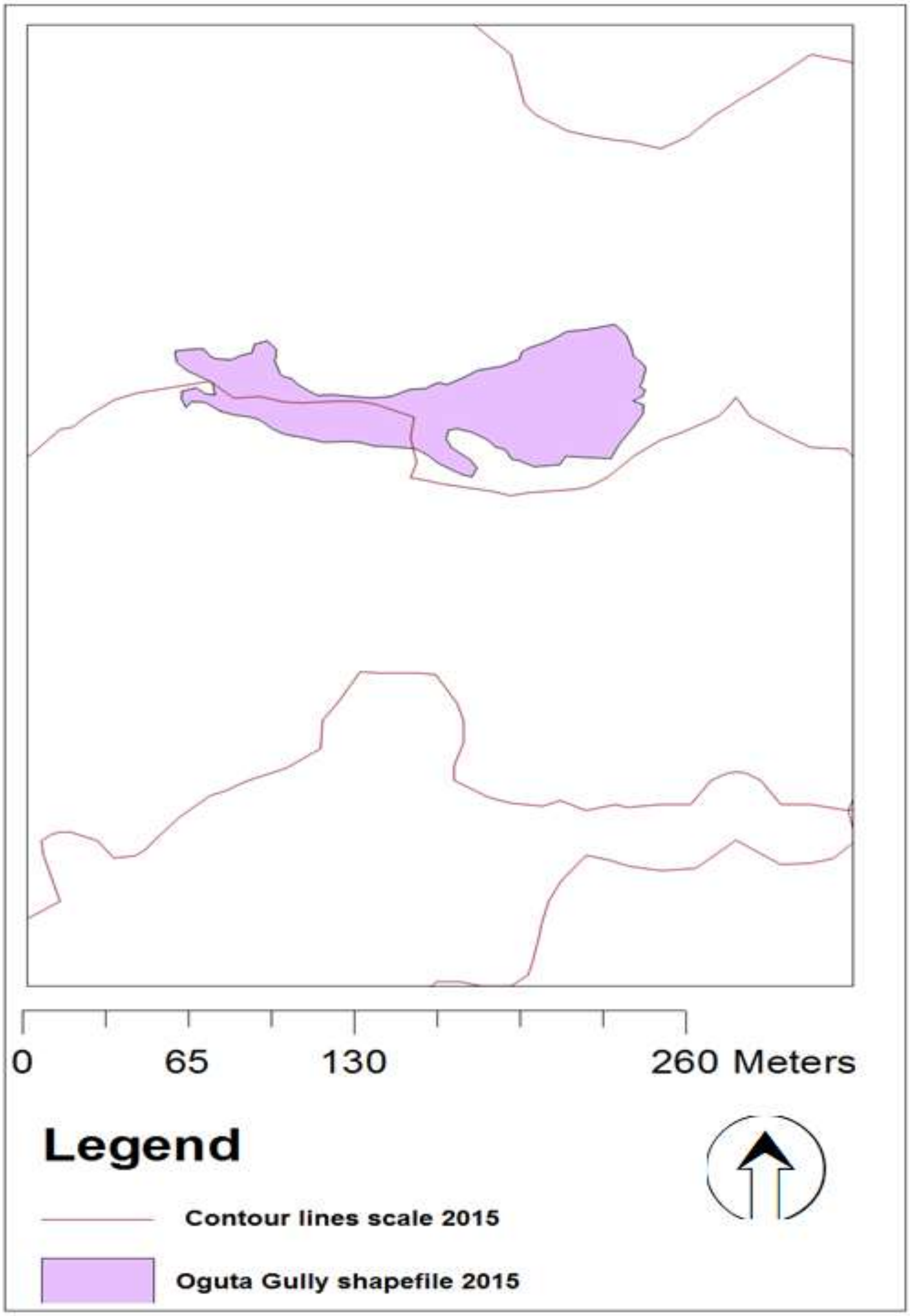

Figure 158: Displayed Oguta vectorised gully of year 2015 on the contour map of the study area with contour interval of 25m

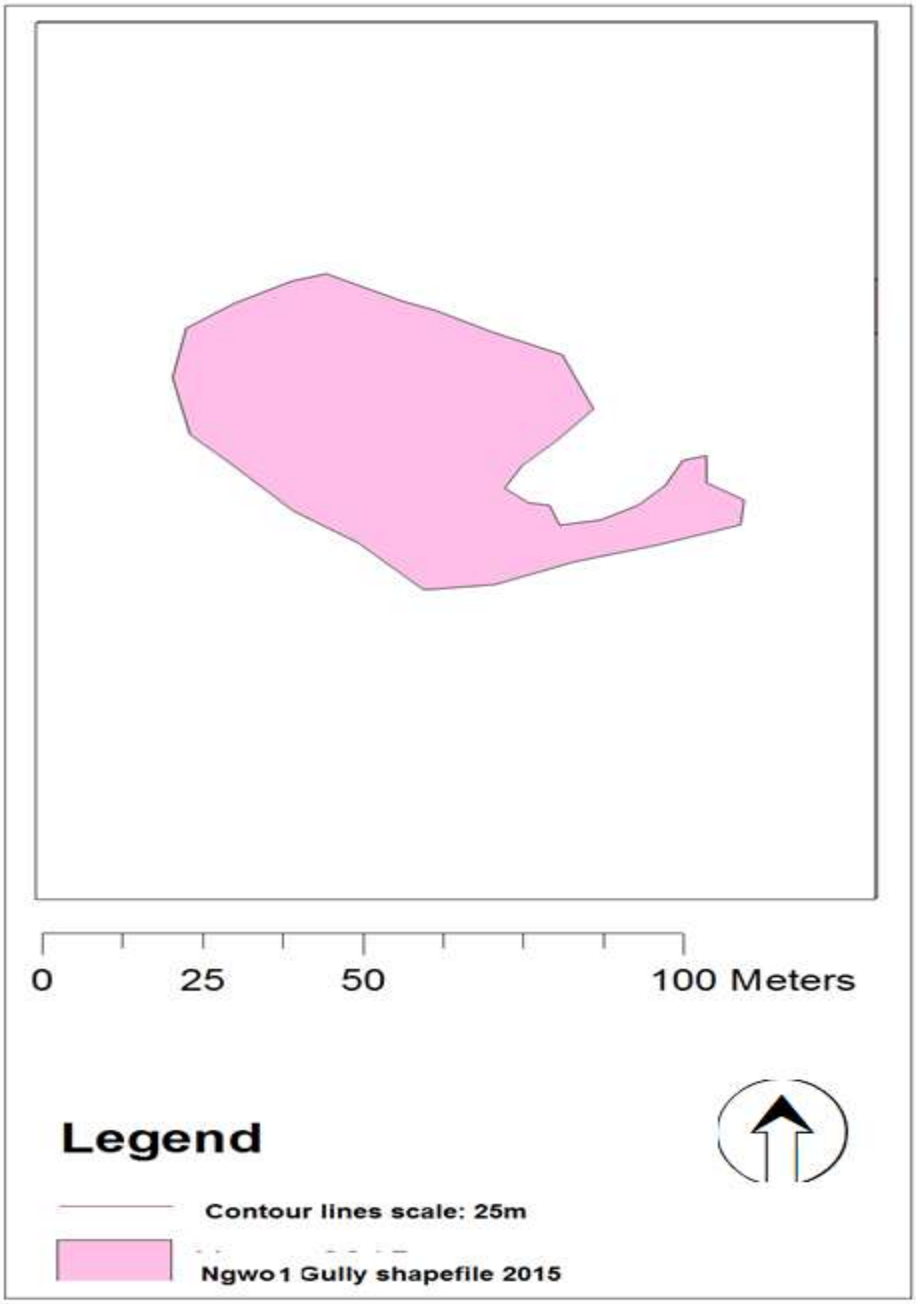

Figure 159: Displayed Ngwo1 vectorised gully of year 2015 on the contour map of the study area with contour interval of 25m

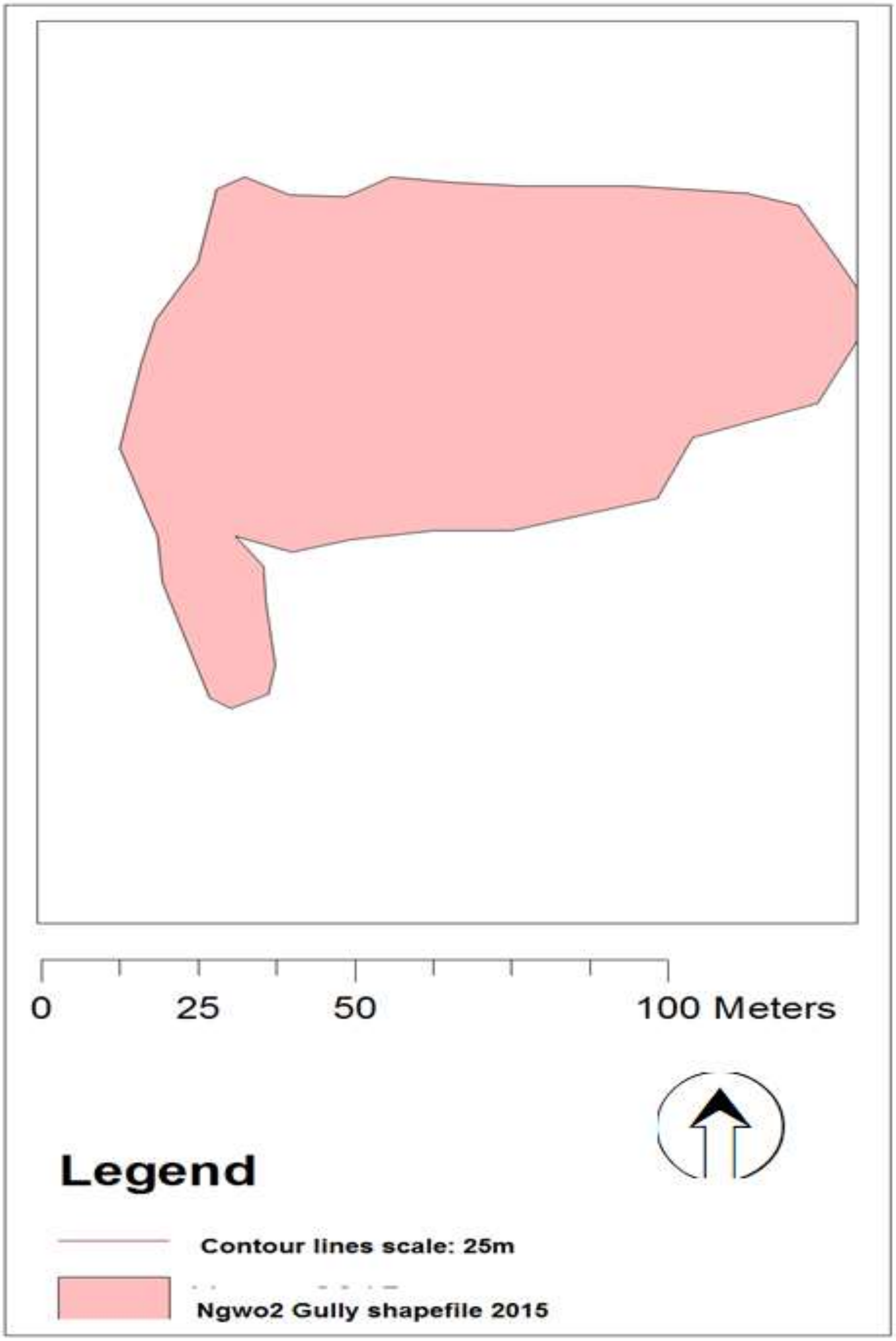

Figure 160: Displayed Ngwo2 vectorised gully of year 2015 on the contour map of the study area with contour interval of 25m

