UNIVERSITY OF NAIROBI

GULLY EROSION AND STABILIZATION IN SEMI-ARID ENVIRONMENT OF WANJOGA RIVER CATCHMENT OF TANA BASIN, EMBU COUNTY, KENYA

BY

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DECLARATION

This thesis is my original work and has not been presented for a degree at any other university.

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DEDICATION

To my husband, Dr Denis Muchangi, and my children Winnie, Alex, and Wayne Muchangi

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LIST OF ABBREVIATIONS AND ACRONYMS

CR:	Consistency Value
DEM:	Digital Elevation Model
ETM:	Enhanced Thematic Mapper
FAO:	Food and Agriculture Organization
GHA	Gullied healing areas
GIS:	Geographic information systems
GNA	Gullied non-healing areas
GoK:	Government of Kenya
GPS:	Global Positioning System
IE	Increased erosion
LU/LC:	Land use/land cover
NDVI:	Normalized Difference Vegetation Index
Q:	Discharge
QS:	Sediment discharge
QD:	Drainage area
RUSLE:	Revised Universal Soil Loss Equation
SRTM:	Shuttle Radar Topographical Mission
UNDP:	United Nations Development Programme
UNEP:	United Nations Environmental Programme
USLE:	Universal Soil Loss Equation
Wi:	Weighted values
WoE:	Weight of Evidence

ABSTRACT

Gullies are prone to occur in semi-arid regions characterized by rainfall variability and increased overland flow, thus affecting thresholds of geomorphic processes and ecological fragility and affecting any landscape restoration required after degradation. Although gully erosion affects less than 5% of the world, most soil loss from gullies generates up to 95% of the global sediment load. As a semi-arid region, gully erosion is the most severe environmental problem in the Wanjoga river catchment of the Tana River basin, Embu County, located about 170 kilometers from Nairobi. The present study examines gully erosion and rehabilitation in a semi-arid environment of Wanjoga river catchment, specifically; (a) evaluating geomorphological factors that initiate and promote progressive development of gully erosion, (b) establishing the relationship between gully morphometry and rate of gully development, c) determine the threshold factors of gully development and (d) to evaluate the suitability of different gully rehabilitation methods used for controlling gully erosion in the semi-arid environment. Data for creating an inventory map of gullied areas, rate of gully development and threshold analysis were obtained by carrying out extensive field surveys and acquiring Landsat images. A series of mapping using Landsat images at 1.5m spot and 15m resolution images were employed to identify the most severely gullied locations. A total of 66 gullied sites in the Wanjoga catchment were mapped. Bivariate statistical analysis to evaluate the influence of conditioning factors on gully development showed a significant positive relationship between gully occurrence and gully conditioning factors with a consistency value at CR =0.097. The positive weighted values on steep slopes > 20° covered by clay lithotypes (Wi=7.53) shows gully erosion occurrence is positively associated with soil lithotype. Weighted Overlay Tool helped categorize gully susceptibility into high (12.73%), moderate (36.32%), and low susceptible zones (46.95%), with steep slopes and soil lithotype playing an imperative role in gully susceptibility at 43% and 25%, respectively. Kappa statistic for the gully susceptibility map confirmed accuracy at approximately 0.42, representing a moderate level of agreement with a positive value of 4% and a false-negative value of 7%. The results suggest the relationship between slope and drainage area in Wanjoga River catchment is $S=0.0384^{-0.397}$, with R^2 =0.0321 for gully cut area in the upper segment, $S=0.174A^{-0.032}$, with R^2 =0.498 for gully cut area in mid-segment and $S=0.23A^{-0.020}$,

with R^2=0.088, for gully cut area for the lower segment, representing approximate regions most susceptible for gully initiation. The negative exponent *'b'* values (‾0.397 at the upper segment, ‾0.032 at mid-segment and ‾0.020 lower segment) revealed a relatively weak regression slope, suggesting a dominance of overland flow erosion. Field survey data was tested for the degree of association between variables using ANOVA (Analysis of Variance), Spearman's rank correlation coefficient and paired t-test to determine the relationship between the variables. For the effectiveness of gully rehabilitation, the t-test reveals a p-value = 0.000, which is less than 0.05, showing that structures for gully rehabilitation used by farmers have not healed a significant number of gullies across all segment regions. Thus, the study suggested; that the reduction of overland flow discharge, vegetative measures, designing structures specified for knick-points and controlling gully head cut erosion are essential procedures in protecting gully erosion in a semi-arid region of varied soil lithotypes. The accuracy of predicting gullied areas and areas more susceptible to gully erosion using the bivariate statistical methodology provides the basis for determining the threshold for gully development which dictates more frequent and elaborate methods of designing and siting conservation structures which provide clues to improve conservation and rehabilitation of semi-arid environments of similar sensitivity to overland flow.

CHAPTER ONE: INTRODUCTION

1.1 Background of the study

Gully erosion is a dominant sediment source in most catchment areas of the world (Poesen *et al.,* 2003). In quantitative terms, global soil loss is estimated at 16.75 t/ha/yr or about1*mm* of soil depth of topsoil each year (Costa *et al.*, 2006). In many gully's' prone areas, the extent of land affected by gully erosion, defined as the extreme form of accelerated soil erosion affecting large portions of land (Singh *et al.*, 2015; Pathak *et al.*, 2006), is increasing (Kirkby and Brecken, 2009). Gullies are the advanced stages of rills where surface channels are eroded to the point that they cannot be smoothened by normal tillage operations (Poesen *et al.*, 2009).

The initiation stage of gully erosion is often the most critical. After gullies have been initiated and network systems are formed, the erosion process is so fast that they tend to grow larger continually and are difficult and costly to eradicate (Kirkby and Brecken, 2009). Initiated gullies are considered one of the most severe environmental problems since gully erosion can modify the catchment dynamics, escalating environmental and geomorphological processes and land-use sustainability. In the long-term, the threat of gully erosion leads to the initiation and expansion of semi-arid regions; a threat promoted by soil deterioration, extensive soil loses and changes in the landscape (steeper slopes, more rugged slopes) (Valentin *et al.,* 2005; Poesen *et al.*, 1998; Arabameri *et al.,* 2019). In the short term, gullies have detrimental effects; can result in catastrophic flooding and pollution, triggers landslides, and damaged infrastructures such as buildings, roads and bridges, minimizing agricultural activities (Vandekerckhove *et al.,* 2000; Frankl *et al.,* 2016)

The threat of gully formation and progression is related to changes in land cover, often induced by the seasonality of rainfall and inappropriate land-use practices and/or geological factors inherent to gully channels such as slope and soil characteristics and gully typology (Lonergan *et al.,* 2013; Abdulfatai *et al*., 2014; Valentin *et al*., 2005).

Alteration of these factors coupled with climate change results in ecological fragility in semi-arid regions, weakening the land's ability to revert to its former condition after degradation. The alteration ability of gullies to landscape enhance drainage, which escalates aridification processes in semi-arid environments with marked seasonal rainfall contrasts, shallow soils and low vegetation density (Canovas *et al.*, 2017). Consequently, many river catchments cannot be appropriately conserved without determining these local geomorphic factors increasing susceptibility and triggering gully development.

Globally, Asia is the continent most affected by gully erosion, with 35 million hectares of soil removed each year, then Africa, America and Europe (Conoscenti *et al.*, 2014; Panagos *et al.*, 2015). Iran, for instance, reported having the most initiation of gullies globally, having 75.8% of the land exposed to gully erosion due to the geographic setting. The land is mainly arid to semi-arid areas experiencing alternate extended dry seasons followed by short-wet seasons, promoting excessive runoff and limited infiltration processes. (Arabameri *et al.*, 2018). In Poland, France and Spain, gully erosion is viewed to be promoted by several geomorphic processes such as anthropogenic activities including land use/land cover changes, expansion of infrastructure and farming mechanization (Costa and Bacellar, 2006; Kartz *et al.*, 2013; Zhao and Hou, 2019; Ghosh and Guchhaitsik, 2016; Dobek *et al.*, 2011). Thus, gullies are viewed as morphological evidence of past erosional periods, reflecting impacts of land use/land cover changes and rainfall events in a river catchment.

In Africa and East African regions, gully erosion rates are associated with increased overland flow resulting from intensified degradation of vegetation cover as a consequence of overgrazing, intensification of agriculture and poor farming practice related to encroachment into semi-arid land (Nyssen *et al.*, 2002; Abdulfatai *et al.*, 2014; Sirvio and Reberiro-Hargrave, 2004). Although gully development has been viewed as resulting from human interferences, other researchers have shown the occurrence of gully development processes without human influence (Valentin *et al.*, 2005). A combination of intrinsic (gully slope, morphological characteristics) and extrinsic factors (land cover, rainfall variability, soil characteristics) are often overlooked as contributing factors in gully formation.

To avert the rapid initiation, limit the growth of gullies and minimize further damage to the landscape, it is vital to understand the geomorphic factors which trigger susceptibility to gullying. Further, it's crucial to understand morphological factors that cause the further development of gullies for proper conservation and restoration of river catchments. Improper diagnosis of gully erosion threat factors has resulted in ineffective mitigation and rehabilitation (Dong *et al.*, 2011; Arabameri *et al.*, 2019). The study shall suggest appropriate tool to predict critical conditions and locations for gully initiation.

1.2 Statement of the Problem

Gully initiation, growth and damage are imperceptible. While gullies occupy less than 5% of the semi-arid catchment area, most soil loss result from gullies, generating up to 95% of total sediment mass at the catchment scale area (Poesen, 2011). Although studies on soil conservation have been conducted over several decades (Wilson *et al.*,2007), the extent of land affected by gully erosion has increased (Canovas *et al.*, 2017). It is, therefore, necessary to quantitatively and qualitatively assess gully erosion and gully systems in a semi-arid environment such as the Wanjoga River catchment, where the intensity and persistence of the problem are evident. The study results are essential for effective rehabilitation and consequent prevention of gully initiation; both upstream and downstream regions of a gully system must be considered since they contribute to the gully volume. Conservation structure in use for gully control depends upon proper delineation of the drainage area; its size and characteristics, as well as rainfall variability and seasonality, to be effective.

The intensity and effects of geomorphic factors on gully development are poorly understood, and little is known about gully morphological eroding state (intrinsic characteristics) and their impact on gully initiation and progression. The threshold factors controlled by rainfall seasonality and variability likely cause initiation and further growth of gullies. Further, human pressure on land, which increases unsustainable human practices on gully susceptible areas, the impact of climate change and vegetation alteration are likely to accelerate gully growth, thus increasing soil degradation and poverty of subsistence farmers.

Threshold factors of gully initiation and growth, when assessed quantitatively in relation to geomorphic factors of soil characteristics and gully morphology, human factors are resulting in changes in land cover/land use and climatic factors such as rainfall, as reflected in climate change scenarios, appropriate solution for conservation and restoration of degraded river catchments and arresting water scarcity, poverty and food insecurity in sustainable development targets. An understanding of geomorphic factors which trigger gullying threshold factors has been evaluated, for instance, in Northern Ethiopia (Frankl *et al.*, 2012) and West Bengal, India (Ghosh and Guchhait, 2016) with excellent results.

But the information generated from these previous studies cannot be generalized since overland flow caused by rainfall is susceptible to small changes in factors such as differences in slope, soil type and land cover leading to variation in gully development across landscape units.

Since gully erosion is a common problem in the semi-arid region of the Wanjoga river catchment, it is essential to use methods appropriate for predicting gullying with accuracy. Identifying critical conditions and locations for gully initiation and areas prone to gullying can lead to applying appropriate gully rehabilitation methods, avoiding gully development and progression, and promoting sustainable development.

1.3 Study Questions

The key questions that the present research addressed itself included:

1. To what extent do intrinsic and extrinsic geomorphic factors promote gully initiation and progression in the semi-arid environment of Wanjoga River in Tana Basin?
2. In what way do morphological characteristics of a gully influence the rate of gully development in the semi-arid environment?
3. To what extent does threshold condition of slope and drainage area determine gully development in the semi-arid environment?
4. To what extent have gully stabilization methods succeeded in controlling gully development in the semi-arid environment?

1.4 Objectives of the study

The study's overall objective is to evaluate intrinsic and extrinsic geomorphic factors that influence gully development and stabilization in a semi-arid environment with specific reference to the Wanjoga river catchment of Tana Basin.

The specific objectives of the study were;

1. To evaluate geomorphological factors that initiate and promote progressive development of gully erosion in the semi-arid environment of Wanjoga River catchment in Tana Basin.

2. To establish the relationship between gully morphology and rate of gully development in the semi-arid environment of Wanjoga River catchment in Tana Basin.
3. To determine the threshold of gully development based on geomorphological, human factors and rainfall characteristics in the semi-arid environment.
4. To evaluate the different gully stabilization methods used for controlling gully erosion in a semi-arid environment.

1.5 Study Hypothesis

Ho Geomorphological factors (rainfall variability, soil characteristic, slope characteristics, land cover) do not affect gully initiation and progression in the semi-arid environment of Wanjoga River catchment in Tana River Basin.

Ho Gully's morphological characteristics do not influence the rate of gully development in a semi-arid environment.

Ho Critical conditions of slope and drainage area do not influence gully development in Wanjoga River catchment in Tana River Basin.

Ho Gully stabilization methods installed have not successfully controlled gully development in the semi-arid environment.

1.6 Significance of the Study

River Tana Basin is an important water catchment in Kenya with four major hydroelectric power generation dams. However, the dams are faced with the threat of siltation and sedimentation brought about by gully erosion in the upper Tana catchments (Ongwenyi *et al.*, 1993; Hunink *et al.*, 2013), such as the Wanjoga river catchment. Further increased soil loss has led to the loss of agriculture land, a scenario significantly impacting on water scarcity, poverty and food insecurity in sustainable development targets. Therefore, it was necessary to establish local factors that increase susceptibility to gully development; once isolated, gully rehabilitation and control methods were proposed.