Appendix III - Gully Shapefile 2015 Overlaid by 1986 Shapefile

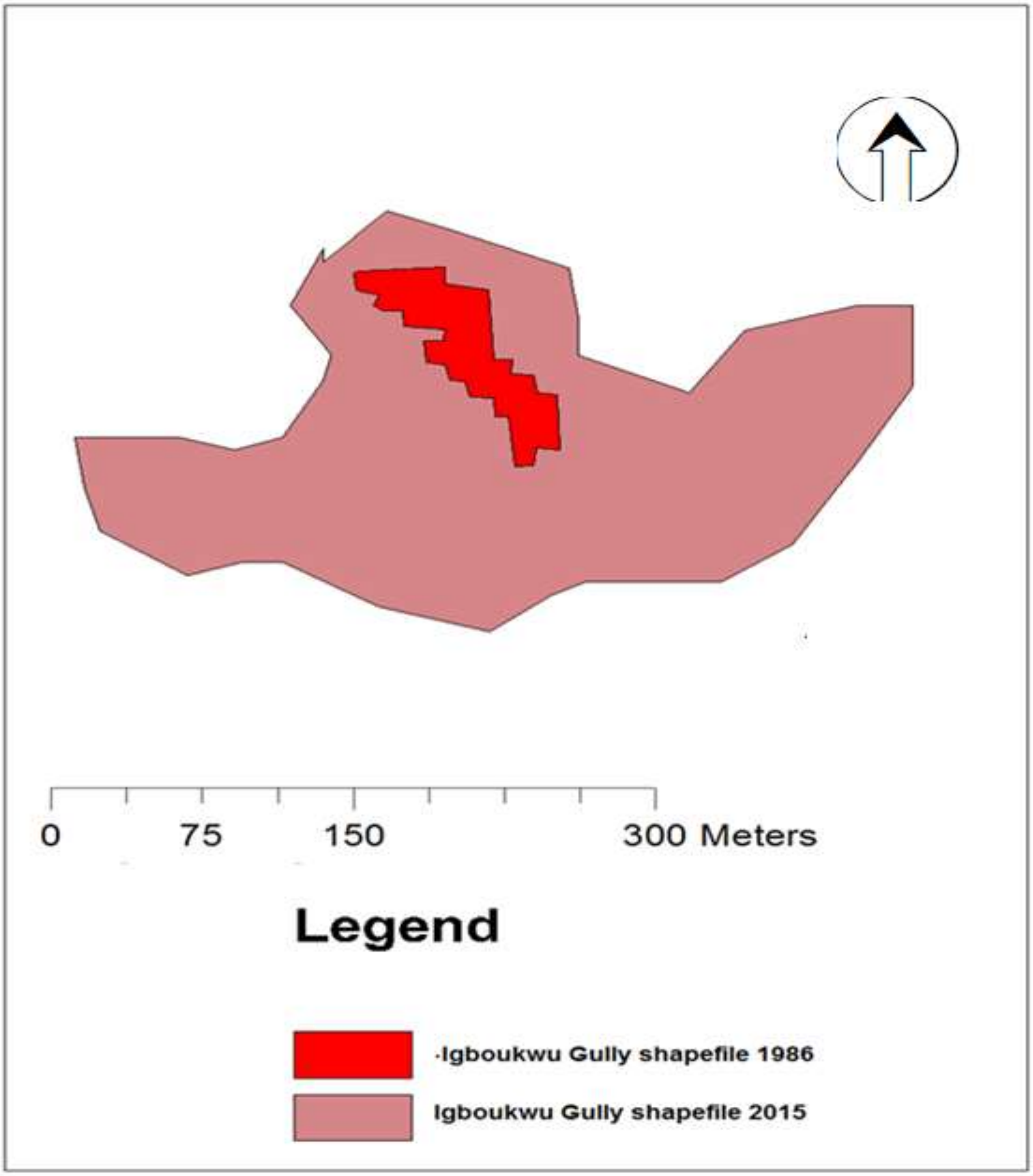

Figure 161: Igboukwu Gully shapefile 2015 overlaid by 1986 shapefile

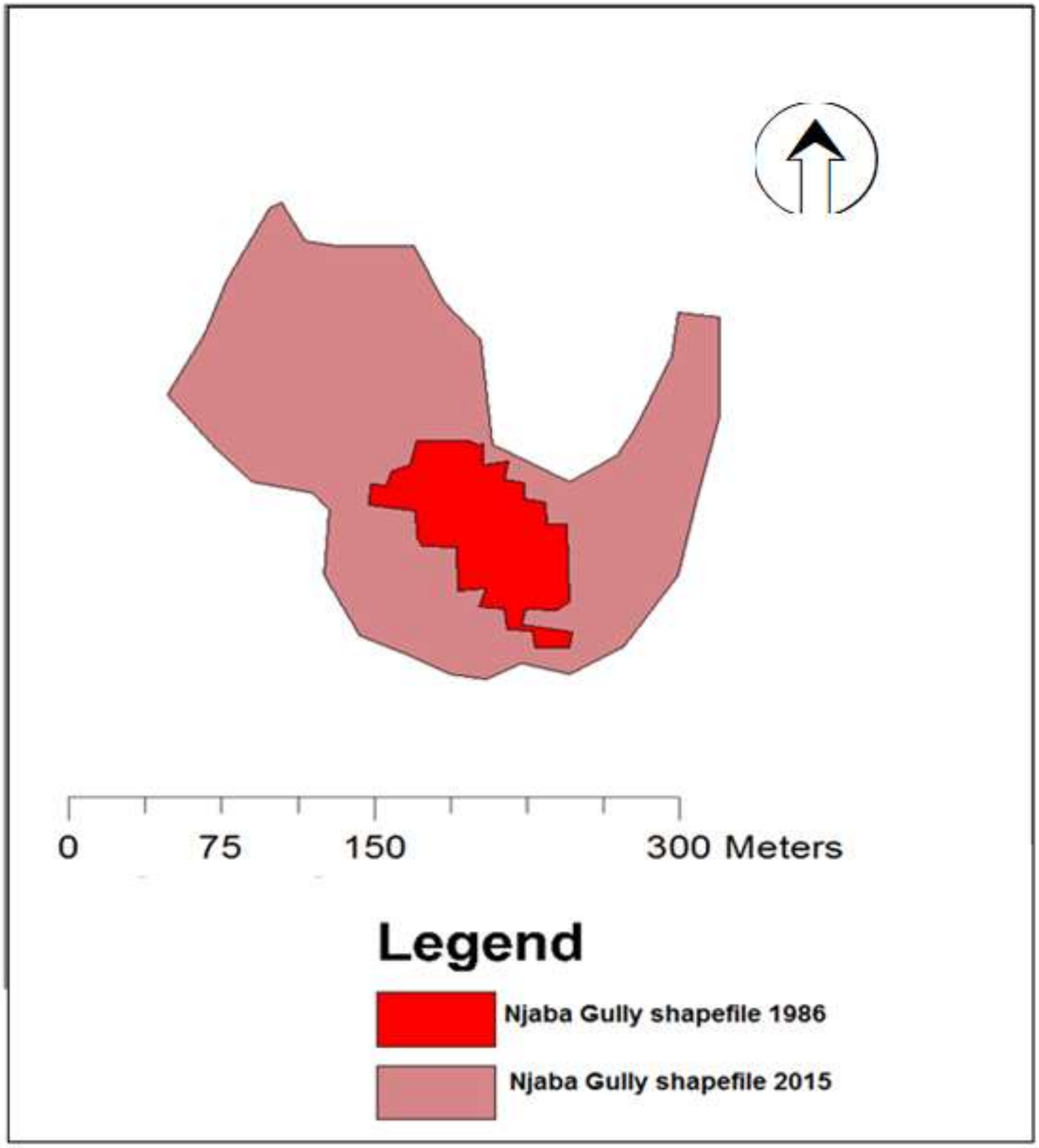

Figure 162: Njaba Gully shapefile 2015 overlaid by 1986 shapefile

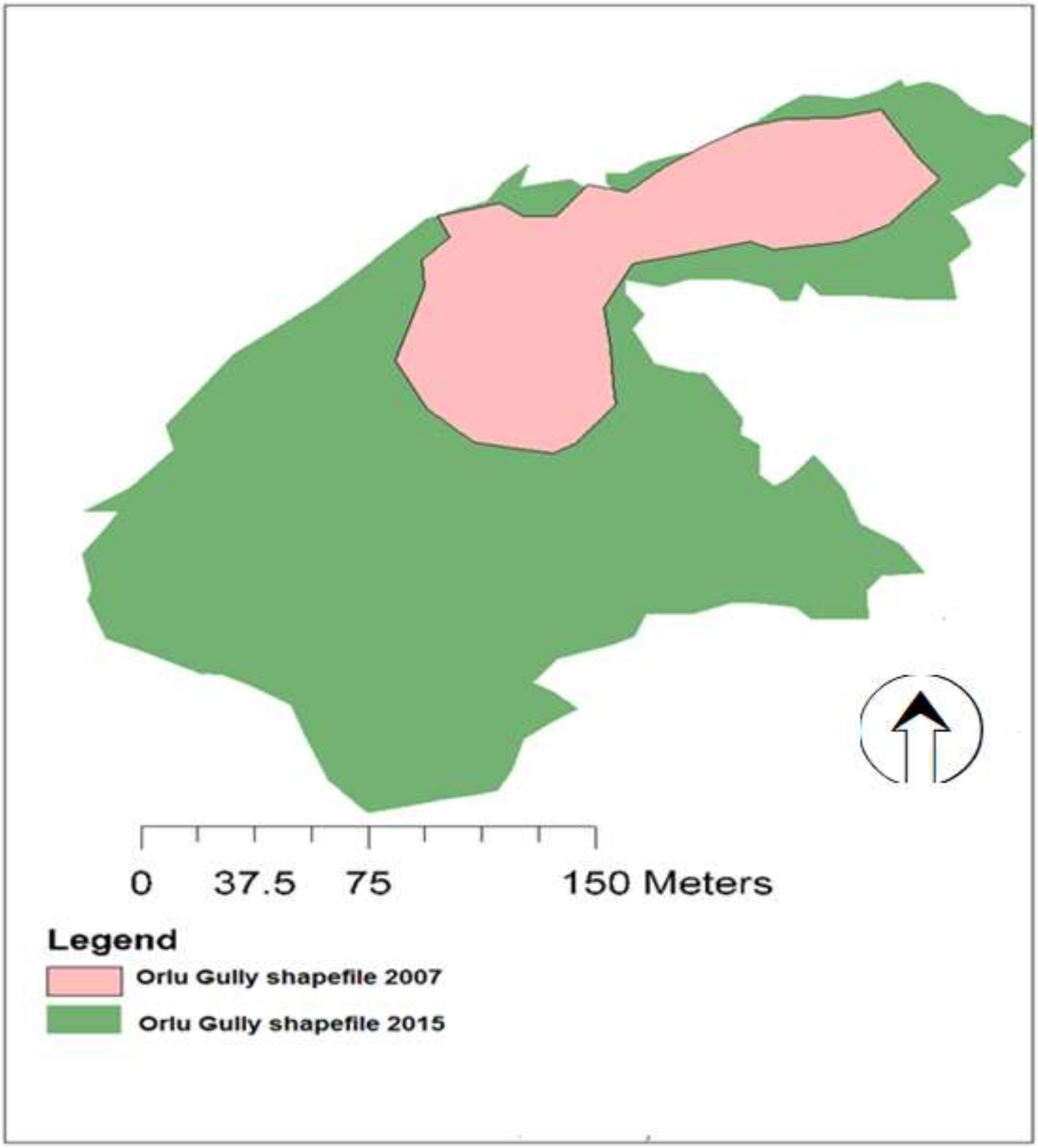

Figure 163: Orlu Gully shapefile 2015 overlaid by 2007 shapefile

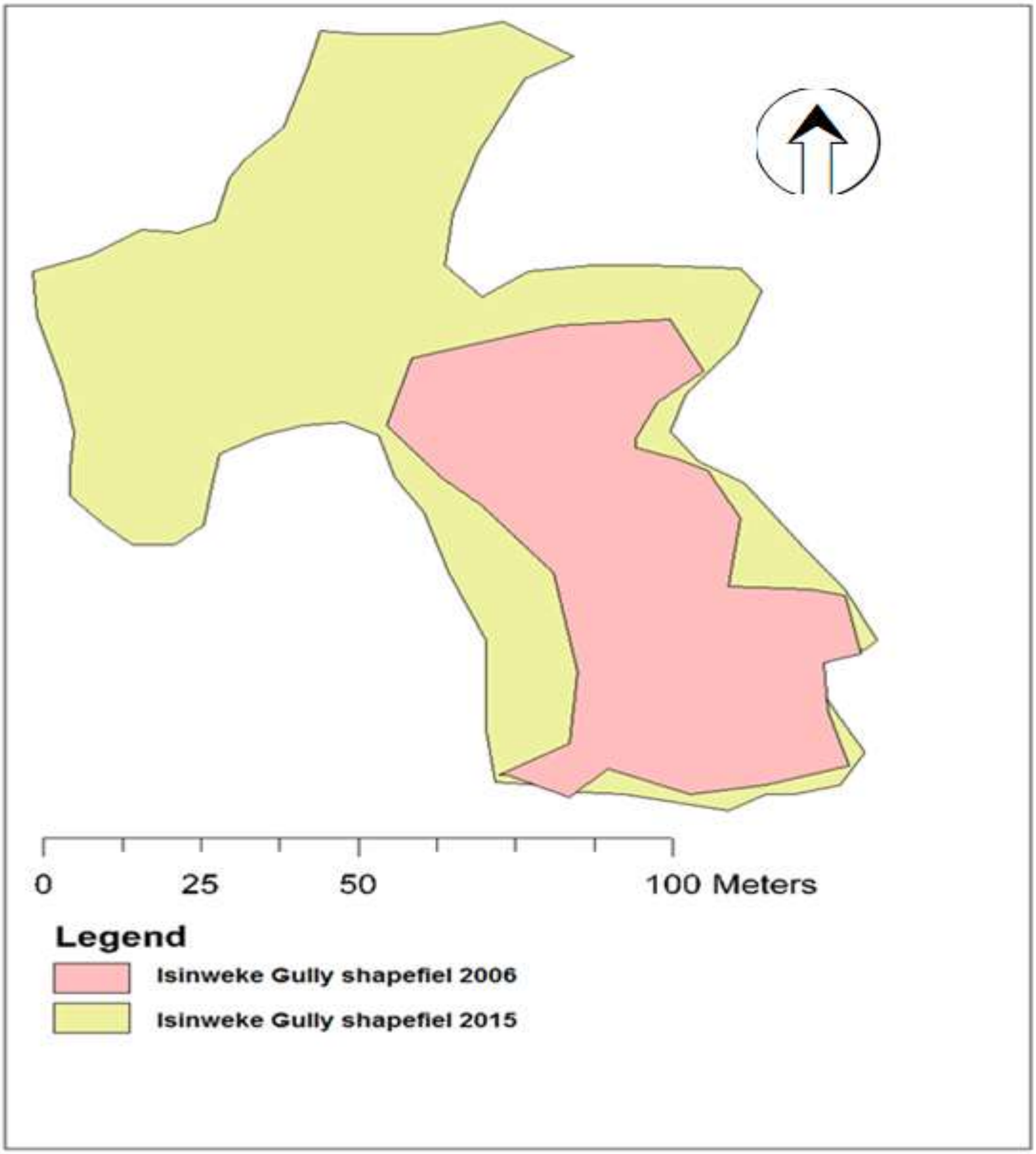

Figure 164: Isinweke Gully shapefile 2015 overlaid by 2006 shapefile

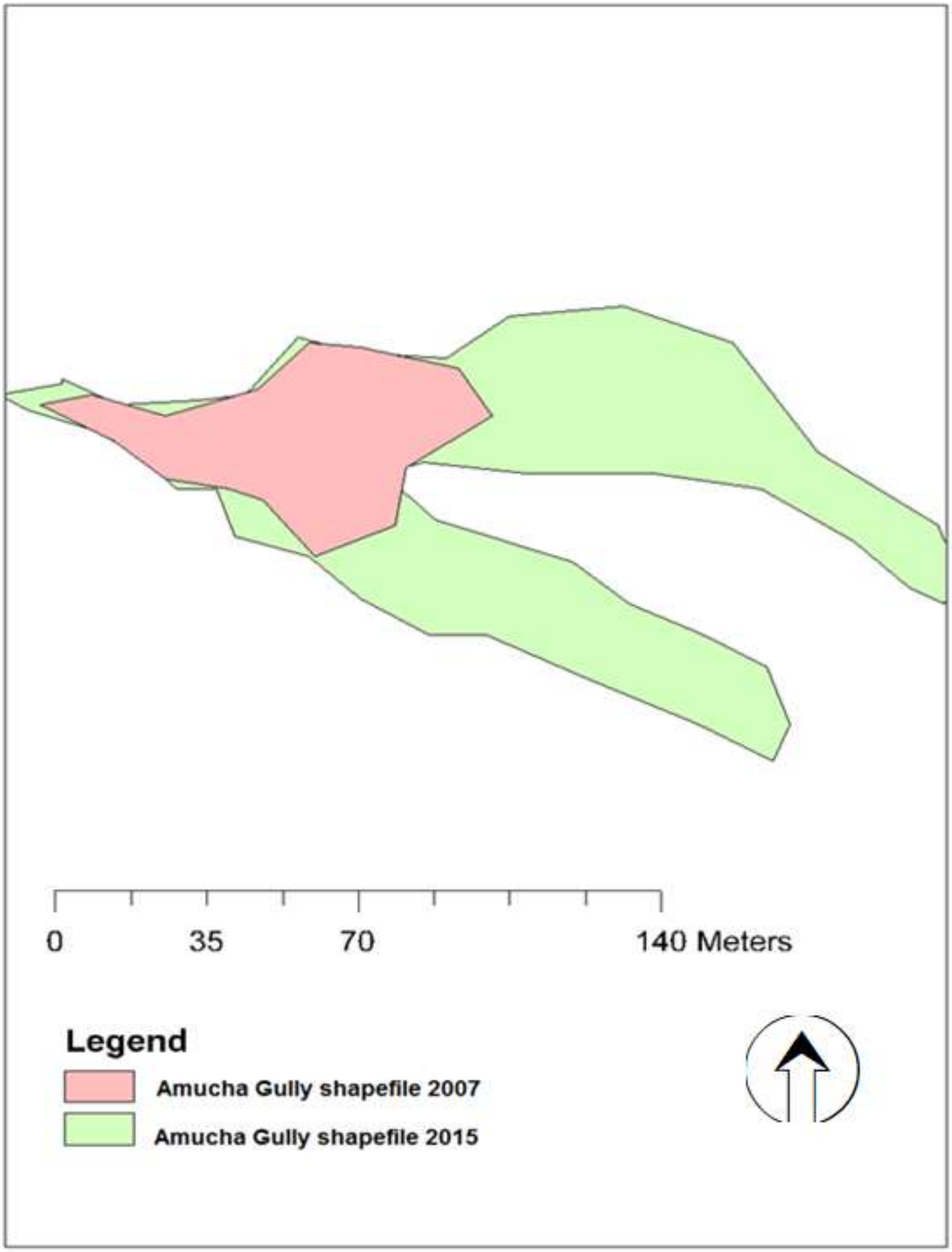

Figure 165: Amucha Gully shapefile 2015 overlaid by 2007 shapefile

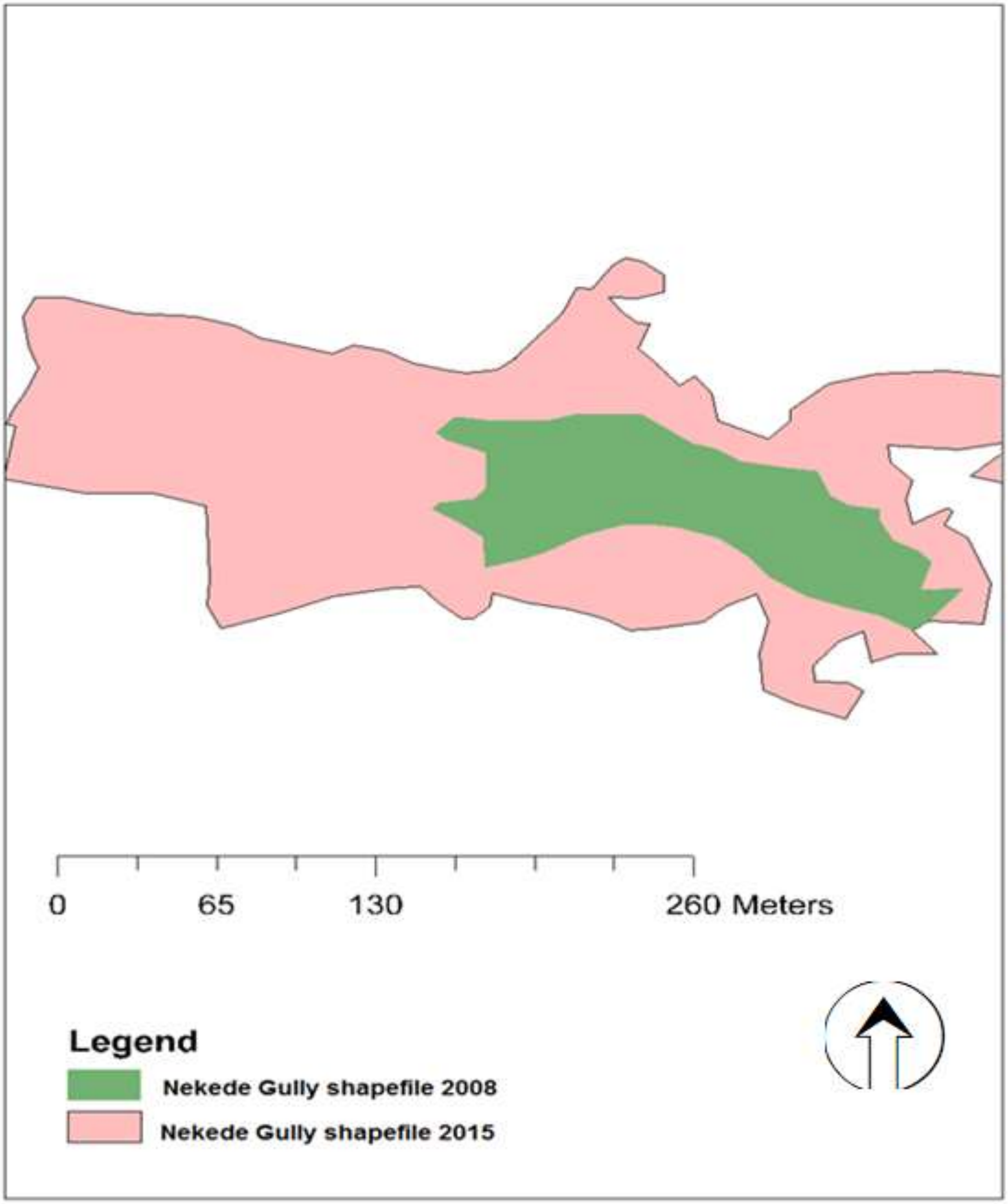

Figure 166: Nekede Gully shapefile 2015 overlaid by 2008 shapefile

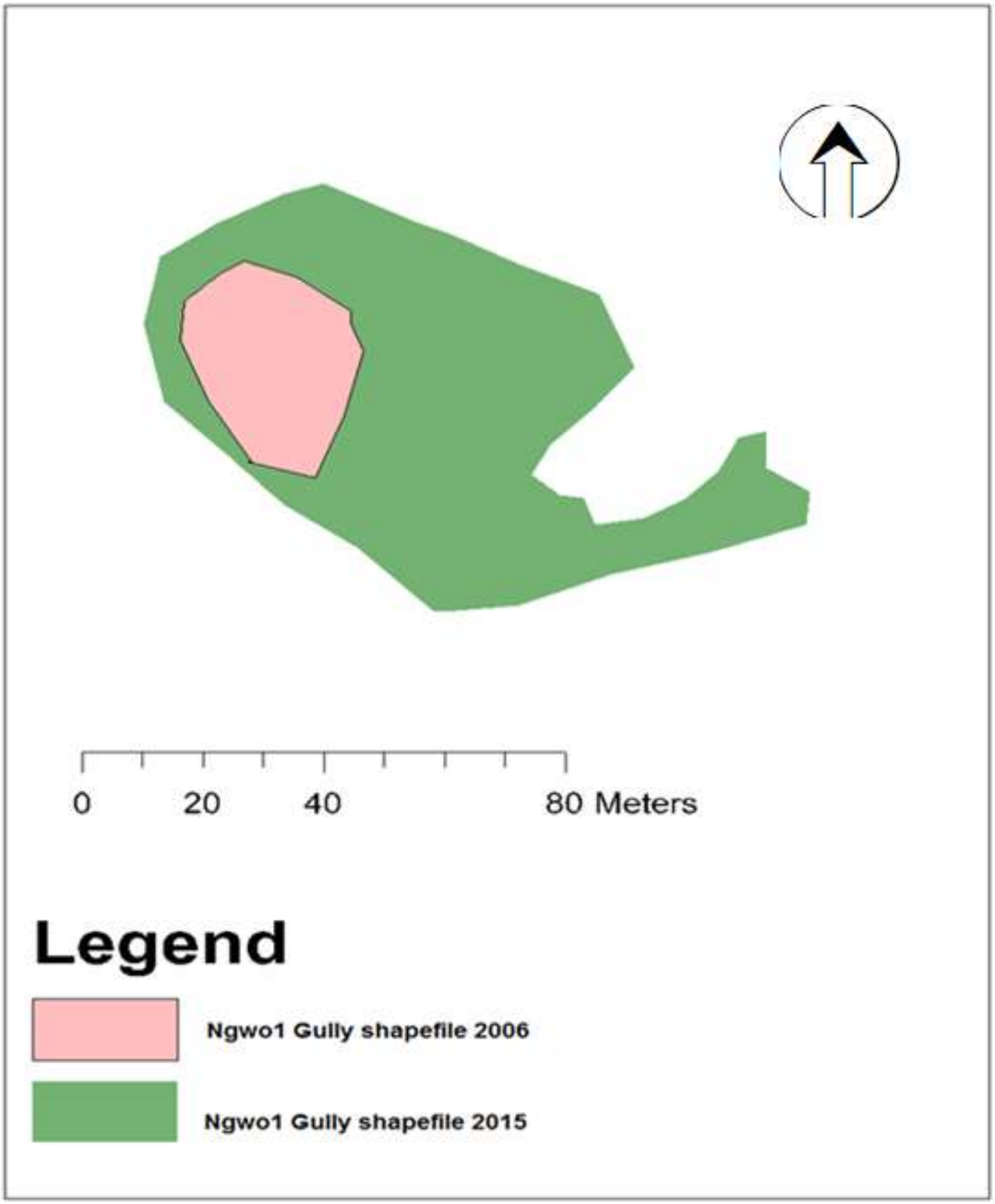

Figure 167: Ngwo1 Gully shapefile 2015 overlaid by 2006 shapefile

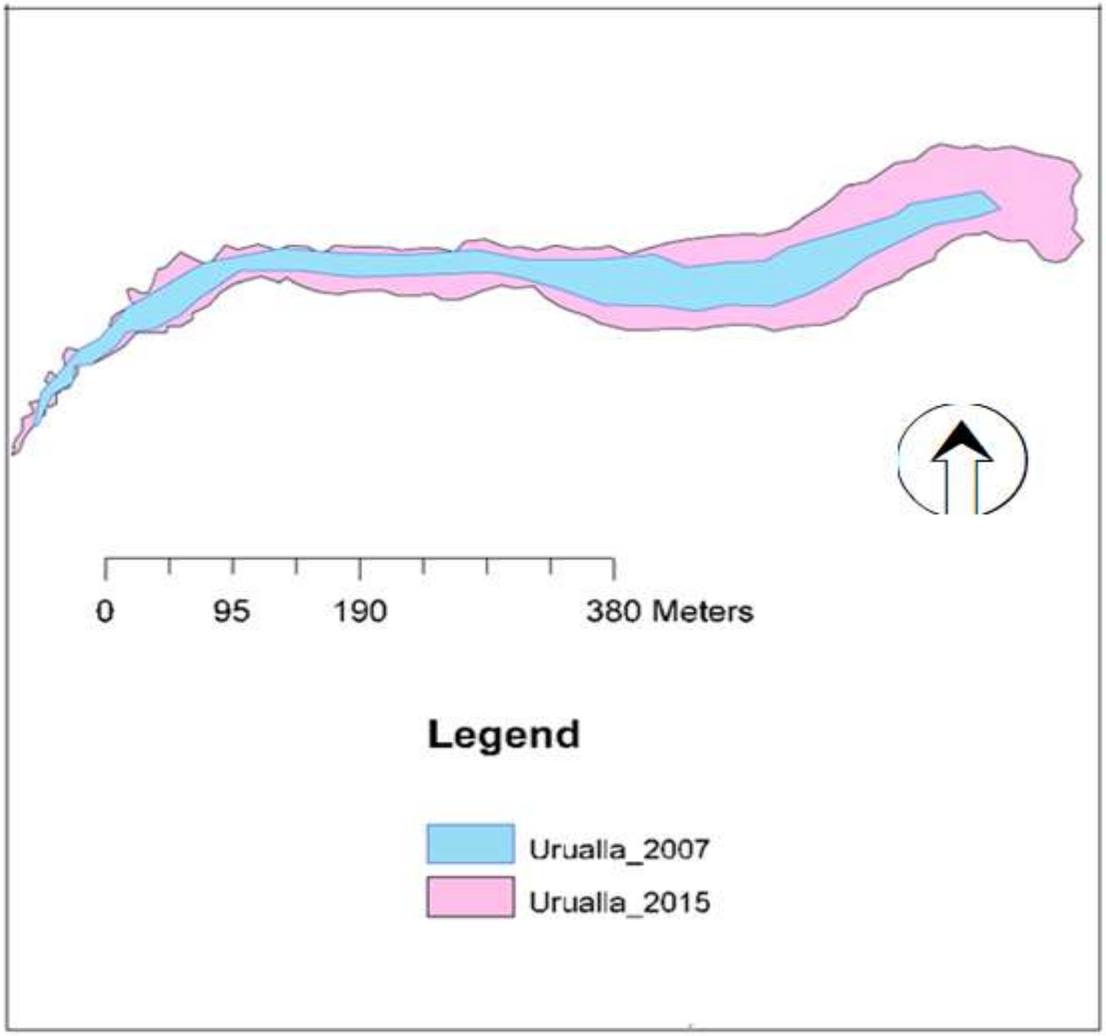

Figure 168: Urualla Gully shapefile 2015 overlaid by 2007 shapefile

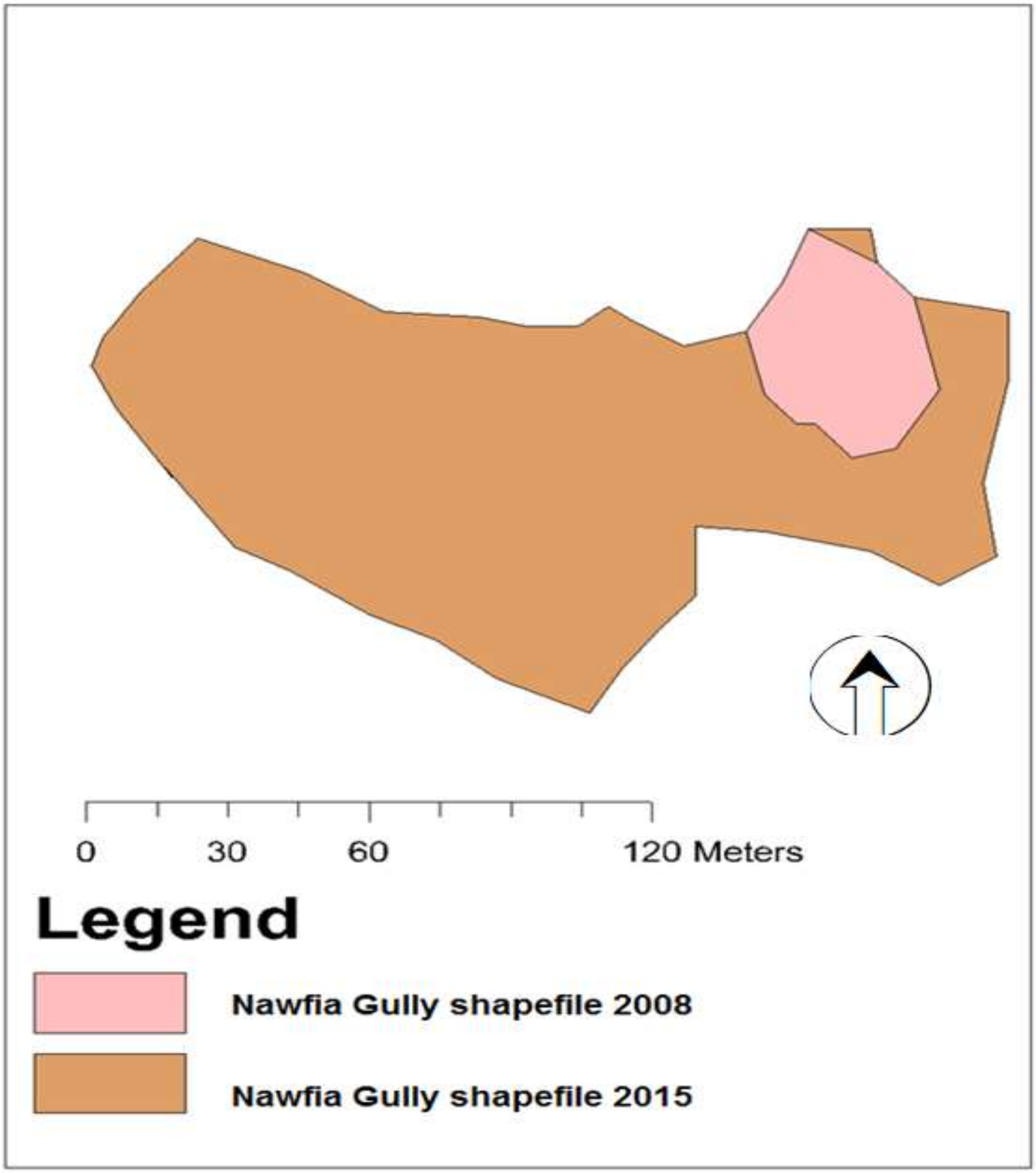

Figure 169: Nawfia Gully shapefile 2015 overlaid by 2008 shapefile

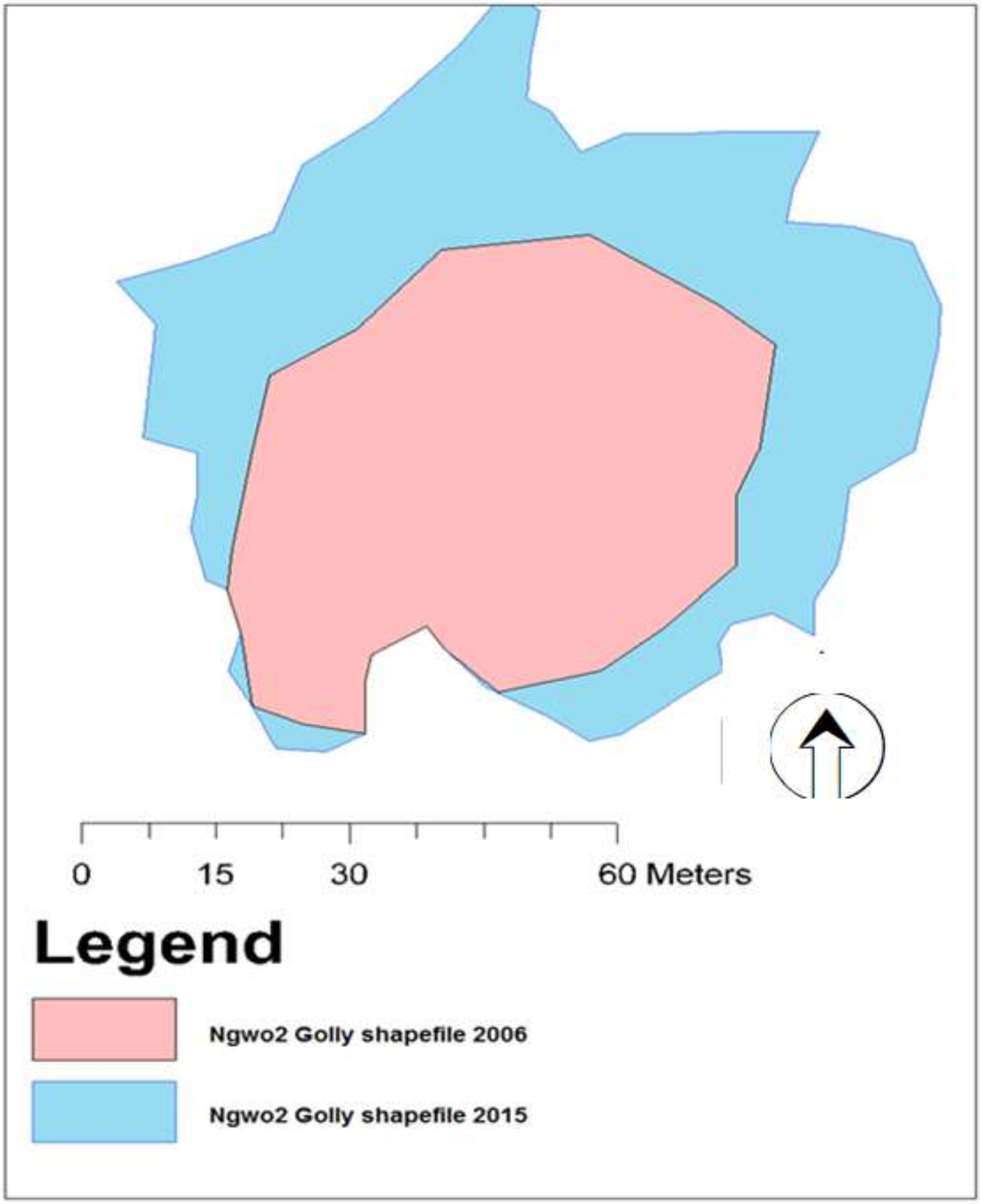

Figure 170: Ngwo2 Gully shapefile 2015 overlaid by 2006 shapefile

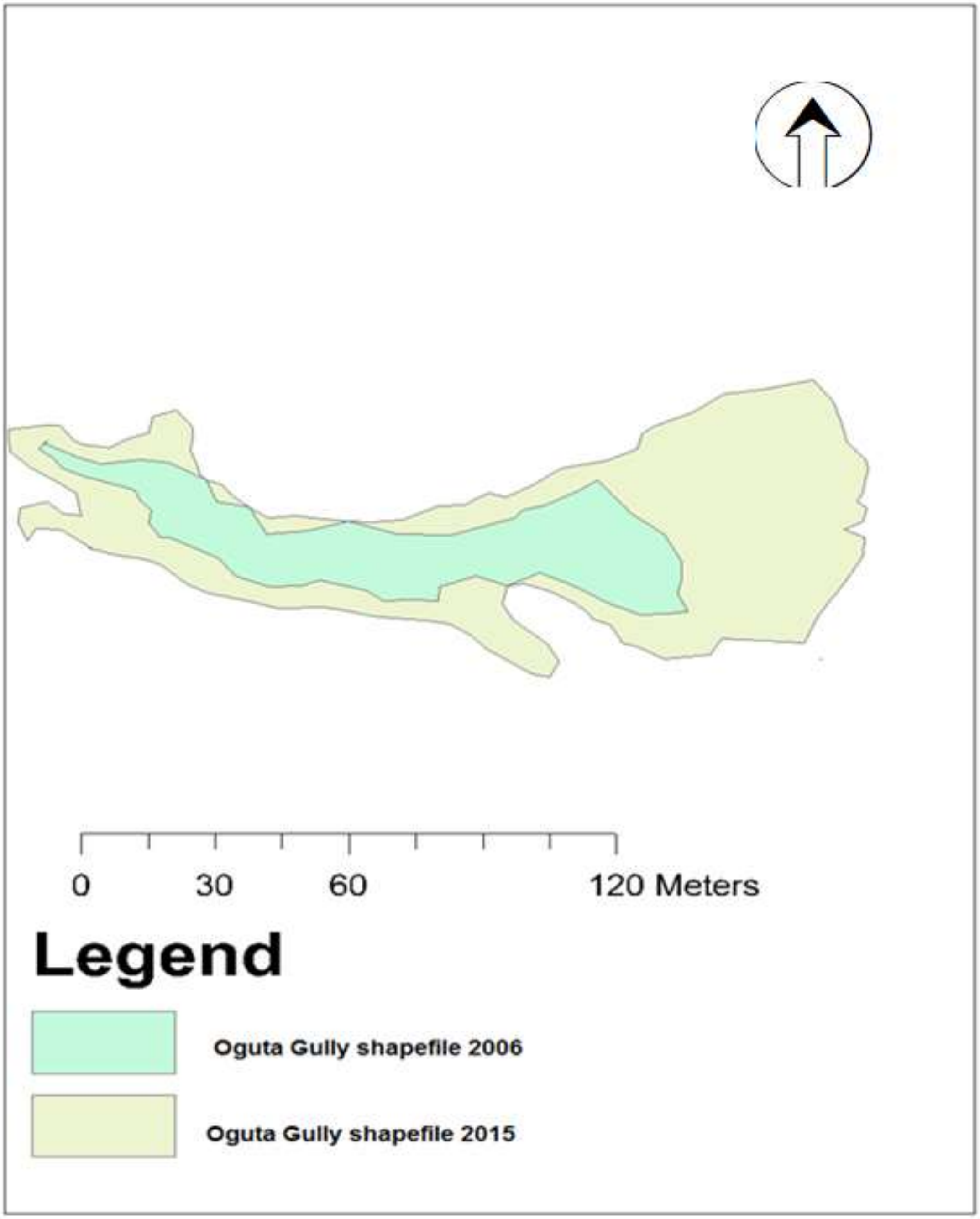