The study helped diagnose and understand the river catchment and recommend appropriate preventive measures to the risks of formation of new gullies or slow/reverse channel growth. Knowledge of gully development guides decision-making at local and national levels. It may further be used in devising appropriate by-laws, plans and policies governing land use. Accurate prediction of sections more susceptible to gully erosion and establishing slope–area threshold relation for gully erosion represents a valuable tool for planning and monitoring semi-arid regions more sensitive to concentrated overland flow for targeted conservation strategies. The findings can be generalized to other areas with similar; soil type, slope characteristics and rainfall characteristics; however, caution must be taken in wholesome generalization since semi-arid areas have unique features.

1.7 Scope and Limitations of the study

The scope of the study was confined to gully systems within a semi-arid environment of the Wanjoga river catchment. The study excludes the river Ena catchment since it extends beyond the semi-arid region focused on the study. The study focused on medium and large gullies across the three-segment regions, with medium-sized gullies ranging from 0.5 – 1m and a large gully >1m in width. Other forms of soil erosion, such as sheet and rill, were excluded from the study. Therefore, while the findings may be generalized to all forms of soil erosion in different climatic regions, this should be treated with caution since gully channels within a semi-arid environment may possess characteristics different from gullies in other settings.

The sparse nature and rugged terrain of the semi-arid environment make the area not easily accessible physically for study. For such regions, drone cameras and satellite images were used. Skeptical respondents not willing to participate in the study were assured that the study might be used in policy formulation, which may be beneficial in rehabilitating degraded areas.

1.8 Operational definitions

Active gullies: Gully channels that are eroding; erosion is retreating upslope in the landscape at the gully head position and lateral extension at the banks.

Concentrate flow: Accumulation of runoff into a well-defined channel.

Drainage area: Refers to the area above a gully that contributes to a gully system.

Erosion: It's the loosening and transportation of soil by water, wind and gravity grains over the earth's surface.

Erodibility: Decrease resistance capability of soil shear strength (relating to soil characteristics; content of organic matter, soil permeability, soil aggregate), which heightens the susceptibility of soil to be eroded (Poesen *et al.*, 2003)

Erosivity: It's the power of a storm (rainfall intensity and energy) that increases runoff power and decrease soil shear strength, subsequently increasing gully erosion (Poesen, 2014)

Extrinsic factors: These are factors surrounding a gully that affect gully development (land cover and storm characteristics) (Phillips, J. 2010).

Excessive geomorphic processes: Sections within a gully channel with elaborate slumping, undercutting and mass failure on gully head and banks, and increased scouring on the gully bed

Geomorphological factors: A combination of intrinsic (gully head slope and soil characteristics) and extrinsic factors (land cover and rainfall variability) contribute to gully initiation and expansion.

Geomorphic processes: Processes that act on gully channel banks, bed and head (slumping, failures and undercutting), which results in its lengthening and extension (Canovas *et al.*, 2017).

Gully: Is a gaping deep channel on the surface, cut by flowing water without constant flow (Bull and Kirkby, (1997).

Gully sediment discharge: Is the volume of sediment load eroded in a gully channel.

Gully erosion: This is the loosening of soil particles by concentrated overland or/and sub-surface flow leading to the formation of incised gaping channels that may grow into gullies deeper than 30 cm over a short time.

Gully growth: Is an increase in length (headward extension), width (lateral extension), and depth of a gully cross-section.

Gully head: Is the uppermost limit of a gully, in the form of a distinct vertical or undercut scarp face.

Gully development: Is the process of gully initiation, deepening, lengthening and widening over time.

Gully prevention: Methods used to prevent initiation, incision and widening of gullies.

Gully morphology: the shape of the gully channel created by geomorphic processes (U, V and T shapes).

Gully morphometry: Are the dimensions of gully landforms created on the earth's surface (length, depth, width)

Gully rehabilitation: Conservation structures installed across gully channels aimed at preventing increased soil loss by reducing further lengthening, widening and deepening of a gully channel.

Gully bank erosion: Is the action of wearing out of gully channel banks by flowing water and load in peak discharge time.

Gully thalweg: It is the deepest channel (likely having the strongest current) of a gully that marks the direction of the natural flow of a watercourse, increasing sediment evacuation along a gully.

In-active: Gully channel that has ceased to be actively eroding its head, banks and bed.

Intrinsic factors: Term used in geomorphology representing characteristics inherent to gully channels such as slope, soil characteristics and gully morphology affecting the development process of a gully.

Landform: It is a recognizable landmark on the surface of the earth, having a distinct shape and produced by natural or artificial causes (Bates and Jackson, 1987).

Overland flow: Flowing water over the surface of the earth either as diffuse sheet flow (mixed laminar flow) or channeled flow (turbulent flow) in gullies

Rainfall variability: The spatial differences in mean rainfall amounts and pattern of rain over a river basin

Semi-arid environment: This is a region of limited vegetation cover influenced by rainfall variability and extreme rainfall events, which generate increased overland flow and exacerbate the geomorphic sensitivity of an area resulting in ecological vulnerability, which decreases the land's ability to return to its original condition after degradation (FAO, 2015).

Threshold: Thresholds is a concept in geomorphology to describe a situation when external energy source or variables such as land use and rainfall characteristics remain relatively constant, or internal variable within the system cause a progressive adjustment in the system, rendering it unstable, and failure occurs (Schumm, 1979)

Threshold phenomenon: Channel initiation by hydro-geomorphic processes related to the gully contributing area (A) and gully head slope (S) (Torri and Poesen, 2014)

Threshold conditions/limits: include rainfall, topography, lithology, land cover/land use, responsible for gully initiation in different localities (Valentin et al., 2005)

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Literature on gully erosion in semi-arid environments was used as a threshold, influenced by geomorphic factors which relate at a local scale to increase overland flow. Gully rehabilitation and conservation methods were examined since they affect drainage area, critical slope and overland flow. Models and theories which inform the study were examined, while a conceptual framework was designed to show the possible relationship between variables in the study.

2.2 Gully erosion conditioning factors in a semi-arid environment

A gully is a steep-sided incised culvert on the surface cut by running water and often eroded to a point where normal tillage operations cannot smooth it (Bull and Kirkby, (1997; Poesen *et al.,* 2009). Gully development is attributed to an initial incision by flowing water along a narrow channel that occurs in the drainage area due to seasonal rainfall (Kartz *et al.*, 2013). After initiation, gullies develop further due to geomorphic factors both inherent to the gully channels and those influenced by rainfall characteristics (Li *et al.,* 2005; Abdulfatai *et al.,* 2014; Marden *et al.*, 2008). Depending on the prevailing conditions of the soil in a semi-arid area, rain drops course disintegrate the soil particles and surface compaction, reducing soil infiltration capacity and creating necessary conditions for overland surface flow (Costa *et al.*, 2006)

The range of mean rainfall in semi-arid regions (Rundel *et al.*, (2007) ranges from 500–750 mm per annum, enabling savanna vegetation to be predominant (UNEP, 1992; Lohmann, 2012). However, mean average values have little meaning since rainfall in the semi-arid environment is characterized by extreme rainfall events between years, months and days, which trigger fast flows of debris along slopes and channels, damaging natural and anthropogenic structures (Costa *et al.,* 2006; Nyssen *et al*., 2005) The spatial and temporal rainfall variability (differences in mean rainfall amounts and pattern over a river basin) in semi-arid regions determines vegetation cover, equally overland flow affecting geomorphic factors and generating a gully system (Camarasa-Belmonte and Soriano, 2014; Istanbulluoglu *et al.,* 2003). Extrinsic geomorphic factors include; rainfall characteristics, and land use/land cover change, while intrinsic factors are; soil characteristics, slope characteristics and gully type. The present study investigates the intensity of geomorphic factors on gully development in a semi-arid environment.

2. 2.1 Rainfall characteristics

Rainfall in semi-arid regions is characterized by long dry periods that debilitate vegetation cover, followed by intensive rain over a short period resulting in high susceptibility to gully erosion (Kisaka *et al.*, 2014). Rainfall variability (spatial differences in mean rainfall amounts) influences soil erodibility, and landcover brought about by modification of the morphological setting created by climate change. The aptitude effect of climate change on gully erosion processes can be attributed to shifts in average monthly and annual rainfall amount, rainfall intensity and temporal distribution (Angileri, 2012). Uneven rainfall distribution across seasons affects the hydraulic flow, soil resistance to erosion and soil moisture content (Arabamei *et al.*, 2018). Deficit of moisture in the soil; drying and wetting is a fundamental factor in forming cracks in soils with high clay and silt content, eventually developing rills and gullies (Arabameri et al., 2018).

The principal factor that increases erosivity is the frequent occurrence of extended dry periods followed by rainfall bursts causing high soil vulnerability (Angileri, 2012). During dry seasons with excessive soil drying and vegetation removal, the first sudden rainfall concentrates the runoff on cracks (formed when soils with high clay content and silt dry and contract), causing concentrated overland flow. Intensive rainfall after a prolonged dry season increases the strength of the overland flow, which brings about concentrated flow dominating surface flow (Bacellar, 2000). The concentrated flow produces rills in any topography leading to the continuous extension of the drainage network and, if not conserved, becomes a permanent feature of the drainage network (Smith and Bretheton, 1972). Studies by Arabameri *et al*. (2018) and Angileri (2012) reveal the amount of soil moisture changes brought about by prolonged dry season followed by heavy rainfall bursts is the main parameter in creating high soil vulnerability, ultimately developing rills and gullies.

Initial gully erosion is determined by an interruption of a slope, which determines the size and amounts of materials transported (Vandekerckhove *et al.*, 2000). Duration of rainfall controls the transport of materials of different sizes selectively for a distance, depending on grain diameter (Wilson *et al.*, 2007; Kirkby, 1992). The flowing water and sediment load scour the channel bed and gully channel banks, producing more materials by lateral widening and deepening of gullies (Vandekerckhove *et al.,* 2000; Kumar *et al.,* 2013). Angileri (2012) reveals the effectiveness of flowing water in scouring gully channel beds is determined by the initial precipitation amount. Also, Sirvio and Rebeiro- Hargrave (2004) and Marden *et al*. (2008) conclude that the rate of mass failures on gully channel banks is generally high during storms and is the primary process by which many gullies increase laterally. Wilson *et al*. (2007) conclude gully progression is dependent on local storm producing overland flow leading to active gullies. Also, Costa *et al.* (2006) revealed that water carries large amounts of sediments in an eroded catchment, especially in rainy months eroded from upstream. Many field observations of previous studies concluded that concentrated overland flow during a storm is adequate at the initial stages of gully development. However, concentrate overland flow amount is not uniformly delivered to all sites for any given rainfall event due to differences in land cover/land use, gradient and soil lithotype, making the role of rainfall variability in gully development hard to generalize. The present study analyses the local storm characteristic and their effects on gully development

2. 2. 2 Land cover

The land cover determines soil infiltration capacity and overland flow generated in the hydrological cycle (Pathak *et al*., 2005; Pratama *et al*., 2016). Increased demand for cultivation land brings about unsuitable human practices, low vegetation density and construction of rural roads reduce infiltration capacity and generate excessive overland flow (Dunne, 1983; Valentin, 2004). Vegetation cover protects the soil from erosion by intercepting raindrops, reducing soil compaction and increasing soil infiltration capacity (Ritter, 1978). Gully initiation and progression are often controlled by the tree root system that binds soil particles together until the root system mat collapses (Costa *et al*., 2006). Utilizing land for Agricultural activities removes the tree root system and leaves soils bare most year-round, increasing overland flow accumulation. The human ability to shape the landscape (Wang et al., 2016; Kendie *et al*., 2015) in the vulnerable ecosystem (Angileri, 2012) is considered the most contributor to gully erosion (Butzer, 2005; Nearing, 2001).

Devegatation results in poor soil structures, making soils susceptible to gullying. Studies by Conoscenti *et al*. (2014) conclude that gully head-cuts occur in zones of shallow landslides, where sediments are inadequately consolidated. The study is in line with Krause *et al.* (2003), which reveal that gully erosion is responsible for up to 90% of the sediment generation in areas used as grazing pasture. Also, Li *et al*. (2003) and Wu and Cheng (2005) conclude that gullies develop in regions where soil structure is poor due to intensive land use. Valentin *et al.* (2005) concludes that, the growth of non-cover and annual cropping in the semi-arid areas intensify gully erosion by leaving soils bare most year-round. Consequently, vegetation cover applied in many conservation projects can limit overland flow, though care must be taken in the choice of cover. The choice of vegetation cover may be a temporary solution and perhaps even counter-productive since gullies can be reactivated with unforeseen consequences (Canovas *et al.*, 2017). Vegetation cover for gully rehabilitation should be applied cautiously since certain plant roots are known to increase slumping along channels (Ritter, 1978). The study attempts to analyze the nature of land cover/land use across gully systems to establish its effects on geomorphic processes on banks.

A change in land cover determines the cohesiveness of materials and soil shear strength (Poesen, 1998), affecting gully side slopes. (Nyssen *et al*., 2006). Abrupt and uncontrolled land-use changes such as abandonment of tilled land, tillage mechanization and deforestation are some leading causes of increased soil loss (Conoscenti *et al*., 2014). Studies by Kendie *et al*. (2015) on gully erosion concluded that the prime cause of gully initiations are areas with human-induced factors such as; overgrazing, clearing of vegetation, poor farming methods, and removing crop residue, which leave the soils bare. However, other factors presently unknown will influence the rate of erosion. Angileri (2012) reveals that soils characterized by low organic content increase soil erodibility.