Figure 171: Oguta Gully shapefile 2015 overlaid by 2006 shapefile

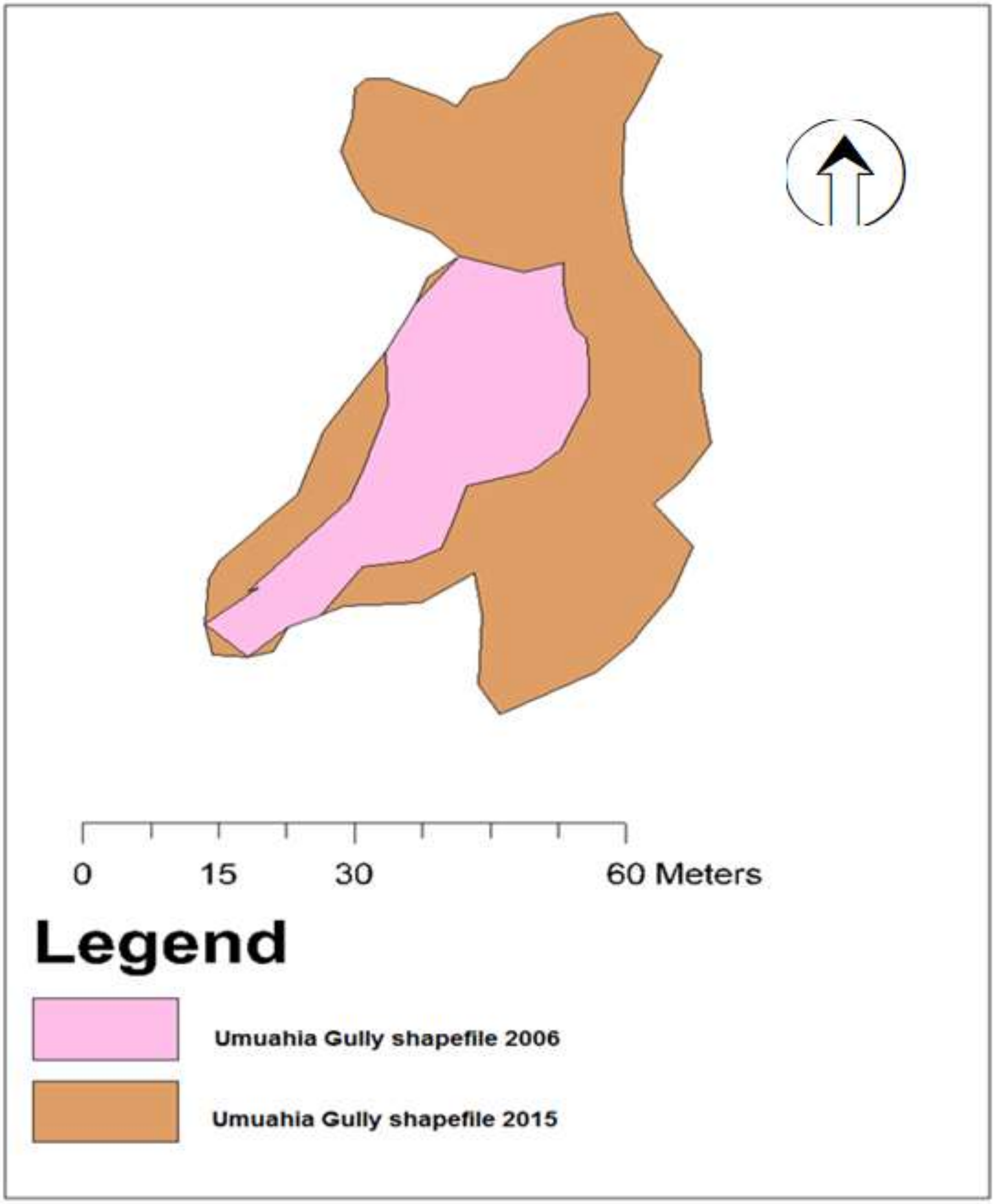

Figure 172: Umuahia Gully shapefile 2015 overlaid by 2006 shapefile

Appendix IV- Three Backscatter Change Maps using the four Temporally Separated Images

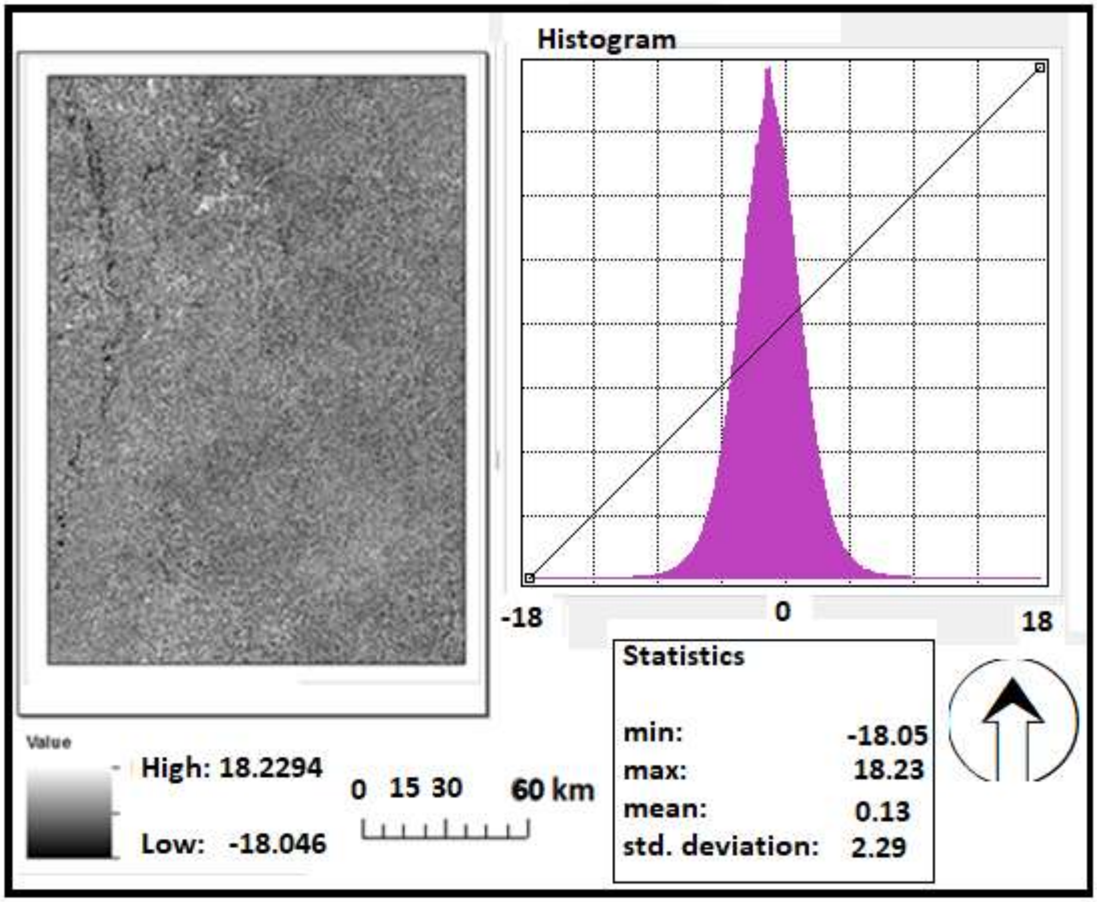

Figure 173: The change detection of Year 2010 – 2007; -18 represent forest disturbance

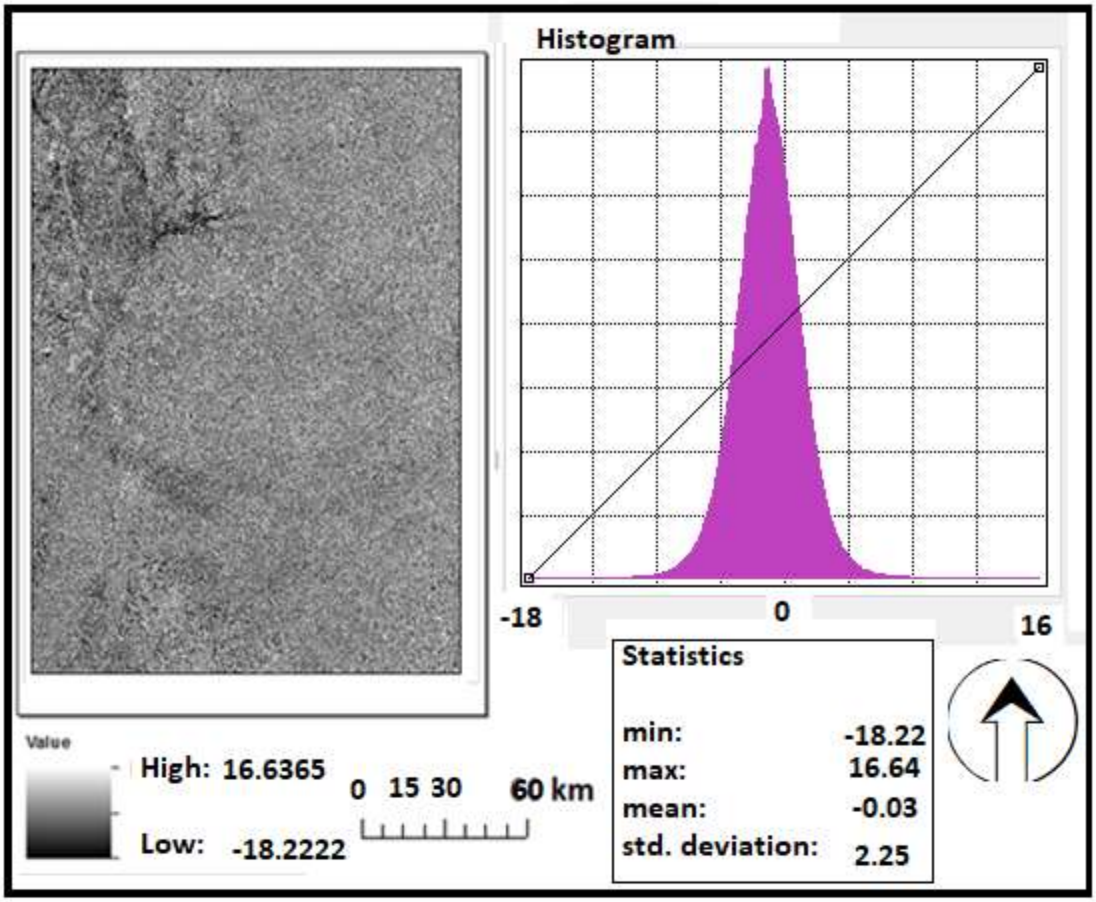

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Figure 174: The change detection of Year 2008 – 2007; -18 represent forest disturbance

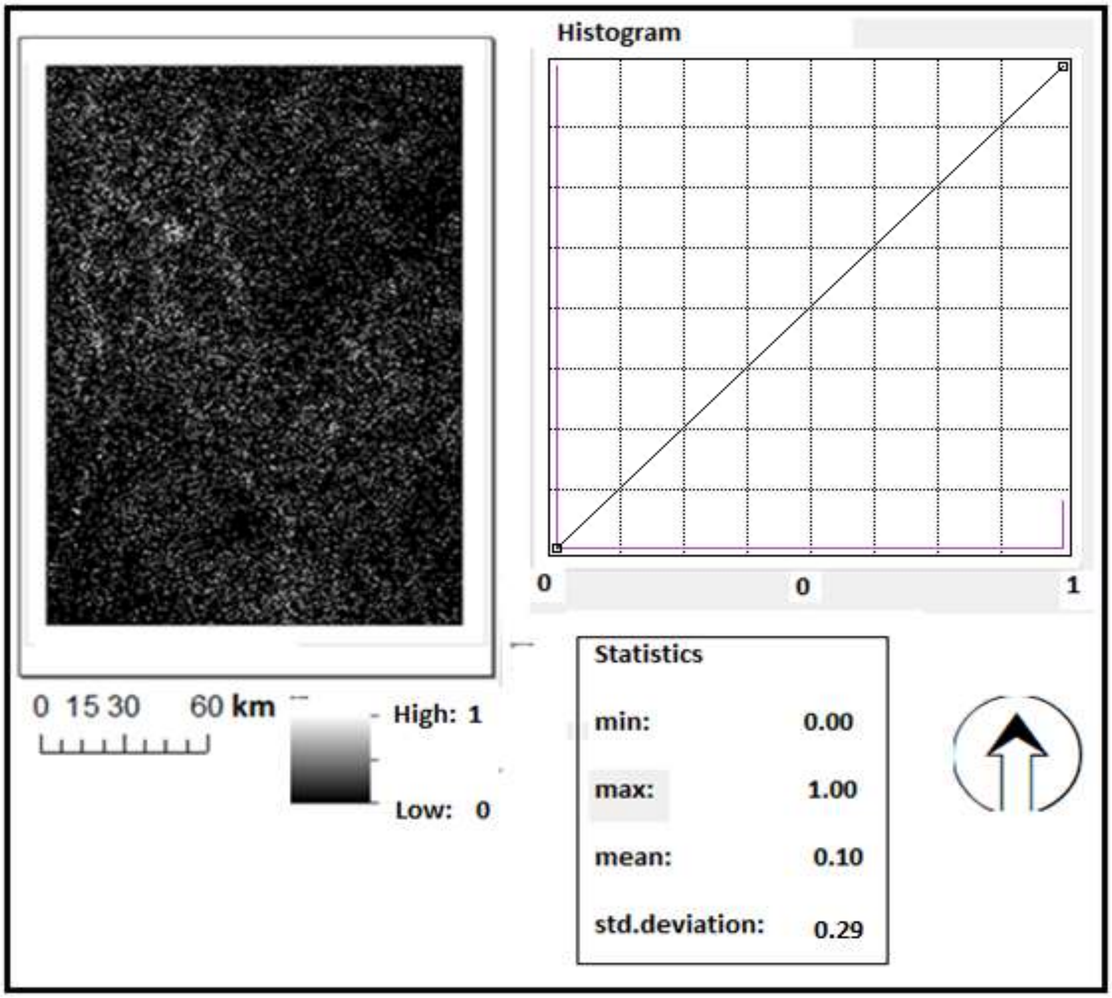
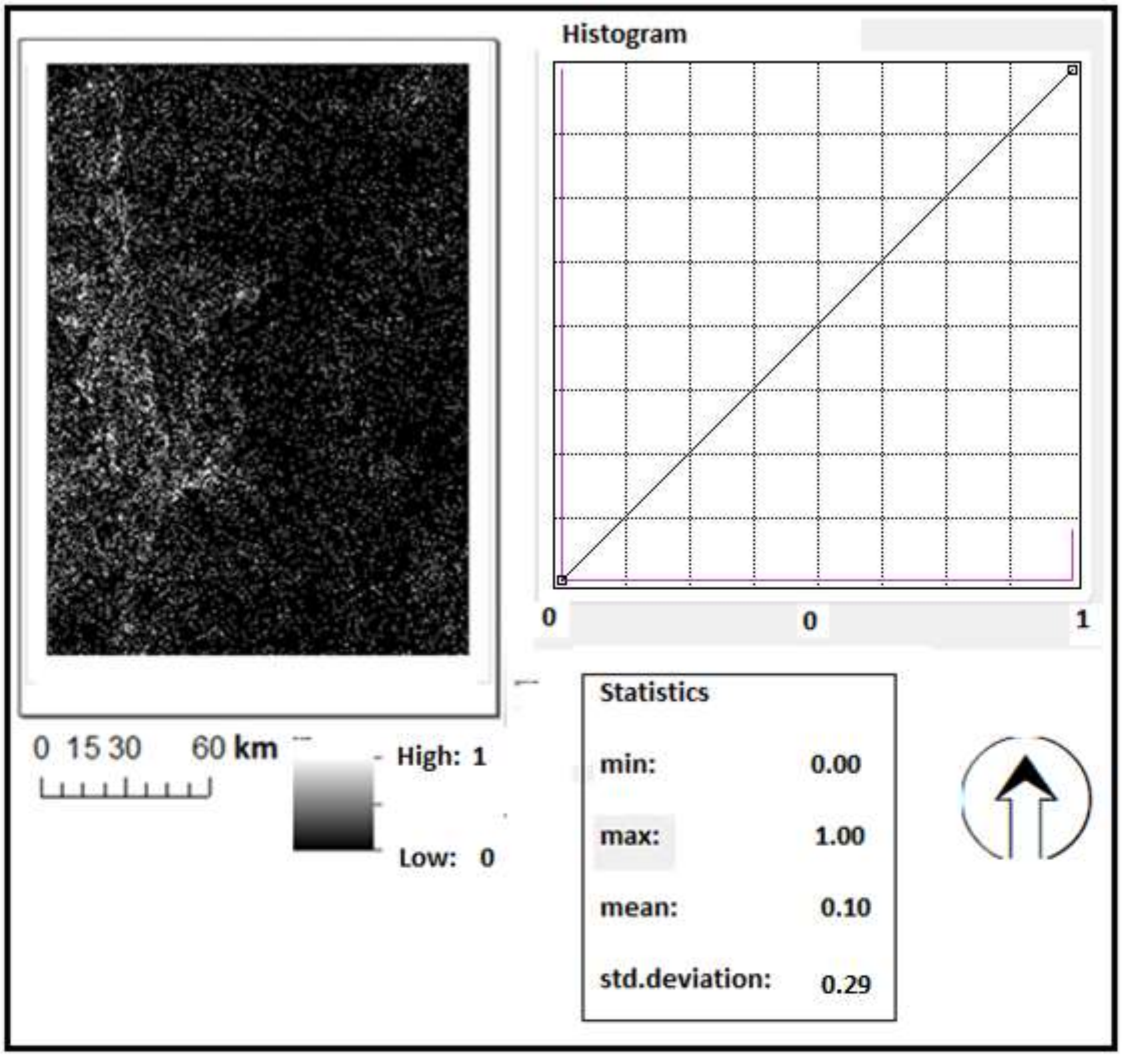


Figure 175: The Threshold map of 2009-2007; 1 represent deforestation, 0 represent forest and other land-cover



Statistics

min: 0.00

max: 1.00

mean: 0.10

std.deviation: 0.29

Figure 176: The Threshold map of 2008-2007; 1 represent deforestation, 0 represent forest and other land-cover

Appendix V- correlation of the Gully Area from Landsat with Gully Area from Google Earth

Table 95: Correlation Table of Iyioku Landsat and Google Earth image

Correlation

		IyiokuLandsat	IyiokuGoogle
IyiokuLandsat	Pearson Correlation	1	.723*
	Sig. (2-tailed)		.018
	N	10	10
IyiokuGoogle	Pearson Correlation	.723*	1
	Sig. (2-tailed)	.018	
	N	10	10

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

Table 96: Correlation Table of Njaba Landsat and Google Earth image

Correlations

		NjabaLandsat	NjabaGoogle
NjabaLandsat	Pearson Correlation	1	.734*
	Sig. (2-tailed)		.016
	N	10	10
NjabaGoogle	Pearson Correlation	.734*	1
	Sig. (2-tailed)	.016	
	N	10	10

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

Table 97: Correlation Table of Igboukwu Landsat and Google Earth image

Correlations

		IgboukwuLandsat	IgboukwuGoogle
IgboukwuLandsat	Pearson Correlation	1	.990**
	Sig. (2-tailed)		.000
	N	10	10
IgboukwuGoogle	Pearson Correlation	.990**	1
	Sig. (2-tailed)	.000	
	N	10	10

Appendix VI Nonlinear Regression Analysis for Year 2014/15

Independent variables against yearly gully change in metre squared per square metre dependent variable

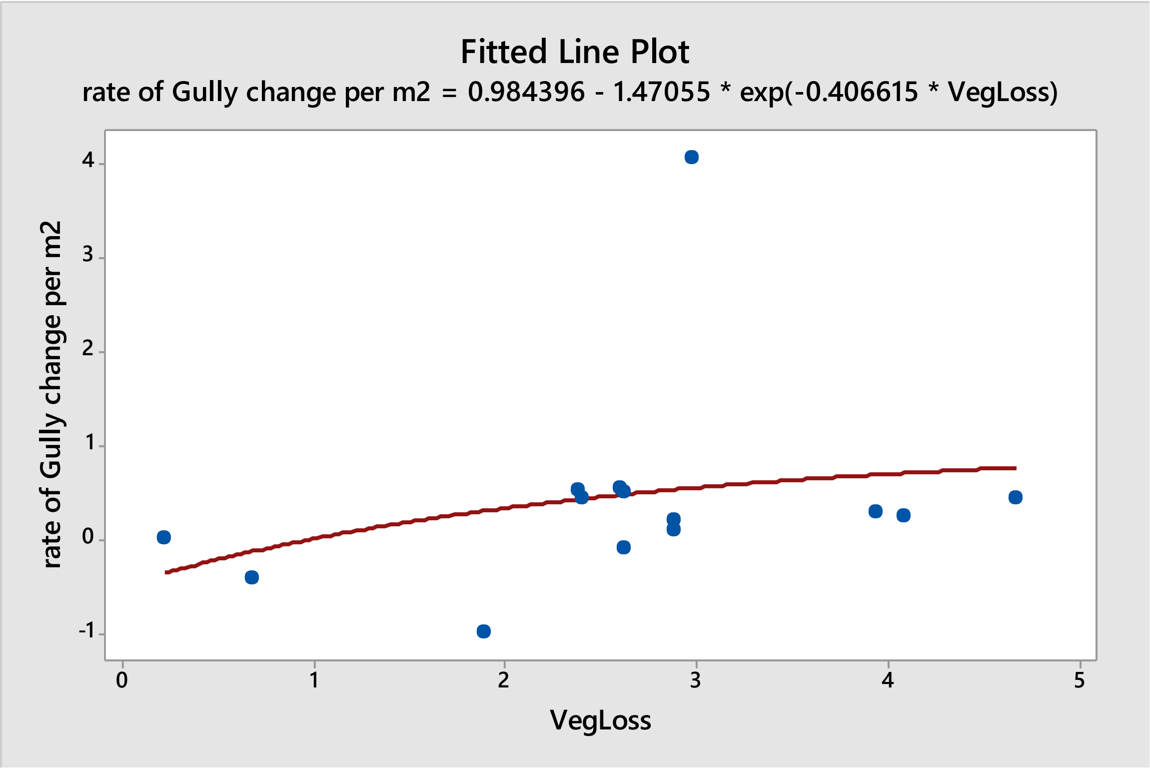


Figure 177: Fitted Line of yearly gully change in metre squared per square metre versus Vegloss: An exponential increase in the yearly gully change in metre squared per square metre is expected as the Vegloss increases.

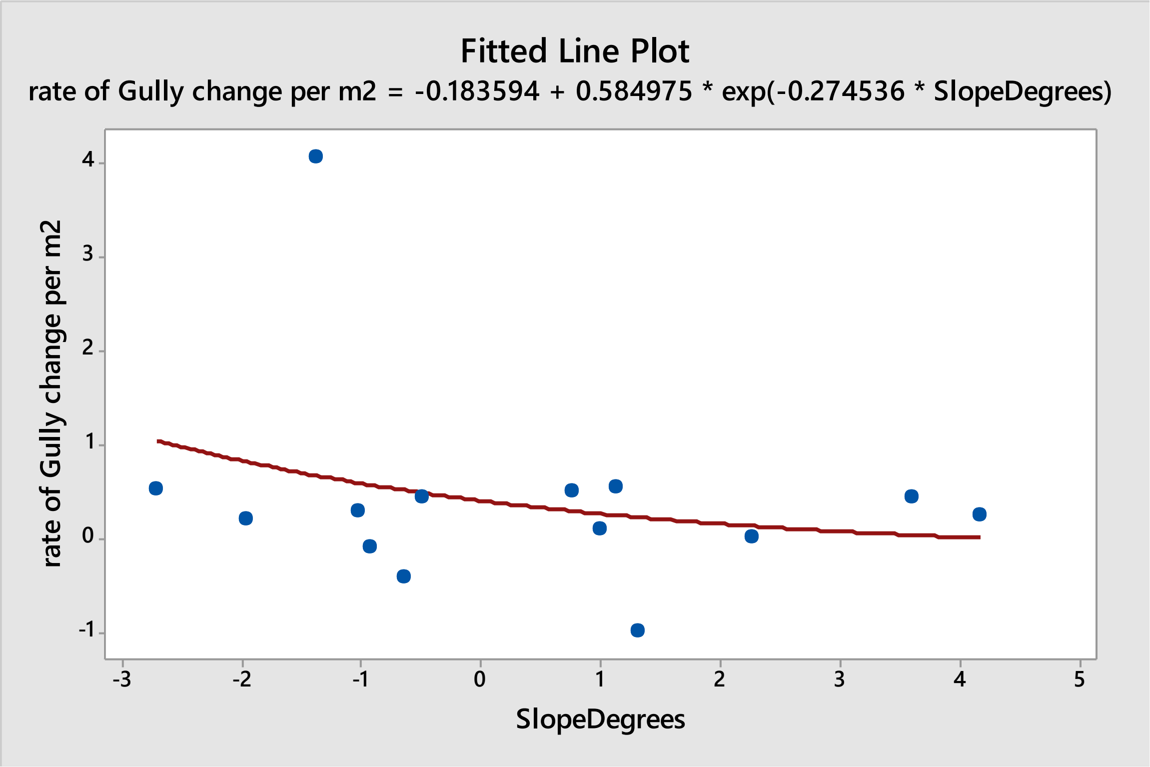


Figure 178: : Fitted Line of yearly gully change in metre squared per square metre versus Slope Degrees. There is an exponential decrease in the yearly gully change in metre squared per square metre as the slope degree increases.

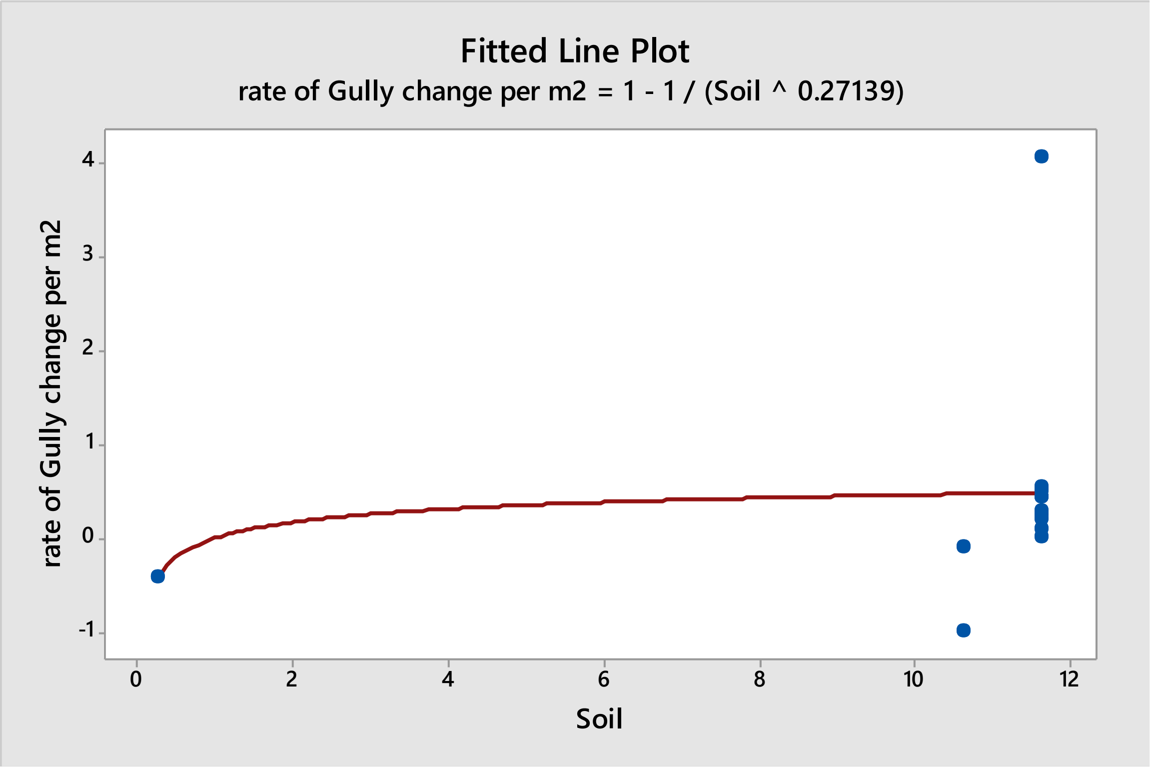


Figure 179: Fitted Line of yearly gully change in metre squared per square metre versus Soil. The analysis show that there is an asymptotic relation (didn’t intersect with the curve) between yearly gully change in metre squared per square metre and the soil.