Also, changing land cover from vegetation to other cover forms can accelerate gully development (Osuji *et al*., 2010; Kartz *et al.*, 2013). Building activities in rural and urban environments lead to channelization resulting in the creation of compacted and/or concrete surfaces (Valentin *et al*., 2005; Poesen, 1998). Gullies often start close to the artificial drain outlets of roads, where channeled overland flow is directed onto the downstream fields (Conoscenti *et al.*, 2014). Access roads to farmlands, urbanization and other trucks result in a massive gully erosion increase. Frankl *et al*. (2012) conclude gully growth rate is higher in catchment areas with roads since they can modify drainage patterns. Mega-gully systems are artificially induced by the establishment of urban structures which generate artificial runoff channels like trenches, sewer lines, and tracks over which 43%

of the gullies develop (Imwangana *et al.,* 2015). Thus, to understand and predict the driving force that increases the initiation and progression of gully erosion, it is necessary to monitor and characterize spatial changes in land cover/land use over time. The present study evaluates land cover/land-use changes for 19 years to establish the original hydraulic balance of the catchment for proper conservation.

2.2.3 Soil classification and characteristics

Soil characteristics include; soil structure (blocky, columnar, granular), soil texture (silt, sand, clay, loam, and organic matter content), level of soil development and porosity. These soil texture factors are mineralogy and chemical properties soil. A soil mass's shear depends on the clay minerals present (Igwe *et al.,* 1999). Soils with high clay content are vulnerable to gully erosion since they result in concavities that collapse when soils are wet or dry (Abdulfatai *et al.,* 2014). During dry seasons, clay soils tend to fracture and crack; they act as starting points for weathering processes in soils, where flow concentrate (Valentine *et al.,* 2005). The cracks create a path to flow, expanding micro-fissures that can reach several meters and triggers gully erosion (Sidorchuk, 1999).

The development of cracks is related to periodic shrinking and swelling and the development of wide cracks, which results in infiltration then flow into the sub-soil and drains underground (Frankl *et al.,* 2012). Sub-surface drainage results in the development of cracks, with the tunnels' roofs eventually collapsing. These tunnels can change into a gully even after a single storm (Valentin *et al.,* 2005). Pathak *et al.* 2005 reveal that gully headcut is more vulnerable in areas of vertisols (with high clay mineral content) which are highly pulverized, resulting in the formation of deep, wide cracks when dry, thus prone to pipe development that turn into large gullies after collapsing. Also, Arabameri *et al*. (2018) reveal that prolonged dry seasons followed by wet seasons result in concertation of flow into cracks, ultimately leading to the development of gullies.

Smectitic soils deteriorate more readily than soils containing a small percentage of smectite (Poesen, 2003). On the contrary, soils with low content of smectite are more stable, less erodible and less prone to deterioration. Soils with sodic layers (Poesen and Vandekerckhove, 2004) and non-sodic areas with a high percentage of clay minerals (Nyssen *et al.*, 2004) are prone to evolving pipe development into gullies when their roofs collapse. Structurally, gullies tend to develop faster and are more numerous in Cretaceous areas where soils have weak structures (Marden *et al.,* 2008).

The average shear strength of the soil affects the cohesiveness of materials around gully head and gully channel banks, attributed to the level of development of soils and soil type (Abdulfatai *et al.*, 2014). Poorly developed soils (soils with weatherable materials and high sand content) have poor average shear strength resulting in an increased rate of gully progression. Shallow mass failures result in sub-surface seepage brought about by weatherable materials. Similarly, a poorly developed top layer may affect shallow landslides by re-directing surface runoff (Kirkby and Bracken, 2009). Gully channels increase bed geomorphic activity by removing materials displaced by the landslide (Poesen, 2011). Ghosh and Guchhait's (2016) studies reveal that gully erosion is acute in the upslope catchment areas in lateritic regions since it is dominated by surface and sub-surface flow, which deeply incises the soft-rock terrain Wauter *et al.* (2008) conclude high susceptibility to gully erosion could partly be attributed to weakly developed soils which are generally sandy with higher clay content in the subsoil. However, these studies were conducted in areas with lateritic or vertisols prone to piping and mass failure. The present study will establish gully development in a catchment of different soil types within a small catchment; lithosols, cambisols and aerosols and how they affect gully development in the area.

2. 2. 4 Slope characteristics

Gullies are runoff products concentrated along natural drainage lines or artificial landscape segments such as furrows, land track borders, animal trucks and roadsides along a slope (Poesen, 1993). The amount of discharge (Q) on slopes determines the energy gradient, which affects the rate of soil erosion (Hughes and Prosser, 2003). Runoff velocity is determined by slope angle and length (Kartz *et al*., 2013). Extended gully networks occur if the soil slope at the gully head remains steep, a condition initiated by a localized relief often created by upslope incising the main river, which increases the slope (Smith and Bretherton, 1972; Kartz *et al*., 2013). As a gully incises in the upper slope, the rate of material removal at the talus slope and down incision of the gully bed is determined by the effectiveness of the lower layer to rapidly evacuate sediment material handed over to it (Hughes and Prosser, 2003). If a gully's ability to remove the added materials is low

(Poesen, 1998), gullies typically develop a steep slope, often associated with the down-cutting of the channel bed below the gully head (Pratama *et al.*, 2016; Zhang *et al.*,2015). In some instances, volumes of load resulting from massive wall failures occur suddenly, which is problematic since added materials hinder the gully thalweg and minimize the successful removal of added materials (Kirkby and Brecken, 2009). To remove the large load (Pratama *et al*., 2016), the gully must be more rapid in incision at a lower gradient to maintain steep slopes downward (Ghosh and Guchhait, 2015). A steep gully slope minimizes the large volume of material by allowing the transportation of the erosional products (Kirkby and Brecken, 2009). Ghosh and Guchhait (2015) conclude that, steep slopes if maintained for a short distance, can evacuate all materials in a gully channel. In any gully system, the volume of materials transported through the channel is determined by the slope for which, for a given critical gully catchment area, a critical gradient must be exceeded (Ghosh and Guchhait (2015). Therefore, the critical slope required for effective bed load removal must be determined.

Although a steeper slope increases the sheer force of the water and the channel sediments, slope angle is not the only factor increasing the development of the gully channel (Wang et al., 2016). Net erosion at a specific point on a slope is also defined by its distance to the top of the slope and the slope shape (Prosser *et al.*,2001). The slope length determines the rate and/or point of physical transfer of soil particles, ranging from a few millimeters to thousands of kilometers (Lal, 2001). On concave slopes most of the sediment eroded on the upper part of the slope does not arrive at the channel bottom since it is deposited in the lower part of the concave profile due to energy loss (Pratama *et al*., 2009).

Secondly, longer and gentle slopes have a higher gully erosion rate caused by channelization (Kartz *et al*., 2013). The channelized flow requires a lower critical slope for gulling (Dobek *et al.*, 2011) since it rearranges drainage patterns, increasing flow concentration at discharge points. Where channels deliver water into steeper and debilitated slopes, gully progression can be rapid and voluminous. Studies by Istanbulluoglu *et al.* (2003) conclude that surface overland flow concentration results in the development of small gullies where culverts release their flow into bare hillslopes, creating shallow, narrow, but lengthy gully systems. Arabameri *et al. (*2018) reveal that volume of gullies is controlled by the geological attributes, including slope, aspect, and gully heads catchment area covered by the gully system. Wang *et al.* (2016) conclude elevated areas are more favorable for the initiation and progression development of gullies due to longer steeper slopes. The studies, however, considered gully erosion due to slope length without putting into account land area between upper elevation and lower elevations which indicates diverse geomorphic processes at junctions. The study determined the effect of slope characteristics and lithological junctions on gully erosion.

2. 2. 5 Significance of geomorphic characteristics on gully development

The concentrated overland flow results in major geomorphic processes that have left significant prints on the landscape (Verachtert *et al.,* 2010). The surface and sub-surface dominant processes (Wilson, 2000; Vandekerckhove *et al.*, 2000) increase concentrate flow on slopes due to shear stress caused by surface flow which exceeds the shear strength of soil (Haile *et al.*, 2006), producing rills that progressively develop into gullies. Surface mechanisms for soil erosion are well understood and acceptable (Haile *et al.*, 2006), while processes controlling initiation and progression to gully erosion are poorly understood (Nyssen *et al*., 2006).

Gully erosion is described as an erosion process in which overland flow accumulates in narrow channels and moves substantial material delivered to the formed channels over time (Wilson, 2000). These processes concentrate flow on slopes due to shear stress caused by flowing water which exceeds soil shear strength (Haile *et al.*, 2006), producing rills that progressively develop into gullies. These conditions are exaggerated by hydrological drivers such as catchment area, steep slopes, soil seasonality, low ground cover and poor land management practices, complex factors which vary in specific forms and processes as they influence gully formation, as increased by unsuitable human practices (Ghosh and Guchhait, 2015). Studies by Tebebu *et al.* (2010) conclude that lower slopes have more elaborate channelization had significant soil loss, which is significantly impacted by rills and gully formation than upper slopes.

Regions of compacted soils such as roadsides, paths and animal trails are similarly impacted by concentrated overland flow, which results in gully initiation and progression (Kartz *et al*., (2013; Ghosh and Guchhait, 2015). These surfaces increase concentrate overland flow, often in regions of increased rain seasonality (Shakesby *et al.*, 2000), which increase concentrate flow leading to gully initiation. Once microscopic gullies are formed, the fluid turbidity over short rainy periods can increase gully channels rapidly in all directions, making it difficult and costly to control (Wang *et al.*, 2016; Dobek *et al.*, 2011).

In areas of overland flow accumulation, an assessment of elaborate erosion processes within gully banks, bed and head, influenced by similar or different geomorphic processes, results in undercutting, failures and slumping, an essential strategy for gully extension. The processes can lead to the accumulation of flow below the surface, forming narrow channels that remove a considerable amount of soil over time and creates sub-surface pipes that eventually collapse (Nichols *et al.,* 2016; Wilset *et al.*, 2008; Verachtert *et al.*, 2010). Tunneling processes depend on soil characteristics or disconnection brought about by plant root systems, burrowing animals, non-decomposed organic matter and un-weatherable rock materials (Wilset *et al.,* 2008). Gullies formed through these processes enlarge suddenly caused by the collapse of overlying soil (Cavalli *et al.,* 2013). Tebebu *et al.* (2010) reveal that cultivated fields have a higher density of rill, which corresponds with non-decomposed organic materials leading to increased sub-surface channelization.

The mechanisms for channelization and sub-surface geomorphic processes which interact at gullied channels are difficult to understand and evaluate (Nyssen *et al.,* 2006). This poses a challenge in gully erosion modeling since it is difficult to capture surface and sub-surface geomorphic processes that interact as gullies develop. The collapsing pipes and/or incisions result in undercutting, failures and slumping of banks and extension at the head (Fu *et al.,* 2011). Failures and slumping of gully channel banks mainly occur when wet soils are impacted by increased weight (Bull and Kirkby, 1997), while bed deepening results from scouring at peak discharge. As the gully channel deepens, failure processes prevail over surface processes (Poesen *et al.,* 2003; Xu, 1999)

Increased processes for gully initiation and progression make it challenging to capture these processes in models for gully development (Verachtert *et al.,* 2010). For a start, field identification of factors that increase surface processes; land cover data, soil characteristics, slope steepness and human activities can help identify areas of increased geomorphic processes for gully erosion modeling. Determining the interaction between these processes for gully initiation and progression is an essential step in gully rehabilitation and conservation (Fu *et al.,* 2011). The study assessed the effects of hydrological factors which increase surface and sub-surface geomorphic processes resulting in gully development using different morphological structures to compare the rate of gully development over time.

2.3 Rate of gully development

Landforms generated by gully erosion are characterized by morphological structure (the shape of the gully channel), which defines the extent of the gully. Once initiated, the rate of gully expansion in any catchment is significantly affected by structure and shape since they affect geomorphic processes acting on gully head, bed, and gully banks (Dobek *et al.,* 2011)

2.3.1 Initiation and gully morphology

Based on morphological consideration (shape of the gully channel created by geomorphic processes), gullies can be V-shaped or U-shaped (Dobek *et al*., 2011). Gullies are termed V-shaped if their banks are near the angle of the rest of the unconsolidated materials (Bull and Kirkby, 1997). A V-shaped cross-section is an indication that the erosion process is predominant in the upper reaches of a gully, where the gradient is steep (Smith and Bretherton, 1972). Gullies in steep gradient regions are organized into dendritic networks or form parallel channels (Pratson *et al*., 2007). The lower horizon layer influences the rate of material removal from the gully and down incision, assumed to be more rapid in incising than the upper zones, attributed to increased concentrate flow (Krause *et al*., 2003). If the concentrated surface flow succeeds in scoring the lower horizons, the gully at the upper profile tends to remain small both in width and depth and is V-shaped (Bull and Kirkby, 1997; Dobek *et al.,* 2011).

Channelization resulting from both natural and artificial flow paths enhances drainage in a landscape (Marden *et al.,*2008). Channelization re-arranges drainage patterns, increasing flow concentration that initiates a gully channel at a point of discharge (Kartz *et al.*, 2013). The intensity and frequency of flow concentration in this channel result in active beds, resulting in actively eroding V-shaped cross-sections even in relatively gentle slope forms. Studies by Dobek *et al. (*2011) conclude that in areas where V-shaped gullies occur, they account for 21% of gullies since they are very active, numerous in number, and result in a sizeable total length. Also, Gordon (2006) concludes concentration of runoff enlarges small gullies on hillslopes, creating shallow, narrow, and lengthy gully systems. Gullies tend to change in form depending on geomorphic processes acting on them over time. Gully can be V-shaped in the upper gradient area and transform into U-shape channels as the slope approaches a gentle slope (Kendie *et al*., 2015). However, the study did not establish factors affecting the change points from V-shaped to U-shaped dimensions. This study will select points of morphometric change along the gully profile to determine geomorphic processes and their effect on gully growth.