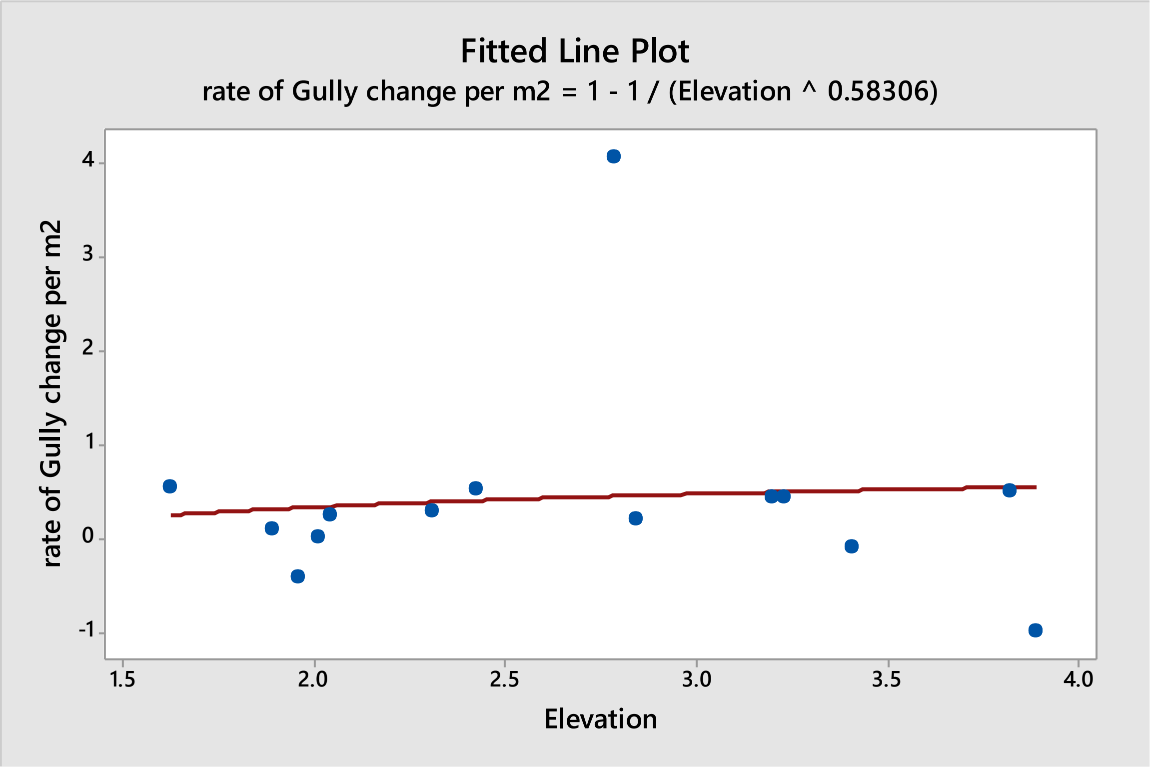


Figure 180: Fitted Line of yearly gully change in metre squared per square metre versus Soil. Fitted Line of yearly gully change in metre squared per square metre versus Elevation. The analysis shows that increase in elevation has no significant effect on the yearly gully change in metre squared per square metre.

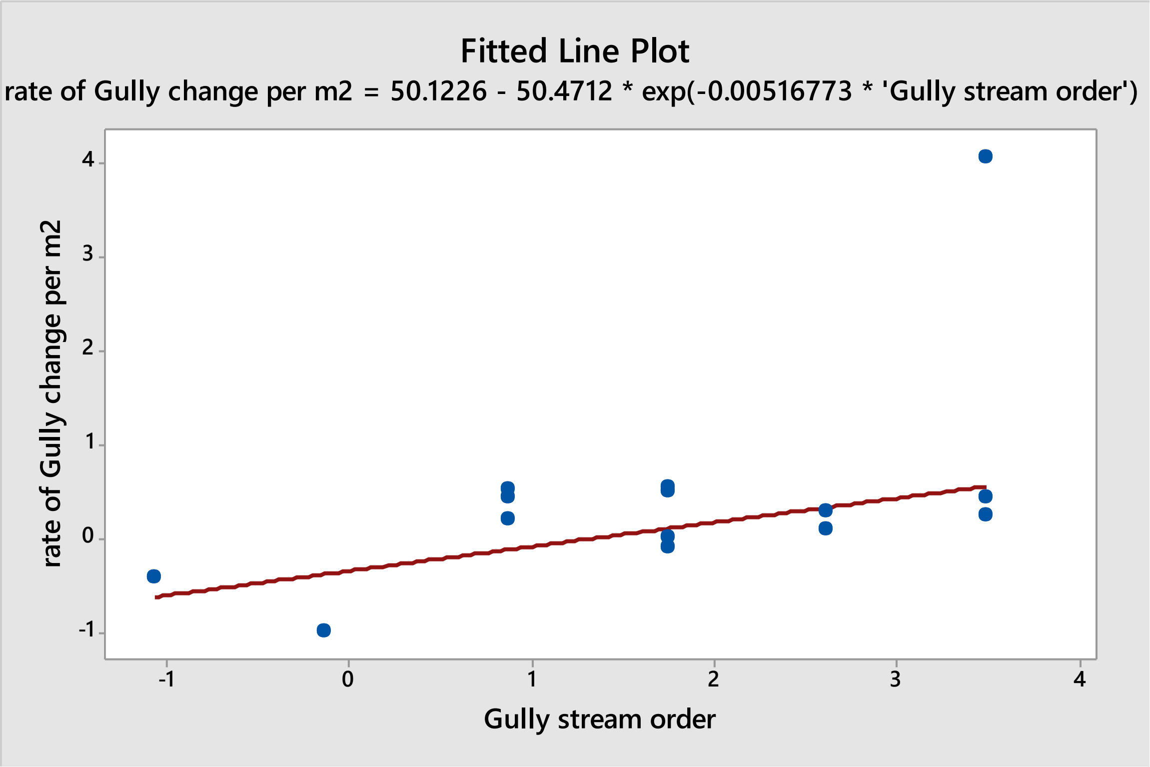


Figure 181: Fitted Line of yearly gully change in metre squared per square metre versus Gully stream order. An exponential increase in the yearly gully change in metre squared per square metre is expected as the gully stream order increases.

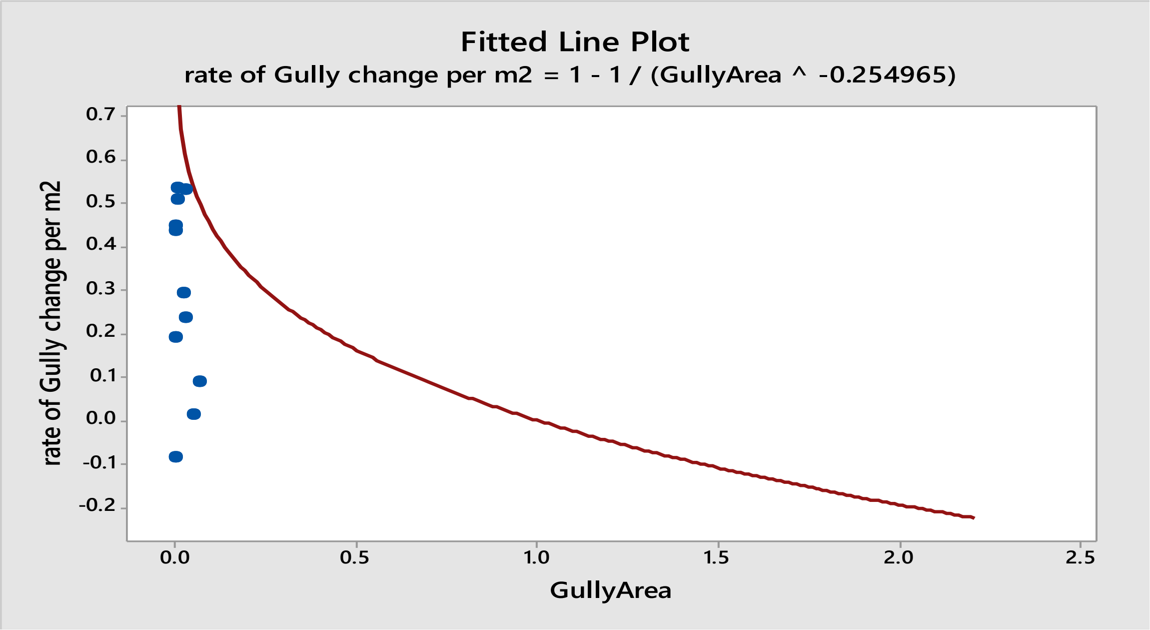


Figure 182: Fitted Line: yearly gully change in metre squared per square metre versus GullyArea. An inverse relationship exists between the yearly gully change in metre squared per square metre and the gully area. The yearly gully change in metre squared per square metre reduces as the gully area increases.

Appendix VII- Nonlinear Regression Analysis for Year 2009/10

independent variables against yearly gully change in metre squared per square metre (dependent variable)

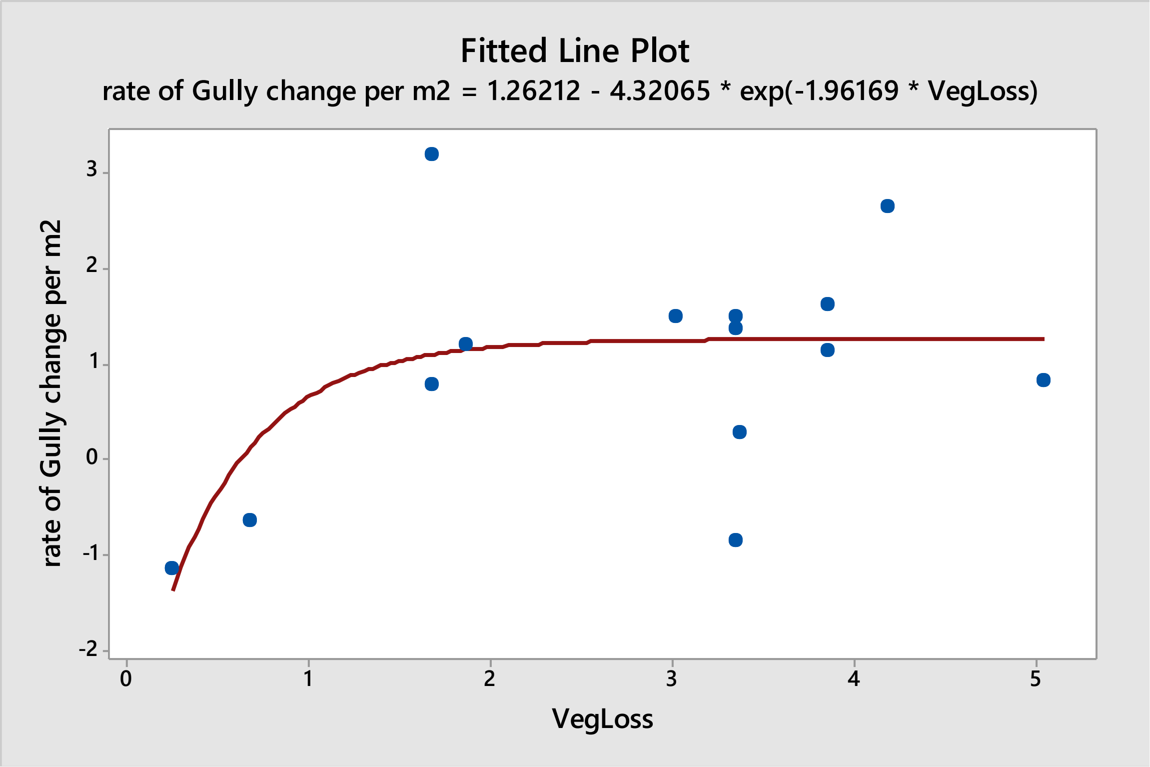


Figure 183: Fitted Line of yearly gully change in metre squared per square metre versus VegLoss.The analysis show that there is a relation between the yearly gully change in metre squared per square metre and the veg loss. As the veg loss increases towards infinity, the yearly gully change in metre squared per square metre also increases.

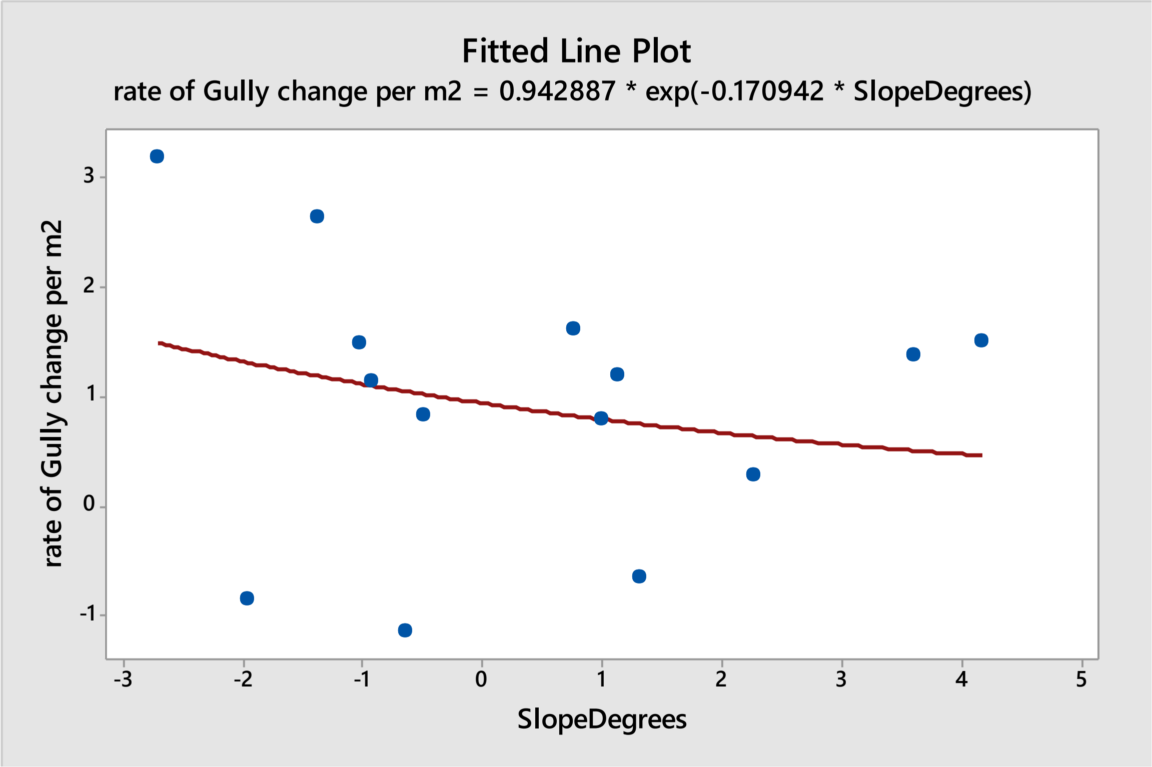


Figure 184: Fitted Line of yearly gully change in metre squared per square metre versus SlopeDegrees.There is an exponential decrease in the yearly gully change in metre squared per square metre as the slope degree increases.

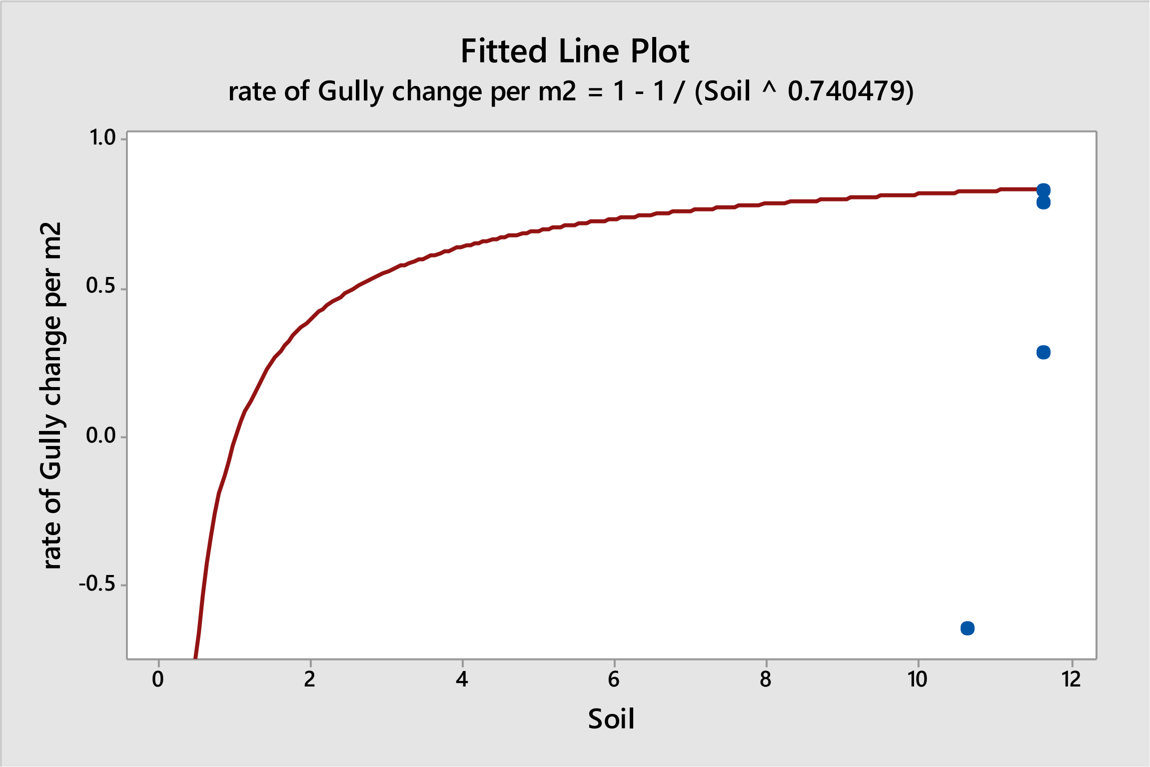


Figure 185: Fitted Line of yearly gully change in metre squared per square metre versus Soil. As the soil value increases towards infinity, the yearly gully change in metre squared per square metre also increases.