U-shaped gullies are formed at any point of a gully cross-section (Dobek *et al.,* 2011). They form predominantly in straight sub-parallel sets, which seldom sub-divides or join into larger gully channels. They start at approximately the same isobaths in gently sloping terrain and develop over a large slope area (Spinelli and Field, 2001). These gully systems are shorter and elongate over a relatively short extent, less than 10 km across landscapes, retaining their density in a downslope direction (Spinelli and Field, 2001. Contrary, Lonergan *et al.* (2013) viewed U-shaped gullies to have a more complex plan view organization, with their spacing and density increasing downslope.

U-shaped systems are influenced by gully wall geomorphic processes resulting in a high rate of gully extension (Kendie *et al*., 2015). U-shaped gullies mainly begin at the edge of the upper gully due to channel undercutting (Ehiorobo and Ogirigbol, 2013) or sub-surface processes which encourage piping and subsequent pipe collapse (Poesen, 2011). These gullies may also originate from mass wasting mechanisms set off by the bank and head failure events at the shelf edge (Pratson *et al.*, 2007). Mass wasting may occur in areas where slope stability is decreased by undermining at the bed due to poor soil grain cohesion recognizable at gully head and banks increasing block failure. Once slumping occurs, the resultant materials tend to modify the gully cross-section transforming a V-shape gully into a U-shaped (Sidorchuk, 1999). These natures of gully structures start at approximately the same isobaths in gently sloping terrain (Spinelli and Field, 2001.

Gullies may also be formed by piping induced by slope or clay deposits or due to mass failures, which can significantly increase further slumping of gully banks (Hughes and Prosser, 2003). In such piping, the tunnel's roof eventually collapses, and the tunnels often become U-shaped gullies (Pathak *et al.,* 2006). Vandekerckhove (2004) reveals that soils with smectite clay develop pipes that result in tunnel erosion that turn to U-shaped gullies after roofs collapse. Also, Lonergan *et al.* (2013) conclude that areas of silty mudstones that have no coarser clastic apron at the gully bed often develop U-shaped gullies. These soil types encourage sub-surface and surface direction of water coursing both pipes, whose roofs eventually collapse at shallow landslide activity.

Once the gully channel has developed, the redirecting of sub-surface and surface runoff may affect shallow landslide activity, Marden *et al*., (2008), a mechanism by which many gullies increase in size horizontally. Also, Zegeye *et al*. (2015) reveal that gullies with U-shape cross-sections occur in actively eroding landscapes by mass failures. While studying gullies and sediment waves, Lonergan *et al.* (2013) also suggest that these gullies could be enlarged by sediment flows dominated by fine-grained suspended load flowing downslope by gravity. The studies viewed U-shaped gullies resulting from soil type, which encourages sub-surface and surface direction of water coursing piping and shallow landslide activity.

Once gullies are cut and lateral expansion begins, the erosion process is fast, and rehabilitation measures which can stop gully development are minimal; actions taken are only likely to restrict growth (Arabameri *et al.*, 2019). To counteract the rapid progression of gullies and minimize the damage gullies cause to the landscape, it's paramount to understand the morphology of gullied channels, the processes that interact in its formation, and their reasons for proper conservation and rehabilitation. The research attempted to determine intrinsic and extrinsic factors which change a gully's original shape, leading to its lateral extension.

2.3.2 Seasonality of gully development

Based on seasonality, there are ephemeral and permanent gullies (Dobek *et al*., 2011).

Ephemeral gullies can grow to any size and are usually larger than rills in the upper reaches of a drainage network (Bull and Kirkby, 1997). They are found in ploughed regions and eroded during one or several continuous runoff events and ultimately eliminated by tillage operations or natural processes since they are temporary erosion features (Vandekerckhove *et al.*, 2000). They recur in consistent places rather than random places on the slope due to poor tillage methods (Dobek *et al.*,2011; Zegey *et al*., 2016). Cultivated farmland with ephemeral gullies, which may be filled with unconsolidated sediments during tillage from conjoining areas in times of storms, are later removed by surface runoff (Conoscenti *et al.*, 2014; USAID, 2015), making them susceptible to recur in the same position during the next rainy season. Also, Wu *et al.* (2007) and Cheng *et al.* (2006) concluded that soil loss averages at 4.3-tones/ha/year due to ephemeral gully.

A permanent gully's cross-section formation can be permanently recognized without flowing water with identifiable banks; in some cases, a head cut (Schumm and Hadley,1957). They enlarge over time by head cutting and lateral enlarging occurring in depressions or natural drainage ways (Bull and Kirkby, 1997). Once these channels are established, self-channeling flows could maintain the morphology over time. (Lonergan *et al.*, 2013).

Permanent gully features mainly occur in rangelands or abandoned agricultural fields and are not eliminated by tillage processes after initiation, associated with longer-term channelized erosion activity (Vandekerckhove *et al*., 2000). Permanent gullies may begin as ephemeral gullies left un-rehabilitated and not erased by tillage or other operations (Dobek *et al.*, 2011). The concentrated flow of water makes these channels too deep for normal tillage operations to erase, thus requiring special operations to rehabilitate (Bull and Kirkby, 1997). Wang *et al.* (2016) also conclude that permanent gullies in the Mediterranean region develop in abandoned agricultural fields, rangelands, or shrublands. The study suggested the best methods of conserving permanent gullies.

2.3.3 Channel features

Gullies can also be continuous or discontinuous based on channel features (Dietrich and Dunne, 1993). Discontinuous gullies can be formed in location on a hillslope and can occur singly or a system of fully evolved or immature gully branches can occur together (Schumm and Hadley, 1957; Ffolliott *et al.*, 2003). They may develop in areas of local steepening after landslides and have no distinct junction with main gullies or stream channel (Dietrich and Dunne, 1993). The alleviation on its channel develops locally, an abrupt gradient to be stable, so it subsequently erodes (Leopold and Miller 1995).

Their extension is affected by redirecting sub-surface and surface runoff, which may affect shallow landslide activity on gully head and side slope or by removing material displaced by the landslide (Bull and Kirkby, 1997). These gullies may also originate from mass wasting action triggered by collapse at the shelf edge (Pratson *et al.*, 2007). Mass wasting actions occur at the gully head when slope stability is undermined, which contributes to the retreating gully head position (Leopold and Miller 1995). Studies by Spinelli and Field (2001) show that these gullies start at approximately the same isobaths in gently sloping terrain. The research established the geometry of the gullies and the point at which discontinuous gullies start.

Discontinuous gullies constitute channels at the early stages of development, occurring at the first 5% of the gully's life (Sidorchuk, 1999), and where the morphometry aspect (length, depth, width and area) is unstable. Gullies tend to change in form depending on geomorphic processes acting on them. Discontinuous channels grade into continuous channels (Sidorchuk, 1999) and occur in the mature stages of a gully when it has attained a dynamic equilibrium. A continuous gully often increases in depth and width rapidly from the head-cut and then maintains a steady gradient region (Ffolliott *et al.,* 2003). These studies evaluated forms of gullies systems found in different land cover types and prominent in arid and semi-arid areas. The present study assessed both natural and anthropogenic factors that determine the morphological structure of gullies and the severalty of geomorphic processes along channels that determine their progressive development.

2.3.4 Gully measurement and monitoring

Semi-arid regions are increasingly becoming fragile with an increasing population which increases the need for pasture, cultivation land and infrastructure (Sun *et al.,* 2005). Increased development activities have increased channelization resulting in varied geomorphic processes affecting soils, topography and surface hydrology making gully control and rehabilitation difficult and expensive (Kartz *et al.*, 2013; Valantin *et al.*, 2005). Wide geomorphic processes for gully formation have made studies and simulating gully erosion complex and inadequate (Gomez *et al.,* 2003). Therefore, regions of increased channelization need to be monitored to predict their impact on the environment to conserve and rehabilitate against gully erosion effectively.

Gullied areas in varied environments increase based on wearing off gully banks, beds and heads. The evolution of gully banks increases gully dimensions laterally caused by an increased discharge which erodes banks by hydraulic and scouring action (Kirkby and Brecken, 2009). Increased concentrate flow during storm undermines the base of the bank by scouring and channel erosion, increasing saturation of big chunks of soil which slide and stemple down; and washed by increased discharge through the gully channel. The undercutting process at the base is optimum during the peak period when discharge increases (Casali *et al.,* 2015). Increased undercutting and slumping of gully banks result in vertical walls, a process brought about by channels eroding by concentrate flow from the bottom-up (Poesen and Vandekerckhove (2004). Studies by Tebetu *et al.,* (2010) reveal that gullies were actively incising, head cutting and widening during the rainy season.

The steady increasing nature of gullies requires a technique to capture gully parameters with high precision (Vandekerekhova *et al.,* 2000). This can be achieved using methods for reconstructing surfaces and monitoring gully channel changes over time. Physical methods have been used for short time gully head and banks retreat monitoring by measuring the extreme distance edge of the gully head and bank and marked points (Pathak *et al*., 2005; Pratama *et al*., 2016; Vandekerekhova *et al.,* 2000; Zegeye *et al*., 2015; Lu *et al.,* 2003). For long-term evaluation, Lu *et al.* (2003) gives a deeper insight into digitally calculating gully dimensions, which involves considering both the gully network's upper and lower apron.

Detecting gully dimensions digitally involves systematic steps of acquiring images, classification, and processing, to determine actual change (Lillesand *et al.,* 2004). The steps for extracting final results are essential since each step can significantly impact the final dimensions, to a more significant extent, a factor determined by the image processing method used. In determining gully depth, the minimum lower limits of the bed and maximum upper limit of the gully channel bank should be considered. The inaccurate depth and/or width parameter determination across gullied cross-sections results in errors that can eventually recur in the calculation of eroded volume from a gully cross-section (Ries and Marzolff 2003).

The magnitude of the occurring error would have a more negligible effect when it involves analyzing a single cross-section but is exaggerated in gully networks volume calculating. Studies by Casali *et al.* (2015) reveal that in some areas, estimated volume can increase by 96%, an error which can be amended by obtaining morphometric parameters by drawing a vertical line along the width, depth and length of a gully in the DEM (Digital Elevation Model), and determine the eroded area by subtracting longitudinal line drawn on width, depth and length of a gully (DEMyear n-1 from DEMyear n). This process must be repeated in different sections of gullied areas to obtain accurate eroded cross-sections (Casali *et al.,* 2015; Ries and Marzolff, 2003).

Since gullied sections are uneven in most regions, projection areas (maximum and minimum projections) are considered in determining gully geometry (Sclumm *et al.,* 1984). Final determination of the whole gully volume, average values of width, depth and length would be the best measure for gully geometric limits (Ehiorobo *et al.,* 2011). To ensure effectiveness in calculating gully parameters, one has to ensure that the maximum pixel used for gully dimension calculation average the size of the most miniature recognizable objects in the mapped area. The present study integrated high resolution 1.5 spot resolution imagery combined with ground monitored stations using GPS and GIS in monitoring identified gullied areas with precision for 21year for effective planning for gully conservation and rehabilitation

2.4 Threshold factors determining gully development

Gullying is the process governed by concentrated flow frequently focused as a threshold process. Concentrated flow is influenced by morphological conditions, soil characteristics and vegetation cover. Gully initiation in a catchment area is determined by the topography of the surrounding area (Poesen *et al.*, 2003), as identified by the Hortonian mechanism of overland flow for gully initiating, while the topographic factors of the gully nature determine the rate of lateral extension. Consequently, the threshold for gully development is gully head slope, gully channel characteristics and drainage area, controlled by other extrinsic or intrinsic geomorphic factors. According to Chaplot (2013), gully initiation is associated with the relationship between the gully head gradient (S) and the gully catchment area per unit contour length (As), which is the up-slope area from which overland flow drains within the gully. The upslope gradient and drainage area determine the flow accumulation and overland flow velocity, and if they reach the threshold, gully formation starts (Chaplot, 2013). Therefore, to effectively assess gully development in a semi-arid environment, hydraulic indicators, namely; the drainage area and the slope, must be used to express and quantify the intensity of the process.

Gully initiation by overland flow has been viewed as a threshold factor (hydro-geomorphic processes attributed to the size of the gully contributing area (A) and slope (S), controlled by a wide range of conditioning factors usually brought about by rainfall, topography, soil characteristics and land use (Torri and Poesen, 2002). A geomorphic threshold is exceeded by changes in gully intrinsic factors (slope steepness, soil characteristics) or by a steady shift in external factors surrounding a gully (rainfall variability, drainage area, land use/land cover) (Jain *et al.*, 2012; Schumm, 1979), which influence the velocity of overland flow. Further, the flow velocity of overland is attributed to slope characteristics, slope length and steepness (Gómez Gutiérrez *et al.*, 2011; Poesen *et al.*, 2003; Vandekerckhove *et al.*, 2000), influencing the rate of gully development.

Gully initiation in a catchment occurs due to exceeding critical slope factors, or for gully initiation to happen in a particular slope, a critical drainage area has been exceeded (Istanbulluoglu *et al.*, 2003). The critical values of slope and drainage area vary depending on rainfall, soil characteristics, and land use/land cover (Vandekerckhove *et al.*,2000). As the gully head retreats and reaches its maximum retreat point, storm discharge contributing to the gully decreases due to reducing flow accumulation (Kumar *et al.*, 2013). Studies by Gordon (2006) concluded that the amount of erosion on a gully system decrease after several storm events due to a shortening of drainage area, corresponding to a reduction in storm discharge in the upper sections of a gully. The study seeks to establish the critical gully head soil slope and gully head catchment area required for gully initiation in different landscapes for effective conservation.

Changes in land use on a landscape affect gully drainage area (Valantin *et al.,* 2005). Changes in field sizes and the establishment of roads, animal trucks and paths may limit or expand gully catchment areas as concentrate flow shifts direction onto trails and roads (Kartz *et al.,* 2013). Areas with channelized erosion often require a lower critical slope for gullying (Kartz *et al.*, 2013). Studies by Wauter *et al.* (2008) revealed that changes in the size of the catchment area, as a result of road construction, lead to the formation of gullies through channelization. Also, Costa *et al.* (2006) concluded that, as a gully system advances downslope, it's limited by the catchment area it can exploit, reaches the catchment's limits, and erosion becomes self-limiting. Gordon (2006) concluded that the construction of terraces reduces overland flow due to a reduction in slope angle and drainage area. In this case, the topographic threshold will vary across regions due to the use and /or lack of use of conservation structures. For effective gully rehabilitation, conservation structures set must depend on a proper delineation of the drainage area and, establish its size, determine rainfall variability and intensities. Studies on gully rehabilitation relied on physical measurement methods to assess gully head slope angle and catchment area, whose accuracy can be affected by a wide range of physical factors. In the present study, gully head-position mapped by use of a GPS mapper, while the areas generating overland flow to gullies were determined using visible water flow-lines by GPS.

2.5 Erosion threshold and social-economic factors for gully stabilization

The initiation stage of gullies is the most critical stage of gully development since, once initiated, the channel progression requires very limited storms (Poeson, 2011). Formed gullies are very difficult to rehabilitate and heal; where possible, it is preferable to take preventive measures against gully initiation (Kirkby and Brecken, 2009). In most gullied areas, classical erosion stabilization methods are applied (gabions, grassed areas, stone barriers, afforestation and reforesting, check-dams and terracing) (Poesen and Valentin, 2004), the majority of which are ineffective (Dong *et al.,* 2011). Studies by Canovas *et al.* (2017) reveals that restoration of degraded areas based on re-forestation alone may be an effective method of rehabilitating other forms of soil erosion but inadequate in controlling elaborate gullied systems, especially in volatile environments like arid and semi-arid regions.

The effectiveness of gully rehabilitation is based upon two principles: first, determine the cause of gullies and second, restore the original hydraulic balance or create new, more effective conditions (Hudson, 1995). Therefore, to control gully growth in any catchment, more information is required on rainfall characteristics, land use/land cover and morphological characteristics, beyond which gully control methods and/or structures will fail. The introduction of gully stabilization methods before a proper course diagnosis is established can affect gully incision capacity for a limited time. Still, often an incision can be cut around any installed structure (Valentin *et al.,* 2005). Thus, the success rate in gully erosion control depends upon correctly detecting the problem and steps taken to arrest the cause (Gosh *et al.,* 2011; Pratama *et al.,* 2016). There is, therefore, a need to evaluate a gullied area over a river catchment over a period of time to establish the original conditions of the land to design appropriate conservation structures suited for the site.

The main challenge in soil conservation results is the limited technical know-how by farmers, who often design and layout conservation structures, resulting in more gully erosion and loss of land. Studies by Kumar *et al.* (2015) in South Bengal, India and Sirvios and Rebeiro (2004), Kenya; Taita Hills, revealed that farmers tend to apply classical erosion control methods on their farms without considering the upstream reaches of a gully. To effectively rehabilitate a gully system, both upstream reaches and downstream systems must be regarded since they contribute to the gully volume. However, the location of gully rehabilitation structures in most studies is not based on calculated critical drainage area and slope since they are designed and cited by farmers. Calculated slope – drainage area threshold relation was used to determine areas most susceptible to geomorphic processes for gully initiation, which aids in locating regions most suitable for citing conservation structures for effective conservation.

2.5.1 Gully stabilization

The farmer's readiness to accept and use specific conservation measures is commonly associated with the perception of the threat posed by the gully (Zegeye *et al*., 2015; Johansson and Svensson, 2002). Farmers rarely accept many techniques suggested for gully rehabilitation since their introduction is costly and hardly related to instant benefit (Valentine *et al.,* 2005). Benefits are perceived in terms of significant improvement in land or labor output commonly attached to incentives. Zegeye *et al*. (2015) revealed that, in gully erosion control, the farmer's perspective on the method is pegged on its capability to boost soil fertility and increase fodder and wood fuel production. Also, Deba (2003) concluded that preference by local communities for methods with fastened implementation is cost-effective and improves the productivity of the natural resources.

Studies by Imwangana *et al*. (2015) show that the lack of rehabilitation of mega-gullies in Kinshasa is due to a lack of financial support and insufficient attention to the problem. UNEP (2015) concludes that farmers often indicate limited technical and sustained support for accepting and implementing rehabilitation measures. Most studies on gully rehabilitation do not consider farmers' needs and acceptance in the implementation plan. The research established the gap for farmers in gully rehabilitation and suggested innovative methods of gully conservation based on the needs of a landscape.

2.6 Gully Erosion Modeling

Gully erosion occurs under different environmental and social-economic conditions (Beck *et al.,* 1995). Models capable of predicting size, location, intensity and initiation points using intrinsic and extrinsic geomorphic factors on gully formation are required. For accurate modeling, detailed monitoring of gully initiation points and progressive development of gullies in diverse environments is paramount. Models used must estimate a gully system extent and predict gully cross-sectional and soil loss rates due to gully erosion. These myriads of factors sometimes are self-reinforcing while others limit gully growth (Samani *et al.,* 2018). Most models combine digital elevation and drainage are variables.

2.6.1 Bivariate statistical analysis

To evaluate gully erosion susceptibility in the river catchments, there is a need to use simple models with reasonable accuracy (Rahmati *et al*., 2016). Therefore, a simple binary classifications model and a statistical bivariate analysis method were used to ascertain the effects of gully geomorphological factors on gully susceptibility in the Wanjoga River catchment. The bivariate statistical approach implementation is simple, accurate, and helpful in assessing the spatial distribution of gullied points and gully erosion susceptibility mapping dependent on different conditioning factors (Gomez Gutierrez *et al.,* 2009; Lee and Talib, 2005). The bivariate statistical method is based probability of the assessment of the spatial distribution of gullied areas in relation to the spatial distribution of analyzed gully susceptibility factors (Bonham-Carter *et al*., 1994; Lee and Talib, 2005) The bivariate model is a simple spatial assessment tool for identifying each influencing element and the location of gullied sites. Single thematic maps produced for each geomorphological factor (rainfall variability, soil lithotype, land cover, elevation, and slope) are transformed into raster format layers through ArcGIS software and merged with the gully inventory map for calculating the density of the gullied areas for each category of the geomorphological factors. Calculated gully density in the region represents the susceptibility magnitude of the examined geomorphological gully category factor (Carrara *et al.,* 1995).

Weight of Evidence Modelling (WEM), which is based on a Bivariate statistical approximation, uses a GIS-based statistical technique to model gully erosion susceptible regions using available spatial data for several topographical thresholds (Poesen *et al.,* 2003; Chaplot *et al.,* 2005), to predict areas of gully formation (Nachtergaele *et al*. 2002). Initially, the model was developed to assess mineral prospects in areas (Agterberg *et al.,* 1990) and used by scholars to map potential areas for minerals in several countries (Emmanuel *et al.,* 2000; Venkataraman *et al.,* 2000; Chaplot *et al.,* 2005). The WEM model applies to diverse phenomena with available evidence themes since it is based on the probability of factors influencing a specific phenomenon. GIS environment enables the creation of themes of condition factors to gully erosion (Kakembo *et al.,* 2009)

The main advantage of Weight of Evidence Modelling is that it calculates weight values on gully conditioning factors based on statistical formulae avoiding subjectivity (Regmi *et al.,* 2010). Also, the model can use maps with incomplete and minimum sample data without significantly impacting the results. The main disadvantage of the model is weighted values cannot be generalized in terms of susceptibility (Regmi *et al.,* 2010).

The model describes the total of pixels of gullied regions in relation to the total number of pixels in the study area (Lee, 2010). In the model, each gully geomorphological factor weight is calculated using the equation (Yin and Yan 1988)

$$Wi = \frac{NpixSi/NpixNi}{\sum PNpixSi/\sum PNpixNi} \quad (1)$$

Where;

Wi = Weighting value of the category i;

NpixSi = Sum of pixels with gullied channels in the category i;

NpixNi = Sum of pixels in the category i;

PNpixSi = Sum of pixels with gullied channels in the study area;

PNpixNi = Sum of pixels in the study unit.

By operating the model in ArcGIS, the spatial relationship of gullied sites and each geomorphological factor advancing the gully erosion phenomenon are extracted. It is based on the probability of assessing the link between the spatial dispersion of gullied areas and the spatial dispersion of gully susceptibility factors (Bonham-Carter *et al.,* 1994). Thus, this study employed the use of a GIS-WEM-based technique to determine areas of gully susceptibility in the Wanjoga river catchment.

2.6.2 Gully susceptibility mapping

Models which can be considered empirical have been substantially used to approximate gully erosion susceptibility over the years (Poesen *et al.,* 2003). However, many models have not been effective in determining sensitive areas to gully erosion since the emergence of gullied sites is controlled by broad interacting conditioning factors, which increase operating geomorphic processes (Gayen *et al.,* 2019).

The wide variety of interacting processes is a prerequisite for accurate data for approximating gully development. This means that, for precise gully susceptibility mapping, the primary controlling variable must be considered (Conoscenti *et al.,* 2008). Diverse studies have shown that statistical models such as the Bivariate statistical method are useful in susceptibility mapping for gully erosion using limited factors and delineated regions of known gullied and un-gullied areas for validation (Gayen *et al.,* 2019; Azareh *et al.,* 2019; Pourghasemi *et al.,* 2017).

Worldwide, several studies on gully susceptibility mapping have been carried out using a limited number of controlling factors that increase proneness to the gully (Pourghasemi *et al.,* 2013; Pourghasemi *et al.,* 2017; Arabameri *et al.,* 2018; Gayen *et al.,* 2019;). Despite the studies, no universally established procedure has been accepted for determining an adequate number of conditioning factors governing gully erosion susceptibility mapping. Studies by Remondo *et al.* (2003) in Northern Spain revealed that an increasing number of gullies conditioning factors does not necessarily increase accuracy in gully erosion modeling determination if the elements are not favorable. Further, Ayalew and Yamagishi (2005) reported that selected gully conditioning factors should not be redundant, such as factors that have double consequences in the susceptibility. Thus, susceptibility analysis by combining; slope angle, length, plan curvature, and stream power index should be regarded as redundant since they all depend on slope angle. In this study, five major gully controlling factors were used based on existing studies and expert reviews (Ayalew and Yamagishi, 2005; Arabameri *et al.,* 2018; Remondo *et al.,* 2003; Conoscenti *et al.*, 2008). The factors included; slope characteristics, soil typology, elevation (represented by DEM), annual average rainfall, land cover/land use

2.6.3 Revised universal soil loss model

The revised Universal Soil Loss Model (RUSLE) is an accepted universal model to estimate soil erosion. It is operated in a GIS environment to calculate soil loss brought about by raindrop impact, overland flow and rill erosion, a process restricted and related to rainfall erosive power (Wischmeier and Smith, 1965). The model is established and grounded on; R-factor (rainfall) K-factors (soil characteristics), LS-factors (slope angle and length), C-factor (conservation management factors) and P-factors (conservation practices). The RUSLE model estimates annual average soil loss per unit area (t/ha/yr) as described by (Dressing, 2003)

$$A = K \cdot R \cdot LS \cdot C \cdot P \qquad (2)$$

Where; A- estimates annual mean soil loss t/ha/yr), R= Runoff factor mm^{y-1}), K= Soil erodibility factor Mg h MJ−1 mm−1), LS=Topographical factor, C= Cover and Management factor and P-conservation practice factor.

The R-factor quantifies the effect of raindrop impact, amount and rate of runoff depending on rainfall intensity and distribution (Bryan, 2000). The runoff factor is directly influenced by altitude and location as modeled by (Sorrentino (2001) using the equation;

$$R= (1163.5+ 4.9H–35.2NGP–0.58_{q})/ 100 \qquad 3$$

Where;

H (mm^{y-1}) = annual mean rainfall, NGP =mean rainy days per year and q= elevation of the point in meters above sea level.

Erodibility K-factors determines the moisture content of the soil, which influences erosion strength based on soil property factor, which in turn influences erosional processes (Bryan, 2000). This factor relates to soil resistance as impacted by raindrops and the amount or/and persistence of overland flow (Schwab *et al.*, (1994). Soil resistance factor is related to lithology and soil characteristics, including; crop residue content, soil texture, soil structure and thus soil erodibility. Calculation of erodibility factor used the available erodibility data obtained from natural runoff plots and simulated rainfall utilizing the distribution of soil particle analysis (clay, silt and sand percentages in the soil), using the formulae developed by El-Swaify and Dangler (1976)

$$K=0.0034 + 0.0405exp[-0.5(\frac{logD_{g+1.659}}{0.7101})^2 \qquad 4$$

$$D_{g=exp[\sum 0.001}f_i \; In\{(d_{max+}d_{min})/23] \qquad 5$$

Where;

D_g=mean soil particle size (sand, clay, silt), d_{max}= maximum diameter of a particle in mm, d_{min}= minimum diameter of a particle in mm, f_i= corresponding fraction of mass

The LS-factor intermingle slope length and gradient the effects, viewed as a measure of the load transport capacity by runoff. The soil loss ratio per unit area from the field slope is approximately 22.13m. LS was calculated using the formulae (Angima *et al.*, 2003) and proved vital in the highlands of Kenya,

$$m\,\frac{(\sin\theta/0.0896)/[3\times(\sin\theta)0.8+0.56]}{1+\sin\theta/0.0896)/[3\times(\sin\theta)0.8+0.56]} \qquad 6$$

$$S = \begin{cases} 10.8 \sin\theta + 0.3\theta < 5° \\ 16.8 \sin\theta – 0.55 \leq \theta \leq 10° \\ 21.9 \sin\theta – 0.96 \geq 10° \end{cases} \quad 7$$

Where;

θ =slope angle in the degree of specified slopes

The model has been used successfully in different climatic areas of varied soil types as adopted in West Bengal India (Shit *et al.,* 2015. The cover and management factor (C), was calculated based on crop development stage, crop residue content of the soil, effects of previous cultivation operations and climate. The value of C depends on the type and percentage of vegetation cover, with values ranging from 0 -1, reflecting the ability to counteract the impact of raindrops and overland flow by ground vegetation (Wischmeier and Smith, 1978). P-factor includes influences of different conservation structures such as the use of contours and terraces and the loss due to upslope and down-slope tillage (Fu *et al.,* 2006).