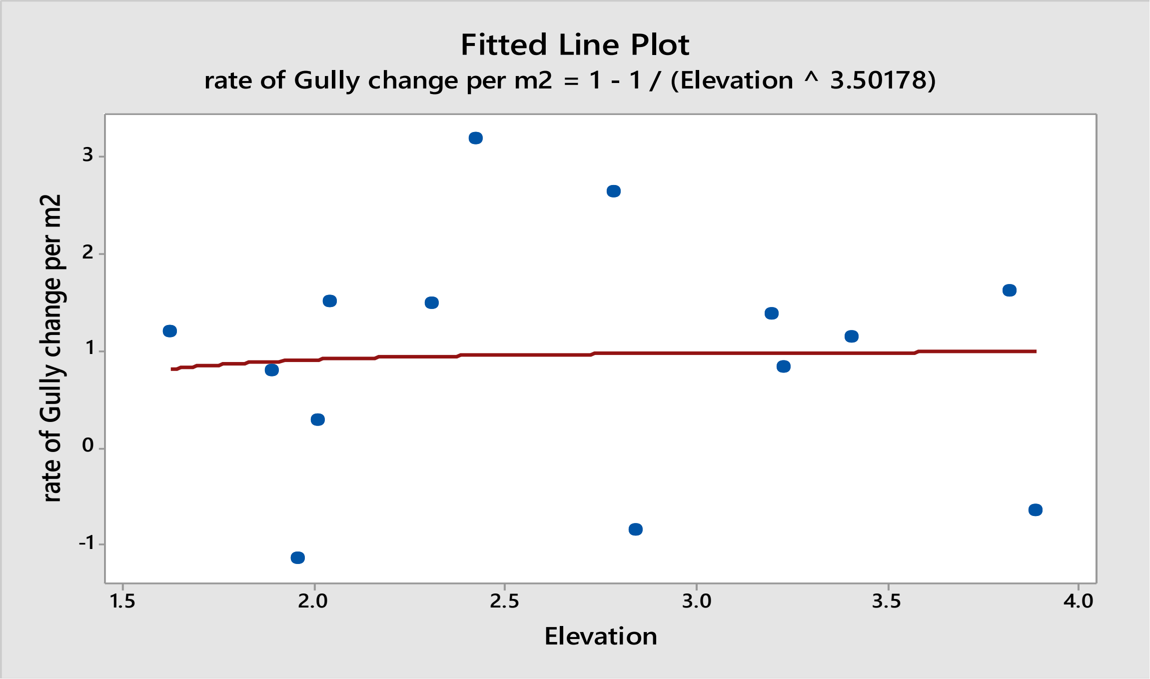


Figure 186: Fitted Line of yearly gully change in metre squared per square metre versus Elevation. The analysis show that increase in elevation has no significant effect on the yearly gully change in metre squared per square metre.

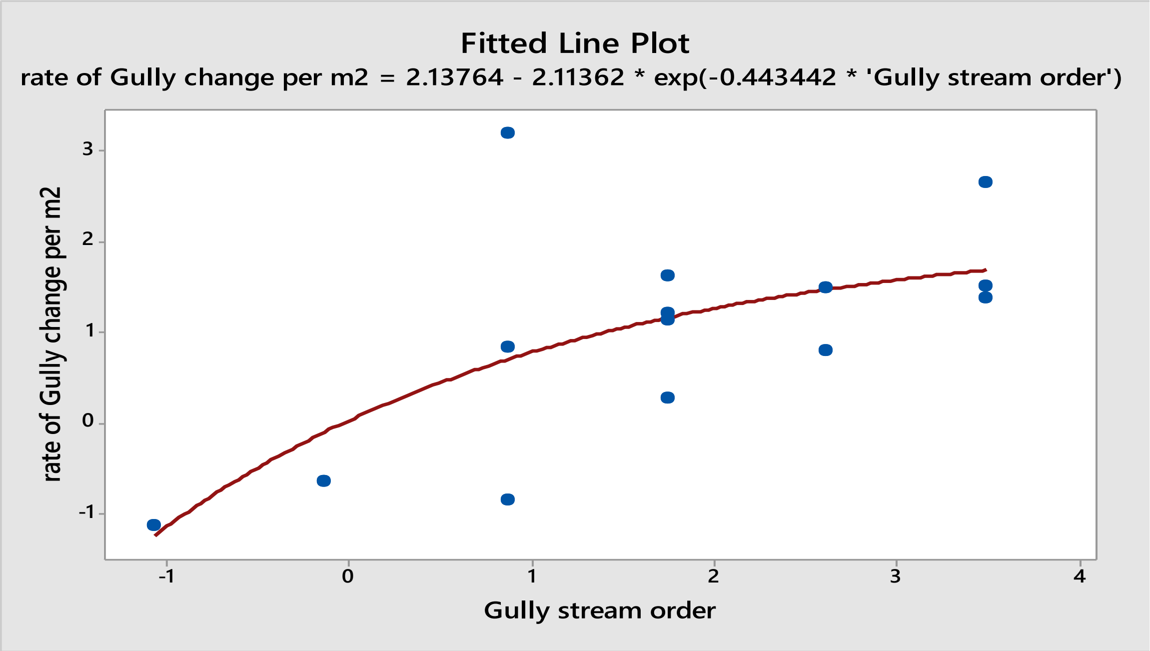


Figure 187: Fitted Line of yearly gully change in metre squared per square metre versus Gully stream order. An exponential increase in the yearly gully change in metre squared per square metre is expected as the gully stream order increases.

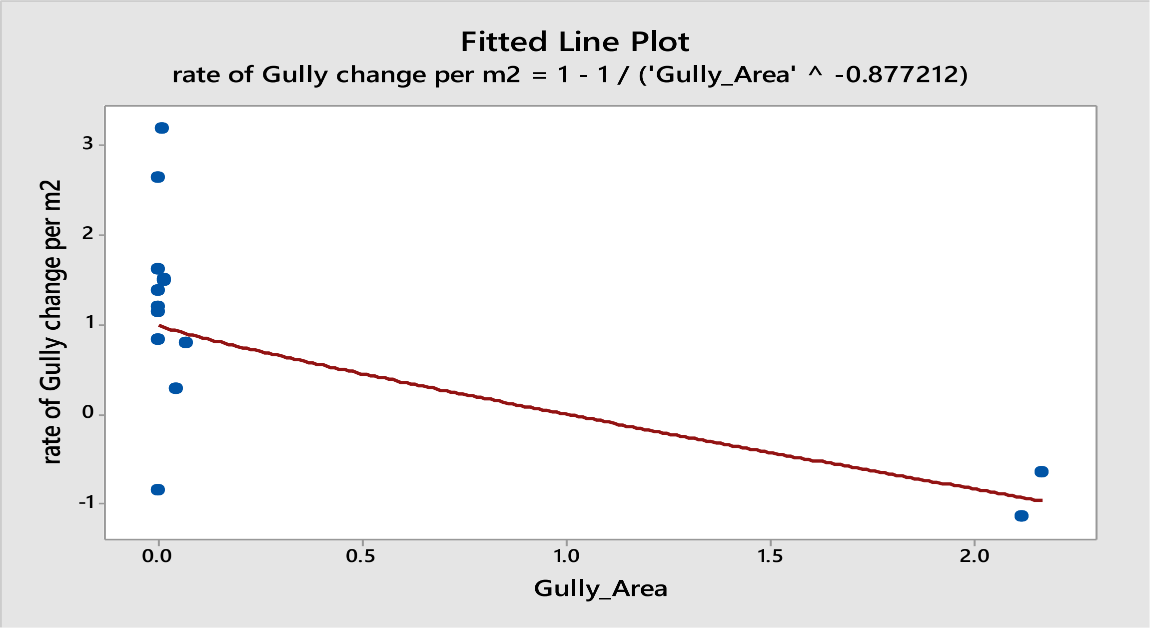


Figure 188: Fitted Line: yearly gully change in metre squared per square metre versus Gully Area. An inverse relationship exists between the yearly gully change in metre squared per. square metre and the gully area. The yearly gully change in metre squared per square metre reduces as the gully area increases.

Appendix VIII- Nonlinear Regression Analysis for Year 2006/07

Independent variables against yearly gully change in metre squared per square metre (dependent variable)

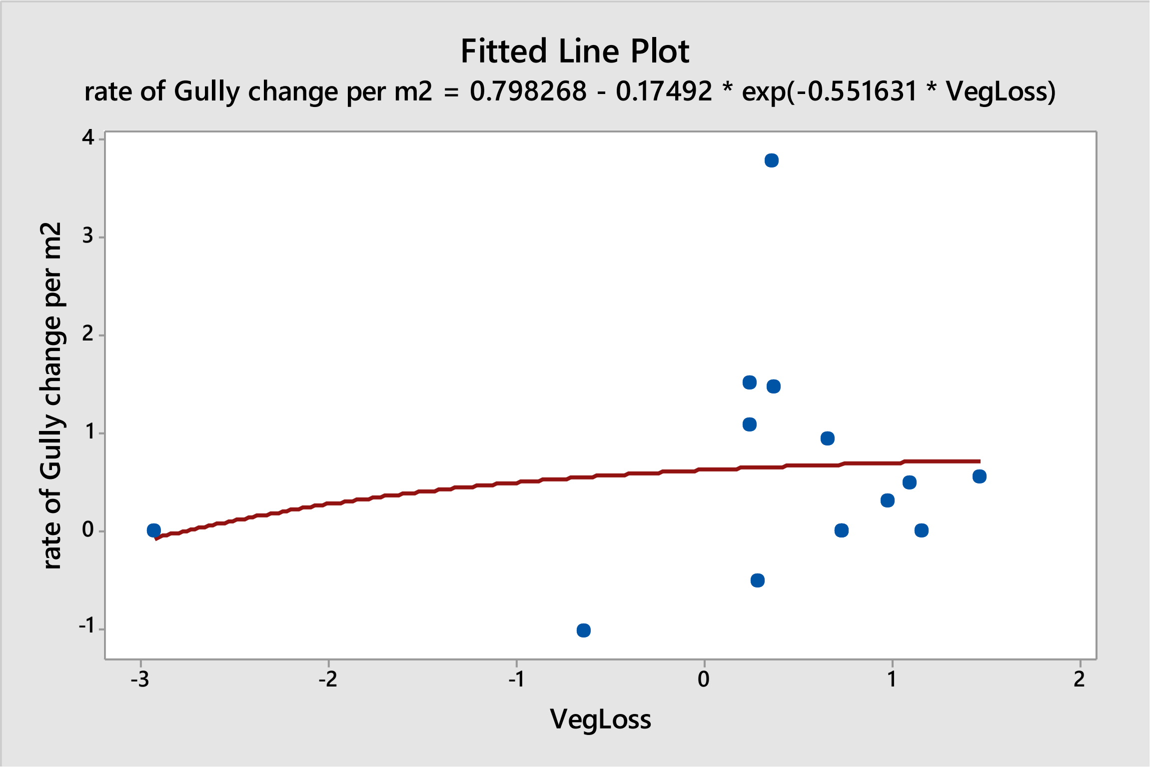


Figure 189: Fitted Line of yearly gully change in metre squared per square metre versus VegLoss.The analysis show that there is an asymptotic relation between the yearly gully change in metre squared per square metre and the veg loss. As the veg loss increases towards infinity, the yearly gully change in metre squared per square metre also increases; as the yearly gully change in metre squared per square metre approaches 0.9421 m^2, it becomes asymptote. This means that any further increase in the veg loss will not bring about a change that is greater than the asymptote value of 0.9421 m^2 in the yearly gully change in metre squared per square metre.

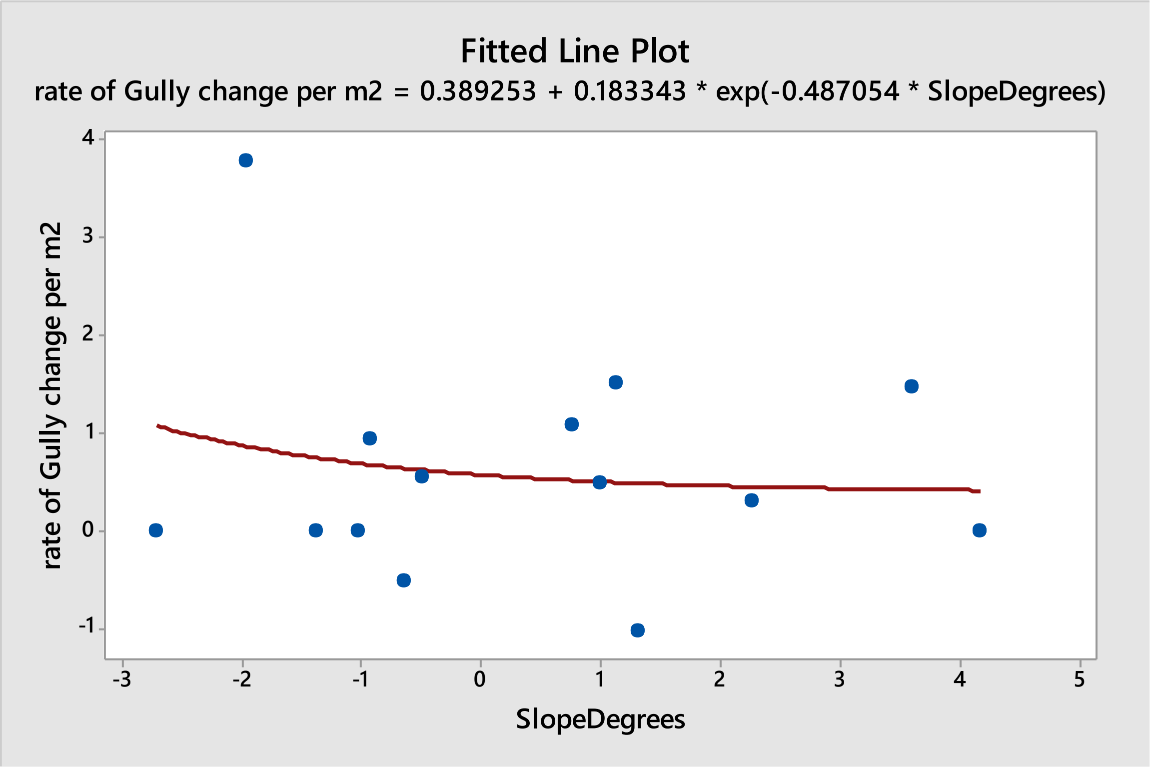


Figure 190: Fitted Line of yearly gully change in metre squared per square metre versus SlopeDegrees. The analysis shows that there is an asymptotic relation between the yearly gully change in metre squared per square metre and the slope degree. As the slope degree increases towards infinity, the yearly gully change in metre squared per square metre decreases; as the yearly gully change in metre squared per square metre approaches 0.490594 m^2, it becomes asymptote. This means that any further increase in the slope degree will not bring about a change that is less than the asymptote value of 0.490594m^2 in yearly gully change in metre squared per square metre.