The model calculated C-factor based on vegetation cover type as a percentage as generated by Morgan (1995), displaying a linear relationship between C-Factor and Normalized Difference Vegetation Index (NDVI) as follows;

C-factor= 1.02–1.21×NDVI 8

Where;

NDVI=(NIR–RED)/(NIR+RED)

(NIR-Near Infrared); NIR light reveals vegetation density

(RED-)

P and C factors represent changes in management such as areas for application of conservation structures which influence soil loss from water erosion, an important factor in determining overland concentrate flow, thus gully erosion. P-factor shows conservation practices implemented to reduce overland flow thus, reduce the rate of soil loss. P-factor used was based on studies of Wischmeier and Smith (1978), which give a table showing types of conservation practices consideration a researcher can adopt based on the study area. Once models were chosen for each individual factor based on the study area, factors were analyzed in a GIS environment which gives correct estimations.

Soil erosion by gullies is not considered in the RUSLE model since soil loss calculations are only based on a straight flow line, which does not include influence by concentrated flow (Warren, 2005; Renard *et al.*, 1997). Therefore, the importance of gully erosion to total soil loss can be calculated as the percent of rill and sheet erosion. Gully erosion by ephemeral gullies is estimated as a ratio to rill and sheet erosion at an average of 80% in the United States of America (USDA-NRCS, 1997). Also, since this model uses a mathematical integration procedure rather than the approximation procedure, it makes this computation more accurate (Fu *et al.*, 2006)

2.7 Theoretical Framework

Theoretically, the study adopted landscape evolution theory, which predicts areas where gully by overland flow begin. As identified by Horton (1945), mechanisms of overland flow for gully initiation begins in locations where the threshold resistance flow of soil shear stress is exceeded. The theory was improved by Smith and Bretherton (1972). They stated that the gully initiation and growth are a continual function of the catchment area (water discharge region) and the gully head slope gradient is affected by surface processes (Bull and Kirkby, 1997). Slope and drainage area is often viewed as a non-linear function of surface processes (Nearing *et al.,* 1997; Kartz *et al.,* 2013). The surface processes are determined by load transport, denoted by diffusive and wash processes (Istanbulluoglu *et al.,* 2003). Diffusive transport of material is the rate proportional to gradient, while wash transport rate is proportional to angle multiplied by a square of discharge. The initiation of gullies occurs when, for a given catchment area, a critical slope gradient has been exceeded or when, for a given slope, a critical catchment area has been exceeded. Exceeding critical values for slope and/or drainage area create conditions that concentrate sufficient overland flows that bring instability to the surface, resulting in the creation of tiny hollows (Montgomery and Dietrich, 1988).

Instability on the landscape occurs due to increased load transport capacity created by flow converging in a proto-hollow that surpasses the sediment load brought into the gully system by the overland flow convergence (Poesen *et al.,* 2003). Increased instability, viewed to be increased with increased slope, generates conditions in which very small proto-hollows grow into small gullies (Smith and Bretherton, (1972). In regions of gentler slopes, such conditions can only be created with additional drainage areas (Maeyersons, 2003). Such conditions occur in regions where the rainfall amount surpasses the infiltration magnitude of soil and overland flows downslope. This character of overland flow depends mainly on the ground characteristics, topography, land cover and soil characteristics (Dunne, 1983).

The critical values of slope and drainage area that converge overland flow on a catchment area vary according to geomorphological factors; terrain, soil and rainfall characteristics and land cover/land use (Vandekerckhove *et al.*, 2000). Gully erosion is described as a threshold factor (Montgomery and Dietrich, 1988), viewed as the topographic threshold. The relationship is defined by the power function:

$$(S_{cr} = aA^{b}) \qquad 9$$

Where;

S=s gully head critical slope,

A =The critical catchment area and

'a' is a coefficient and

'b' exponent value of the relative area; used to predict regions of instability relating to dominant processes underplay during gully formation (Poesen *et al.,* 2003). The value of coefficient 'a' is attributed to the nature of the soil, climatic factors and vegetation cover, which represent resistance to gully initiation. This shows the relationship between slope (m/m) and area in (hectares) *(S-A)* representing regions of gully head cut on a graph plot based on the dominancy of the 'b' and 'a variable. A straight line drawn through a scatter point represents a critical slope above which gully initiation may occur.

2.8 Conceptual framework

Gully erosion was initiated by localized factors that increase overland flow, generating a gully system created by an incising main river channel (Istanbulluoglu *et al*., 2003). As shown in the conceptual framework (Figure 2.1), gully development is determined by rainfall characteristics (erosivity factor), which triggers gully initiation by producing sufficient concentrate flow that brings instability to the surface. Concentrate flow influences the rate of material removal as influenced by geomorphic factors such as soil characteristics, slope characteristics and land cover, resulting in the creation of macroscopic gullies which can grow to channels of different sizes and shapes over time. Once gully channels have formed, the rate of growth and morphometric and morphological characteristics of a gully channel is influenced by the occurrence or/and geomorphic processes such as slumping, piping, scouring, and mass failures on gully side walls and bed.

The influence of rainfall on geomorphic processes can be moderated by applying gully rehabilitation measures. Modification and adjustment of geomorphic factors (use of stone berries, vegetation, terraces, check dams, gabions) reduce overland flow which declines with the reduction in the gully catchment area that corresponds with the reduction in storm discharge in the upper reaches of a gully, thus, healing or low rate of gully development. Modification of geomorphic processes (gully stabilization structures, structure design, citing of structures, number of structures per gullied area, choice of vegetation) would result in stabilization of gully, leading to reduced occurrence of geomorphic processes such as slumping, scouring and mass failure of bed and gully side walls. Once farmers carry out the proper conservation, it would act as the mitigating factors to increase critical values required for gully development, thus reducing the rate of gully development.

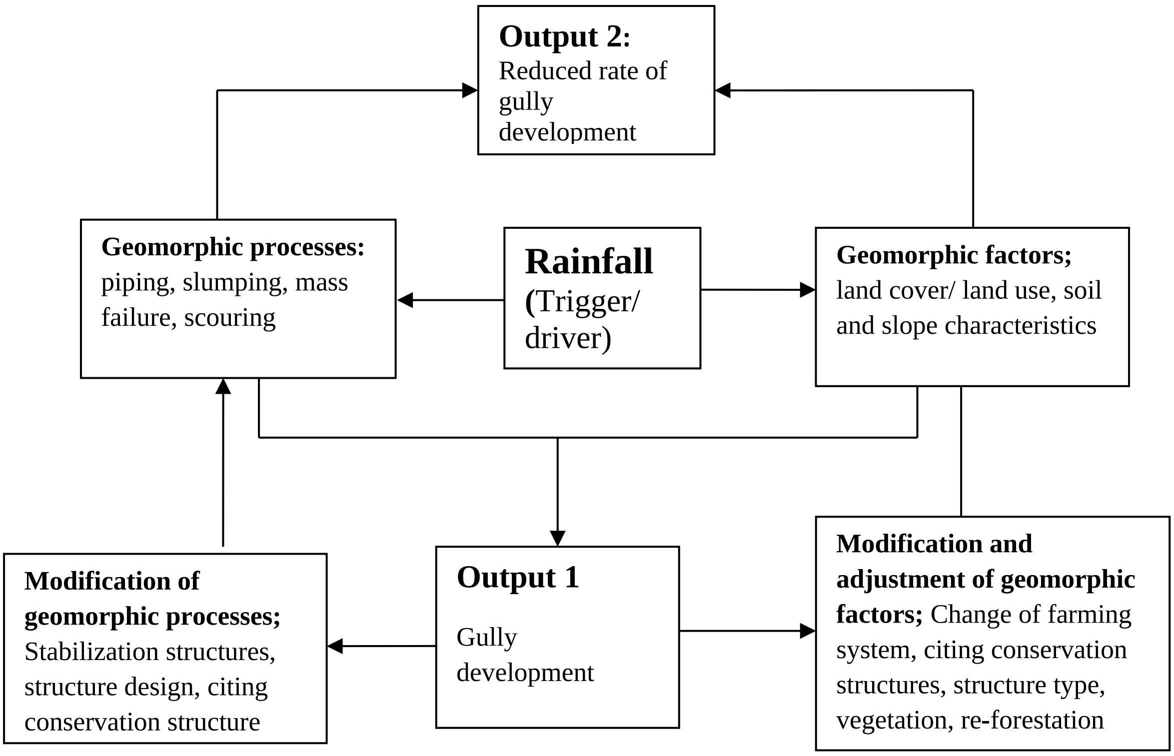


Figure 2.1: Gully development and intervention (Source: Modified from Morgan (1982)

CHAPTER THREE: STUDY AREA

3.1 Introduction

This chapter presents the study area details used to execute the study objectives. It comprises a description of the area's geology, physiographical characteristics, land use, soil lithotypes, rainfall and population characteristics. These study area factors can combine to increase geomorphic processes that generate overland flow that initiate and increase susceptibility to gully erosion.

The Wanjoga River catchment (Figure 3.1), with an area of bout 200.5 KM^2, is located in the semi-arid environment in the Wanjoga catchment, sub-catchment of Tana Basin, Embu County, Mbeere North Sub- County. The basin area is located at latitude 0°, 30'0.33'' to 0°, 35' 0.48''S and longitude 37°, 40' 33.88'' to 37° 50' 35.55'' E. It is located on the southeastern side of Mt. Kenya, about 30 km east of Embu town. The study will cover the Wanjoga river catchment which covers Kathera, Kirie and Ngose sub-locations.

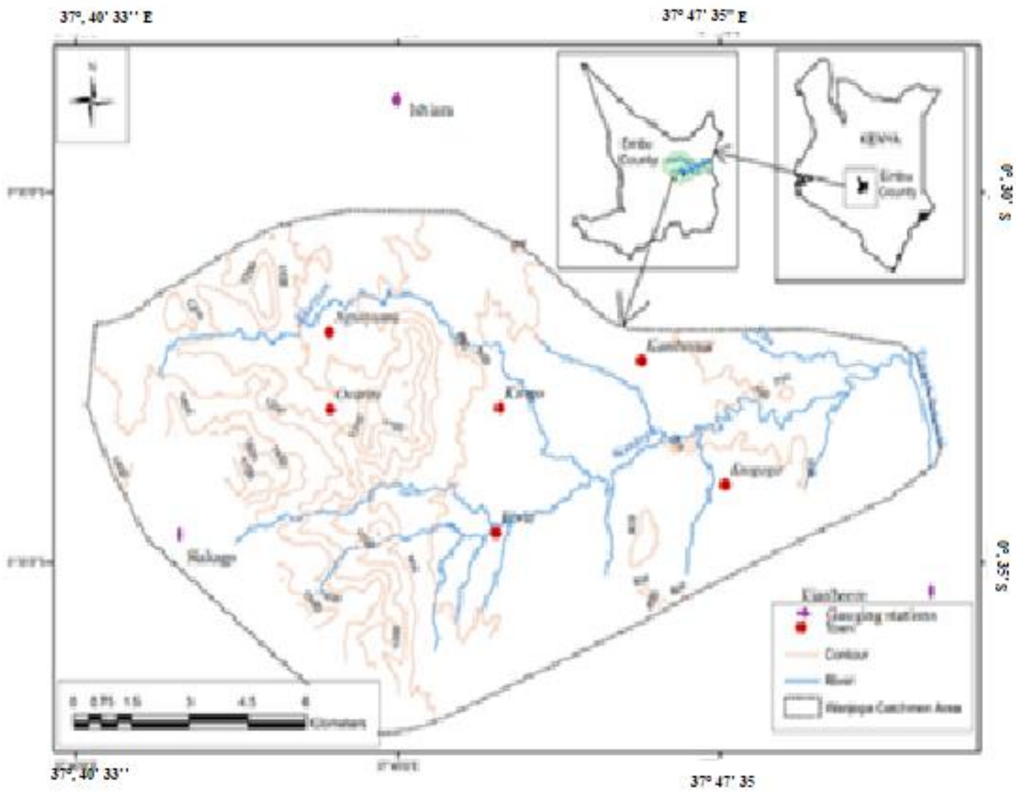


Figure 3.1: Wanjoga River catchment (Source: Survey of Kenya)

3.2 Geology

Geologically, the Wanjoga River catchment falls into four lithological groups, the Archaean rocks (4.0 billion - 2.5 billion years), the Neoproterozoic rock units, including; the Embu Series (2.5 billion - 570 million years) and the Tertiary volcanic and superficial deposits of Pleistocene and Recent age (GOK, 1967). Neoproterozoic rock units in this area consist of various calcareous rocks, gneisses and schists. The Plagioclase amphibolites and hornblende gneisses are widespread, the largest concentrations occurring between Karie and Kiang'ombe (Bear, 1952). Most of these rocks are considered ortho-gneisses with appinitic characteristics and dioritic composition. Smaller areas covering gabbroic rocks occur between the Wnjoga River and Thambu.

A class of hornblende-bearing biotite occurs at the foot of Kibara and north and east of Karie (GOK, 1967). At Wanjoga River valley occurs subordinate biotite flakes in larger plates of pale-green hornblende. These structures are interpreted to occur due to the influence of potash metasomatism, which tends to metamorphose hornblende into biotite (Bear, 1952). Another type of hornblende is found as scattered boulders that resist weathering processes. Medium-grained hornblende exposed on the surfaces has encrustation of soft brownish material. A small exposure of basalt is located south of the Wanjoga River, about six miles west of its confluence with the Ena. The rocks outcrops are exposed for a few meters and their exact relationship to the Basement Systems rocks is covered by the soil.

High relief areas such as Kiang'ombe Mountains showed outcrop blocks of resistant granitoid gneiss. They form the chief mountainous regions and are confined to the northern parts of the river catchment. The relatively impermeable granitoid gneisses resist weathering and create most hilly areas. At the same time, the valley's bottoms are made-up of less resistant and more pervious migmatitic gneisses, biotite gneiss, and banded gneisses (Bear, 1952). Long weathering periods of these rocks determine soil types, forming an essential variable of the current study.

3.3 Soils

The area under study comprised different soil lithotypes characterized by the nature of rocks. At the top of Kiang'ombe hill, impermeable granitoid gneisses that resist weathering soils are poorly developed (Bear, 1952). Soils found in this area include sandy clay loam to clay which is dark red to brown with lithosols. These soils are shallow and excessively drained (Jaetzold and Schmidt, 1983). Other regions of Kiang'ombe hill are covered by stony loam sand to clay cambisols which are well-drained. At the foot-slope plain towards the joining valleys, deep and well, drained arenosols exist. In lowland areas near the Tana River, areas of different basement system rocks, the types of soils are stony loam sand to clay cambisols which are well-drained (Jaetzold and Schmidt, 1983). This is the region of the dissected erosional plain. Parts of river Ena have ferralsols, red to dark red, and deep, well-drained soil. The study will establish the effects of soil characteristics on geomorphic processes and their effect on the intensity of gullies in the area.

3.4 Topography

The area can be divided into two distinct physiographical units; the Kiang'ombe Mountains region and the Tana River valley. The Wanjoga river catchment has risen from $500\,m$-$1700\,m$ above sea level. Kiang'ombe hill is the highest peak rising to $1700\,m$ above sea level, making it the chief mountainous region. The Tana River valley region has the lowest altitude at about $500\,m$, where all the rivers from Kiang'ombe hill drain (Bear, 1952). The topography, particularly near the Tana, is pretty rugged. The study drew a relationship between the topography of the area and the density of gullies over time. The adjacent valleys and features such as dykes, faults and folds affect the direction of movement of surface and underground water (Bear, 1952). The area has relatively impermeable rock at Kiang'ombe hill, where most of the river in the area drains.

The Tana River is the main perennial river. Wanjoga and Marivoe have a limited flow during the dry season, while many other rivers are seasonal. In faulted areas, the rock intrusive and relative hardness of rocks determines the drainage pattern of most of the area covered by the Wanjoga River catchment (Bear, 1952). River networks are characterized by several right-angled bends, potholes, rapids, small waterfalls, and deep, steep-sided gorges cut along the river channel (Bear, 1952). The study established the effect of variation in slope angle and its impact on the rate of gully initiation and extension in the area.

3.5 Rainfall

Rainfall in the area is very variable, with some years averaging from 1,200mm/per while others are 500mm/per annum (Olson, 2004). The annual average rainfall is 550mm with a bimodal pattern in which 60% of the total rainfall is experienced from March to May, being a more extended and more reliable season, while 40% fall in the second rainy season from October to December, which is shorter and unreliable (Jaetzold and Schmidt, 1983). The rainfall distribution over the months is uneven, with most of the rainfall received only over four months of the year (Jaetzold and Schmidt, 1983). The study established the effects of rainfall variability on the rate of gully initiation and growth over time. Average temperatures in the area range from 20° - 32°, with July as the coldest month, having an average monthly temperature of 15° (GOK, 2013).

3.6 Land Use

The study area is located in Mbeere North Sub-County, where over 80% of people derive their livelihood mainly through crop and livestock production (GOK, 2013). At the top of the King'ombe hill, the area is covered by thick forest, a government-protected land. Around the forest, crop growing is practiced since it receives relatively high yearly rainfall. Crops grown in the area include drought-resistant varieties such as; cowpeas, beans, millet, cassava, pigeon peas, maize and khat (*Catha edulis* Forssk), which thrive in the region of low and unreliable rainfall (Jaetzold and Schmidt, 1983). The local people also value livestock and tend to keep large herds, especially in the lower regions of the catchment (Ngugi *et al.*, 2011). With increasing dry spells, livestock herding extends to higher areas, sometimes in the forested part of Kiang'ombe hills, becoming a predominant land use practice. The erratic nature of rainfall with increased farming practices incompatible with the semi-arid region has increased overland flow, which accelerates gully erosion. They established the effects of land use on gully initiation and growth.

3.7 Population

Wanjoga river catchment has an ever-increasing population encroaching on the protected forest reserves at the Kiang'ombe hills (Olson, 2004). Rural to rural migration is pronounced in the catchment where population density in the neighboring high potentials districts has forced the landless people to more marginal areas due to excessive land subdivision and high land cost (GOK, 2013). The people from surrounding rural areas such as; Embu west and Embu east Sub-Counties, Machakos County, Tharaka-Nithi and Kirinyaga counties also migrate into these semi-arid areas, where they increase cattle keeping and grow a variety of crops (GOK, 2013). Improved and intensive land production practices are incompatible with the unpredictable and fragile semi-arid environment

(Southgate and Hulme, 1996). The catchment lies in Mbeere North Sub-County, which has a total population of 99,587 persons and a population density of 129 persons per km^2 This is an increase in population from the 2009 census, where the population totaled 86,186 persons and a density of 111 persons per km^2(GoK, 2019). Population increases any area increases demand for food, water, forage and connecting roads, consequently adding massive pressure on land exploitation, eventually leading to an increase in erosion rates. The research established the effects of population increase on gully development over time.

CHAPTER FOUR: RESEARCH METHODOLOGY

4.1 Introduction

The chapter presents an investigation of the area, methodology and data used in the research work. It discusses; the research design, sampling technique, data collection and analysis and computation to examine gully erosion and conservation and stabilization in a semi-arid environment. To achieve the objectives of this study, different methodological approaches were employed. Data obtained from remotely sensed images and analyzed using GIS, extensive and detailed field surveys were integrated to evaluate geomorphological and morphological factors that initiate and promote gully erosion in a semi-arid environment. These methods combined resulted in the generation of gully inventory and susceptibility maps, morphological structures most affected by geomorphic processes and gully threshold S-A relation establishing areas with more risk of gully occurrence.

4.2 Research design

The study used a quasi-experimental design where control groups were observed against experimental groups within the study area. Control group areas were un-gullied slopes observed against gullied areas against gully conditioning factors; land cover, rainfall variability, soil type and gully morphometry characteristics. The Wanjoga River catchment region was divided into three sections based on elevation and rainfall variability; lower segment region rising from 600m – 900m, rainfall averaging at 550mm, mid-slope segment at 900m -1200m, rainfall averaging at 860mm while upper slope segment rising > 1200m rainfall averaging 1100mm. Each gully conditioning factor was evaluated in its class factors (i.e. slope classes; >20°, 10°-20°, <10°) and in relation to other geomorphological factors (slope, soils, rainfall, elevation) to determine the effect on gully susceptibility and development. The rate of gully erosion was examined for 19 years in relation to land cover changes since gully channels undergo changes over short periods, carrying out mapping for the years 2000 and 2009 and direct gully parameter measurement for 2021.

4.3 Sampling procedure and sample area

The study was carried out at the Wanjoga River catchment in Tana River Basin. The Wanjoga River catchment was purposively sampled due to the intensity of gullies' occurrence and the problem's persistence. The catchment area extends from Kiang'ombe hills (1700m) to River Tana (500m), within which gully developed vary in intensity across landscapes.

A multistage sampling technique was adopted to establish the sampling frame. The first stage involved the selection of the study area. The second stage involved selecting the sample area, and determining gully systems for analysis in the study. Gullies were sampled based on their morphological structure and morphometric size (length, width depth) across the three-elevation segment. All large and medium-sized gullies across the three segments were purposively sampled for the study to evaluate the effects of geomorphological factors (soil and slope characteristics, land cover and rainfall variability) on gully initiation and extension.

Gully size was determined using FAO (1977) classification, where a medium gully width range from 0.5 – 1m and a large gully is >1m in width. Gullies were identified using Landsat 8 images. Gullies whose cross-sections run across the three-slope segment were also purposively sampled and a transect walk across them was taken to establish morphological changes across gully profile and most prominent geomorphic processes at different gullied points. Farmers whose land was affected by medium and large-sized gullies were interviewed to establish social-economic factors of gully conservation since they are responsible for soil conservation on their farms.

4. 4 Pilot Study

Piloting was conducted in the study area to deliver relevant documents, sample gullies for the study and identify farmlands and farmers to be used. A pilot study was used on the questionnaires for farmers to test the research instrument's validity and reliability. To ensure the items on the questionnaires used to collect data on farmlands were adequately adapted to the theoretical concept of the study, the content and construct of a test for the validation of the research measuring instrument were adapted (Sekaran & Bougie, 2009).

Face validity test was carried out on the wording and sequence of items to determine the most suitable among the formants, to ensure the items of this study adequately measured the hypothetical concept, and predicted challenges that could have arisen during the data collection period. The outcome of the reconnaissance was used to readjust the instrument to ensure meaningful inferences were drawn from the measure of the instruments.

4. 5 Data sources and collection

Secondary and primary data sources were used in the study to achieve the stated objectives. Secondary data was obtained from topographical maps and satellite imagery. Primary data was acquired from extensive field surveys on gullied areas and along the gully, networks by; taking GPS points at gullied locations, measuring gully parameters, photographing more elaborate sections of gullied regions and stabilization structures, and identifying and documenting geomorphic processes along gully channels. Interviews were also conducted on farmers whose farms had large or medium gullies.

4.5.1 Secondary data sources

4. 5.1.1 Satellite imagery and topographical maps

A combined mapping approach was used to prepare accurate and reliable gully inventory maps to evaluate the geomorphological factors that modify landscape and influence gullies' initiation and progression development. Data were obtained from different sources, integrating topographic maps and data processed from remote sensing images. Each geomorphological factor was mapped using the appropriate method to create raster maps which would later be incorporated into weighted values and gully susceptibility map.

Slope and elevation images were generated from a 30M resolution Digital Elevation Model (DEM) obtained from Shuttle Radar Topography Mission (SRTM) satellite. The data was re-projected in ArcGIS 10.4 and clipped to the area of interest (Wanjoga River Boundary). This formed ranges of the slope, which later was reclassified into classes of most suitable, moderately suitable and less suitable**.** During data analysis, the concept of surface runoff (areas where rainwater naturally flows) was considered: areas where water tends to flow, downslope and accumulate. Land cover maps were obtained from Landsat 8 images from the USGS website. The Landsat images were acquired from January to February for the years; 2000, 2009 and 2018 to reduce diverse variability in rain events, which can significantly change the land cover. Soil data were obtained from shapefiles from the Kenya soil surveys. The resolution for the soil data map was 1:50000. The classification was then performed based on soil texture and depth.

The spatial data like the rainfall was obtained in (x, y) point format and thus was plotted in ArcGIS to develop a raster format using ESRI ArcGIS software showing rainfall variability in the region. Using Spot image 1.5m resolution available, drainage, and by Google Earth for Wanjoga River catchment, gullies were digitized from September 2018. Ground-truthing was carried out in identified gullied channels. Also, mapping of gullies using GPS during the field visits and the gully set was used for validation. All Datasets were inputted, processed, layered and reclassified to assign categories and levels of susceptibility-based gully influencing factors.

4. 5.1.2 Rate of gully development

To establish the relationship between gully morphology and rate of gully development in the semi-arid environment, long-term gully volume for the three most active gullied channels were selected based on size, and morphology (U, V T-shaped gullies), availability of historical sequence on Landsat images and monitored over 21 years. Gully channels were monitored using three Landsat images for 2000 - 2009 and 2021. Gully morphometric parameters (length, width, depth) were calculated using a measurement tool in ArcGIS software, where a line is drawn along the gully parameters. Distance is calculated and reading is presented in the average form. For 2000 and 2009, morphological parameters were determined using Landsat images. Change in length, depth and width were selected from the initial time (2000/2001) to the current (2021) position from pre-determined points along the gully channel, which was first identified and measured using field surveys and their GPS points recorded for the year 2021. Using a sequence of Landsat images for 2000, 2009, and 2018, frequency and rate of gully increase were determined over time. The linear gully retreat rate in m/yr, was calculated by dividing the gully retreat length by the duration of the observed period (21 years)

4.5.2 Primary data sources

4. 5.2.1 Direct field Measurement and Documentation

Extensive and detailed field surveys were carried out to establish the relationship between geomorphological factors, gully morphological characteristics, the spatial distribution of gullies and the rate of gully development in the semi-arid environment. Gullied areas were mapped using clinometers, rode, measuring tape and a Global Positioning System (GPS) map 62s receiver; to determine gully parameters and gullied position in the study area.

Gully morphology and morphometry in different locations were characterized includes; maximum and minimum gully parameters (length (l), depth (d) and width (w)), which were recorded and used to calculate the volume (Vs) of soil loss per gully unit area (m^3) and volume of soil loss over gully surface area A (m^2).

Gully cross-section parameters were obtained by taking two or three depth and width parameters at the point where morphologies change drastically. Gully system surface area was digitized using GPS, and measurement was compared with physical measurements from field data collection. Repeated photographing of sampled major gullied areas was carried out to establish geomorphic processes affecting gully head, banks and bed as influenced by gully morphology and geomorphological factors. Soil samples were picked within gullied areas for analysis in laboratories to establish the role of lithotypes on gully development.