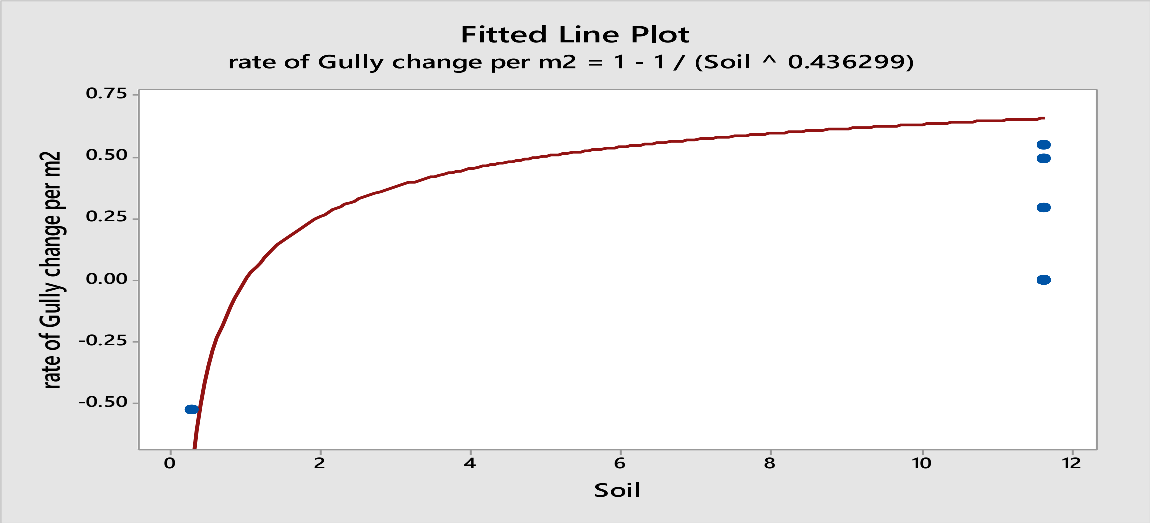


Figure 191: Fitted Line of yearly gully change in metre squared per square metre versus Soil. The analysis show that there is an asymptotic relation between the yearly gully change in metre squared per square metre and the soil.

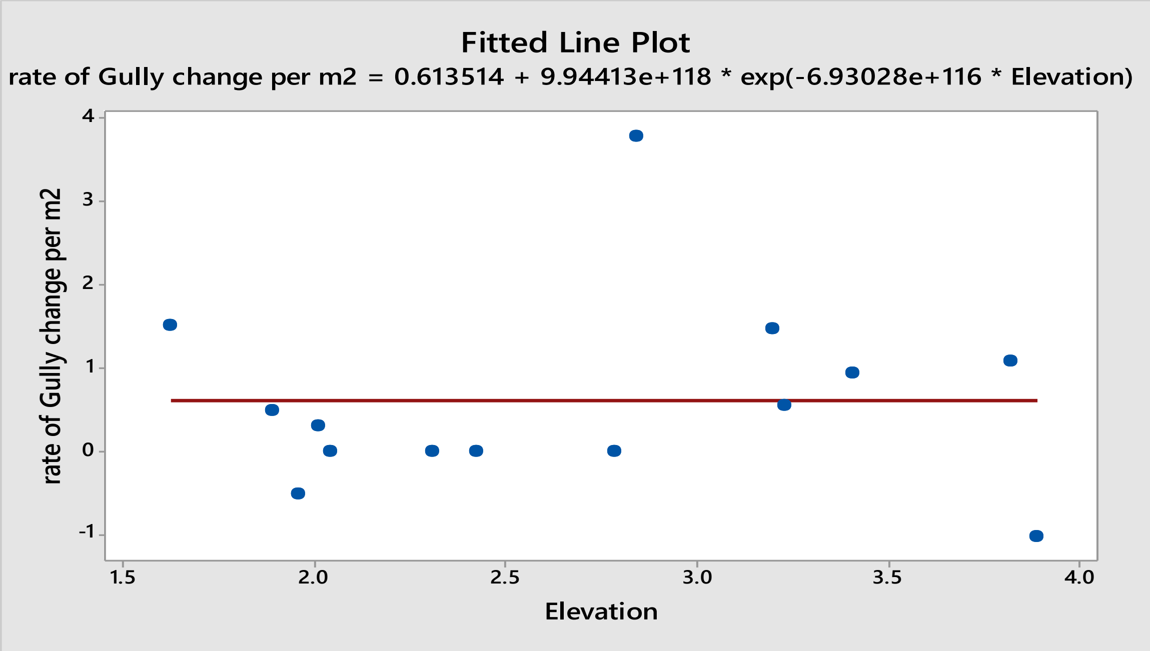


Figure 192: Fitted Line of yearly gully change in metre squared per square metre versus Elevation.The analysis shows that increase in elevation has no significant effect on the yearly gully change in metre squared per square metre.

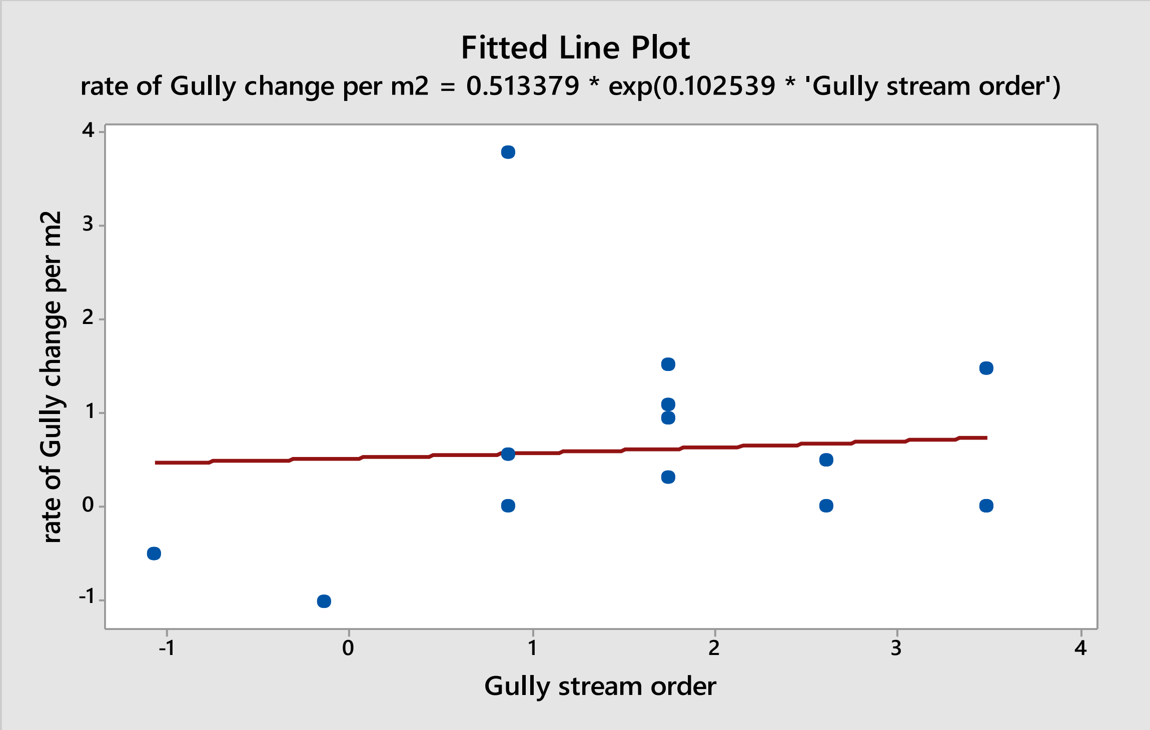


Figure 193: Fitted Line of yearly gully change in metre squared per square metre versus Gully stream order. An exponential increase in the yearly gully change in metre squared per square metre is expected as the gully stream order increases.

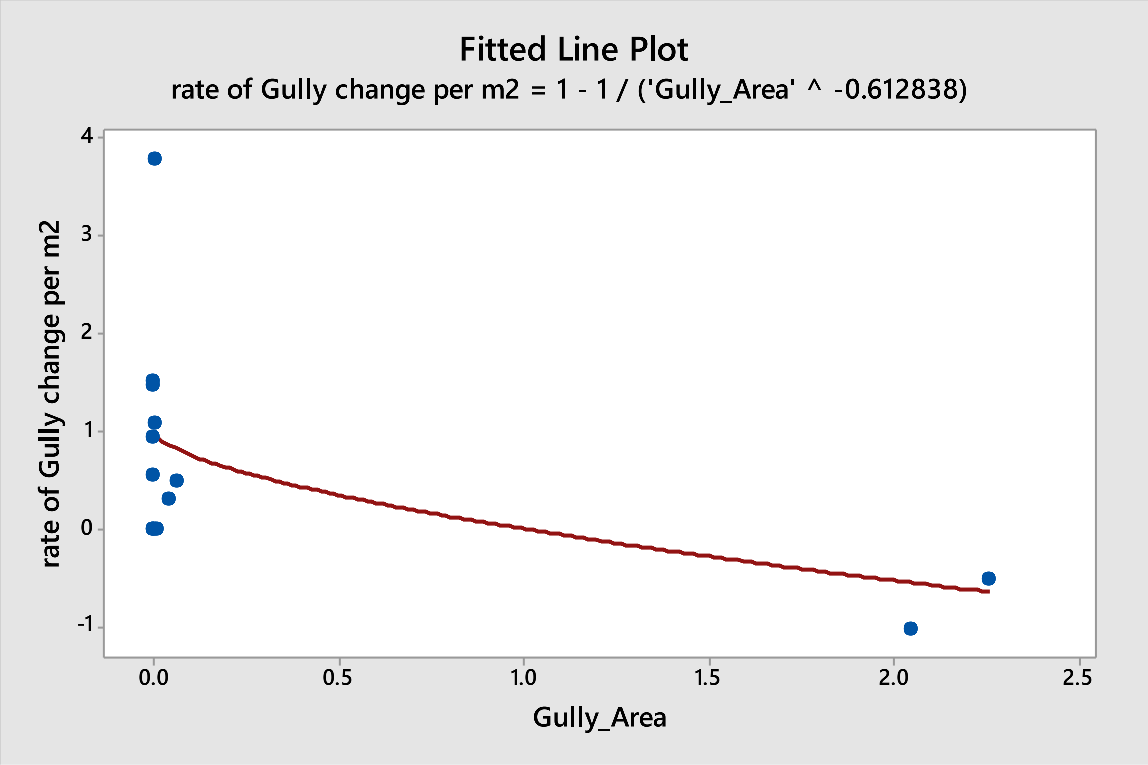


Figure 194: Fitted Line of yearly gully change in metre squared per square metre versus Gully_Area. An inverse relationship exists between the yearly gully change in metre squared per square metre and the gully area. The yearly gully change in metre squared per square metre reduces as the gully area increases.

Appendix IX- t-Test Paired Two Sample for Means of SAR and Landsat Classification

Table 98: t-Test for classification performance of SAR Pixel 2008 against Landsat Pixel 2008 (the t statistic is smaller than the critical value and high Pearson correlation showing no statistical difference between the two datasets).

t-Test: Paired Two Sample for Means		
	Landsat Pixel_2008	*SAR Pixel_2008*
Mean	20	20
Variance	297.5	382.125
Observations	5	5
Pearson Correlation	0.990604	
Hypothesized Mean Difference	0	
df	4	
t Stat	0	
P(T<=t) one-tail	0.5	
t Critical one-tail	2.131847	
P(T<=t) two-tail	1	
t Critical two-tail	2.776445	

Table 99: t-Test for classification performance of SAR OBIA 2008 against Landsat OBIA 2008 (the t statistic is smaller than the critical value and high Pearson correlation showing no statistical difference between the two datasets).

t-Test: Paired Two Sample for Means		
	Landsat OBIA_2008	*SAR OBIA_2008*
Mean	20	20
Variance	374	416.5
Observations	5	5
Pearson Correlation	0.997014404	
Hypothesized Mean Difference	0	
df	4	
t Stat	0	
P(T<=t) one-tail	0.5	

t Critical one-tail	2.131846786	
P(T<=t) two-tail	1	
t Critical two-tail	2.776445105	

Table 100: t-Test for classification performance of SAR Pixel 2009 against Landsat Pixel 2009 (the t statistic is smaller than the critical value and high Pearson correlation showing no statistical difference between the two datasets).

t-Test: Paired Two Sample for Means		
	Landsat Pixel_2009	*SAR Pixel_2009*
Mean	20	20.3
Variance	294.125	383.2
Observations	5	5
Pearson Correlation	0.987613	
Hypothesized Mean Difference	0	
df	4	
t Stat	-0.17802	
P(T<=t) one-tail	0.433681	
t Critical one-tail	2.131847	
P(T<=t) two-tail	0.867361	
t Critical two-tail	2.776445	

Table 101: t-Test for classification performance of SAR OBIA 2009 against Landsat OBIA 2009 (the t statistic is smaller than the critical value and high Pearson correlation showing no statistical difference between the two datasets).

t-Test: Paired Two Sample for Means		
	Landsat OBIA_2009	*SAR OBIA_2009*
Mean	20	20
Variance	366.5	338
Observations	5	5
Pearson Correlation	0.998688	
Hypothesized Mean Difference	0	
df	4	
t Stat	0	
P(T<=t) one-tail	0.5	
t Critical one-tail	2.131847	
P(T<=t) two-tail	1	
t Critical two-tail	2.776445	

Appendix X – Further MLRA of Significant Variables in 2014/15 (slope and gully stream order)

Table 102: depicts the variables that will be used as independent and dependent variables in the analysis.

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Slope, GullyStream[b]	.	Enter

a. Dependent Variable: GullyChange

b. All requested variables entered.

Table 103: Measure of variance of the variables entered in Multiple linear regression

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.544[a]	.296	.168	1.02634382

a. Predictors: (Constant), Slope, GullyStream

Table 104: Anova Table (test using alpha = 0.05)

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	4.869	2	2.434	2.311	.145[b]
	Residual	11.587	11	1.053		
	Total	16.456	13			

a. Dependent Variable: GullyChange

b. Predictors: (Constant), Slope, GullyStream

Table 105: Coefficients of the variables showing significance in Multiple linear regression

Coefficients[a]						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.095	.521		.182	.859
	GullyStream	.581	.282	.707	2.061	.064
	Slope	-.281	.299	-.323	-.940	.367
a. Dependent Variable: GullyChange						

Appendix XI - Atmospheric Correction (USGS)

Landsat Level-1 data can be rescaled to the top of atmosphere (TOA) reflectance and/or radiance using radiometric rescaling coefficients provided in the metadata file (MTL.txt) that is delivered with the Level-1 product. The MTL file also contains the thermal constants needed to convert thermal band data to TOA brightness temperature (BT). Formulas for these conversions are provided below. (USGS 2016)

Conversion to TOA Radiance

Landsat Level-1 data can be converted to TOA spectral radiance using the radiance

rescaling factors

in the MTL file:

$$L_\lambda = M_L Q_{cal} + A_L$$

where:

L_λ = TOA spectral radiance (Watts/(m^2 * srad * μm))

M_L = Band-specific multiplicative rescaling factor from the metadata (RADIANCE_MULT_BAND_x, where x is the band number)

A_L = Band-specific additive rescaling factor from the metadata (RADIANCE_ADD_BAND_x, where x is the band number)

Q_{cal} = Quantized and calibrated standard product pixel values (DN)

Conversion to TOA Reflectance

Reflective band DN's can be converted to TOA reflectance using the rescaling coefficients

in the MTL file:

$$\rho_\lambda' = M_\rho Q_{cal} + A_\rho$$

where:

ρ_λ' = TOA planetary reflectance, without correction for solar angle. Note that $\rho\lambda'$ does not contain a correction for the sun angle.

M_ρ = Band-specific multiplicative rescaling factor from the metadata (REFLECTANCE_MULT_BAND_x, where x is the band number)

A_ρ = Band-specific additive rescaling factor from the metadata (REFLECTANCE_ADD_BAND_x, where x is the band number)

Q_{cal} = Quantized and calibrated standard product pixel values (DN)

TOA reflectance with a correction for the sun angle is then:

$$\rho_\lambda = \frac{\rho_\lambda'}{\cos(\theta_{SZ})} = \frac{\rho_\lambda'}{\sin(\theta_{SE})}$$

where:

ρ_λ = TOA planetary reflectance

θ_{SE} = Local sun elevation angle. The scene center sun elevation angle in degrees is provided in the metadata (SUN_ELEVATION).

θ_{SZ} = Local solar zenith angle; $\theta_{SZ} = 90° - \theta_{SE}$

Conversion to Top of Atmosphere Brightness Temperature

Thermal band data can be converted from spectral radiance to top of atmosphere brightness temperature using the thermal constants in the MTL file:

$$T = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)}$$

where:

T = Top of atmosphere brightness temperature (K)where:

L_λ = TOA spectral radiance (Watts/(m2 * srad * μm))

K_1 = Band-specific thermal conversion constant from the metadata (K1_CONSTANT_BAND_x, where x is the thermal band number)

K_2 = Band-specific thermal conversion constant from the metadata (K2_CONSTANT_BAND_x, where x is the thermal band number)