Rainfall information was acquired from four gauging stations for the period 2000-2018, randomly distributed across the catchment stations in Mbeere North (Isiara, Ciakariga and Kiambere) were acquired from the Meteorological Department of Kenya. Data obtained from the gauging station had several data gaps. Some stations like Ciakariga provided rainfall data for only two years of the required period, while other gauging stations had data gaps between days, months and years. The rainfall data gauging station gaps were filled using the Kriging interpolation method in ArcGIS 10.3 software. Rainfall data was used to prepare the final rainfall raster map in ArcGIS 10.5. The Information obtained was used to depict the role rainfall variability play in gully development.

4. 5.2.2 Gully threshold estimation

The threshold for gully erosion in the study area was determined by demarcating the catchment area contributing overland flow to the gully by measuring the point from which overland flow was assumed to reach the channel cross-section at the gully head position. Garmin GPS mapper 62s receiver was used to record head positions for the 31 most active gullied areas from December 2020. Areas contributing overland flow to gully heads were demarcated using GPS based on visible water flow lines and measured using a 50meter-long surveyor's measuring tape. Gully head slopes were measured at the field using clinometers since it was assumed that a gully initiates at the steepest slope (Nyssen et al., 2002). Geomorphic processes nearest to the gully head position were delineated from the gully head point; 10m up-lope and down-slope. Finally, GPS points from the field were uploaded into ArcGIS and used to digitize topographic parameters and establish critical slope and drainage areas for gully initiation across different landscapes.

4.5.2.3 Interviews schedules

Interview schedules were used to collect primary data. Interview schedules were administered to farmers whose farmlands were affected by gullies of width >1m to establish farmers' perception of gully conservation. Gullied areas with installed rehabilitation structures and un-conserved sites of increased soil loss were repeatedly photographed to show the success rate of installed rehabilitation structures. The perceived success rate was based on evidence of the gully healing process in the upper and lower section of the gully channel. The exercises were geared toward establishing the success of gully rehabilitation methods in the study area.

4. 6 Data Analysis

4.6.1 Gully mapping and determination of susceptibility to gully erosion

Gully susceptibility mapping and determination of the spatial distribution and density of gullies in Wanjoga catchment was carried out using remote sensed Landsat images and data obtained from field surveys; integrated to evaluate geomorphological factors that initiate and promote progressive development of gullies in the semi-arid environment. First, the field's spatial database of the gully features was created to catalogue gully characteristics and facilitate further analysis. The gully points catalogued in the field were transferred from a GPS to a desktop GIS system in a point shape file format and then transformed into a point feature class within a geo-database. Secondly, Gullies in in-accessible areas were detected by use of Spot image 5m resolution availed by Google Earth and analyzed by edge detection operator in Arc-GIS. Gullied area was segregated, and gullies were identified visually by shape, size and tone. Gullies in non-vegetated areas appear bright in red and infra-red (IR) (bands 4 and 5) and follow the drainage pattern of the site, such as dendritic, radial and centripetal.

Gullies which could not be identified visually in Spot 5 resolution image were segregated using an image segmentation algorithm to ensure areas where gullies develop remain and are identified quickly. The edge detection operator is used to identify line-edge from segment images. The edge image obtained from edge detection and flow lines from DEM were used to detect gullies along flow lines. Uses of field data in validation helped in including the omitted gullies in the images and excluding features such as footpaths which were mistaken for gullies.

4.6.2 Creation of maps of evidential themes

The selection of gully conditioning factors was based on the available data needed to create map evident themes. Five conditioning factors, including; slope, soil texture, annual average rainfall, elevation and land use/land cover, were selected and analyzed. Slope and elevation images were generated from a 30M resolution DEM obtained from Shuttle Radar Topography Mission (SRTM) satellite. The data was re-projected in ArcGIS 10.4 and clipped to the area of interest (Wanjoga River Boundary). This formed ranges of the slope, which later was reclassified into classes of most suitable, moderately suitable and less suitable**.** During data analysis, the concept of surface runoff (areas where rainwater naturally flows) was considered: areas where water tends to flow, downslope and accumulate.

Land cover maps were obtained from Landsat 8 images from the USGS website. The Landsat images were acquired from January to February for the years; 2000, 2009 and 2018 to reduce diverse variability in rain events, which can significantly change the land cover. The data were then transformed into one projection system. Image processing was performed before analysis and classification by supervised classification on Landsat 8 image in Arc Map to create a land cover map. The supervised classification resulted in four land cover classes: forest, wooded grasslands, cultivated land, bare lands, and Water. Soil data were obtained from shapefiles from the Kenya soil surveys. The resolution for the soil data map was 1:50000. The classification was then performed based on soil text depth. Reclassification for drainage was performed, which resulted in classes. Since soil data covered the whole country, clipping was done to obtain data for the Wanjoga river catchment. The lithotypes categories in the Wanjoga catchment included; lithosols, cambisols and arenosols.

The spatial data like the rainfall was obtained in (x, y) point format and thus was plotted in ArcGIS to develop a raster format using ESRI ArcGIS software showing rainfall variability in the region. Also, using Spot image 1.5m resolution availed by Google Earth, drainage, and gullies digitized from September 2018; ground-truthing was performed for the pinpointed gullies. Additionally, known gullied sites were mapped with GPS during the field visits and the set was used to validate inventory images created. All Datasets were inputted, processed, layered and reclassified to assign categories and levels of susceptibility based on gully influencing factors.

4.6.3 Gully susceptibility mapping

To establish susceptibility to gully erosion, satellite images for each geomorphological factor (land cover, slope angle, soil type, elevation and rainfall variability) were processed into specific raster layers to show the influence of particular factor classes (i.e., slopes < 10°, 10° -20°, >20°) on gully erosion, while the layering of all the factors was to determine the influence of all the factor to gully erosion.

Once the analysis in Arc GIS converted data to raster format/ raster layers, weights were assigned to each parameter depending on its influence, i.e. 1-3, to represent less susceptible to most susceptible. If one illustrates less sensitivity, it should be the same for all the layers used. This Reclassifies values in the input raster into a similar unifying scale of susceptibility and multiplies the cell values of each input raster by the raster's weight of importance; it then adds the resulting cell values together to produce the output raster.

All datasets were then inputted, processed and reclassified to assign categories. The independent variables were weighted (Equation 1) depending on their importance in relation to the dependent variable. To produce the final susceptibility map, use of Weighted Overlay Tool in ArcGIS was employed to combine the influence for each factor; each factor was assigned a weight depending on the level of influence. The elements were weighted depending on their importance in comparison to each other. Once the weighting of conditioning factors was carried out, overlaying of all factors was executed at ArcGIS version 10.4 to produce the final susceptibility map. All datasets were then inputted, processed and reclassified to assign categories to show the level of susceptibility to gully erosion (Figure 4.1);

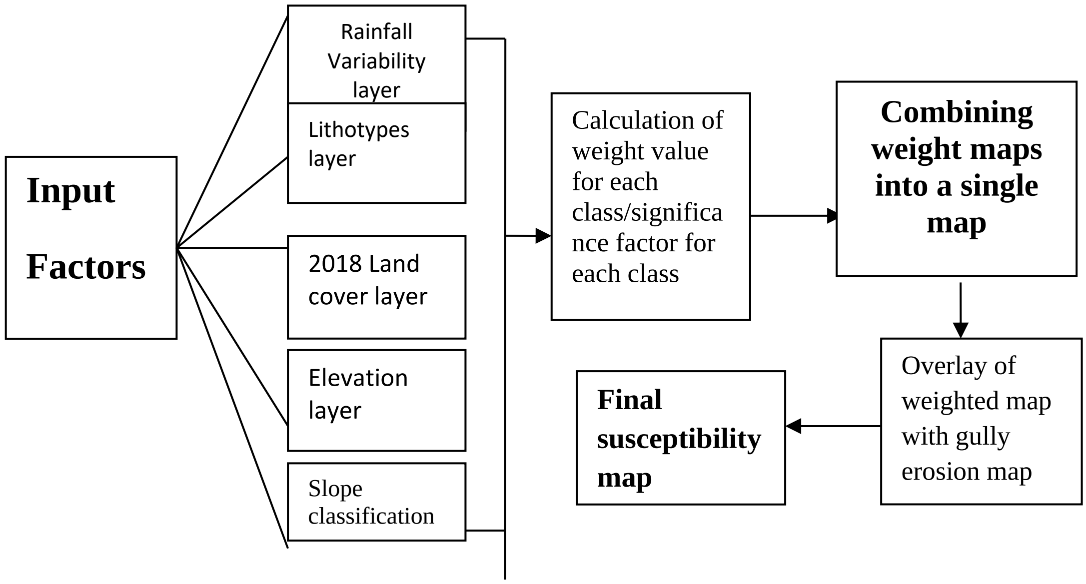


Figure 4.1: Flowchart for gully erosion susceptibility mapping

4.6.4 Testing verification for Landsat images

To access the accuracy of the output, the use of an error matrix was carried out. An error matrix is a standard accuracy reporting system that shows an array of category labels in the classified map against data from field observations using ground-truth reference data. It is used to calculate producer, user and overall accuracy, and the kappa statistic is calculated using the formula of Jensen (2005).

$$\text{Overall accuracy} = \frac{Total\ number\ of\ pixels\ correctly\ categorized}{Total\ numbrtr\ of\ pixels\ in\ the\ map} \qquad 10$$

$$\text{User accuracy} = \frac{Number\ of\ pixels\ correctly\ categorized\ \ as\ gully}{Total\ number\ of\ gully\ pixels\ in\ the\ classified\ map} \qquad 11$$

$$\text{Producer accuracy} = \frac{Number\ of\ pixels\ correctly\ categorized\ as\ gully}{Number\ of\ gully\ pixels\ in\ the\ reference\ data} \qquad 12$$

Once the producer and user accuracy of the determining factors are calculated, the Kappa statistic for the gully susceptibility map was calculated, which considers the overall statistical agreement of an error matrix (Lu and Weng, 2007). Kappa statistic measures the difference between the actual and chance agreements and considers the whole error matrix. The values range from 0 to 1 with values >0.80 indicating a positive correlation between classified images and GPS points acquired during the field study. The reference data taken by GPS and those ranging from 0.4 to 0.8 represents the level of agreement using the equation of Congalton (1991).

$$\frac{n\sum_{n=1}^{k} n_{ii} - \sum_{n=1}^{k} n_{i+}n_{+i}}{n^2 - \sum_{n=1}^{k} n_{i+}n_{+i}} \qquad 13$$

Where:

n=total samples collected

nii=samples correctly categorized in i

ni=samples categorized in i in the classified image scenario

n+i samples categorized in i in the referenced data set

4.6.5 Soil loss prediction

RUSLE model was applied to re-construct the current hypothetical possibilities of soil loss in the river catchment. RUSLE model was used since it is incorporated in the ArcGIS tool. Hence, by integrating RUSLE and GIS, soil loss in t/ha/yr was obtained. Area DEMs were processed with RUSLE- 2D software to calculate the topographical factor and predict soil loss. Soil loss volume was calculated using the USLE equation 2 (Renard et al., 1997). The potential annual average soil loss value (*A*), was calculated by overlaying five grid surfaces over the Wanjoga river catchment. Five types of parameters were analyzed in the GIS environment. Rainfall data were obtained in (x, y) point format and then plotted in ArcGIS to develop a raster format using ESRI ArcGIS software. Using field measurement, soil erodibility factors were acquired based on soil properties (Wischmeier and Smith, 1978). Topography factors were calculated using 30m resolution DEM obtained from Shuttle Radar Topography Mission (SRTM) satellite to generate slope and elevation parameters. Land use was acquired by combining individual *C* factors from empirical models and satellite classification images. Land cover was analyzed using the Normalized Difference Vegetation Index (NDVI) (Millward and Mersey, 1999). The technique estimates potential soil loss and spatial distribution of regions of soil loss with better accuracy for expansive areas (Wang *et al.,* 2003). The rate of soil loss by the RUSLE method was compared with the rate of soil loss by gully erosion to show the seriousness of gullies in sediment loss in a river catchment. It should be noted that, the computation of the rate of soil loss per year in gullies is necessary since the RUSLE model does not include soil losses by gullying

4.6.6 Direct field data analysis

To evaluate the influence of geomorphological and morphological factors on progressive gully development in Wanjoga River catchment, change in gully area and volume was determined by analysis of gully parameters using detailed field data. Once gully parameters were determined by use of physical field data and surface area digitized GPS, the rate of gully erosion was calculated by determining changes in parameters such as length, width and depth of different cross-sections. Eroded gully volume of each crosse-section (V in m^3) and distance between cross-section was calculated; (Angileri, 2012)

$$V = \Sigma A_i L_i \quad 14$$

Where;

L = The gully length between two cross-sections

A - Area of cross-section

Computed gully volume was used to determine the degree of association between influencing factors; geomorphic factors, gully morphology and rate of gully development in the semi-arid environment since it reveals the dynamic nature of the gully based on this predisposing factor.

Soil sample analysis was carried out by use of pore-size filters, which separate grain size and allow for evaluation of sampled soils. In contrast, the USDA-texture triangle defined the soil textural classes of the 66 soil samples collected.

A*chi-squire test* was performed to show the relationship between variables by graphing the overall picture of the gully development system. A Chi-Test test is an excellent measure to show the relationship between variables since the data does not follow Gaussian distribution and most variables are collinear. The test showed the relationship between gully volume, and morphological and geomorphic factors in the area using (Gregory's (1978) formula.

$$X^2 = \Sigma \frac{0 - E^2}{E} \quad 15$$

Where; O is the observed frequencies and E is the expected frequencies

4.6.7 Rate of gully growth

To establish the relationship between gully morphology and rate of gully development, long-term gully volume for the three most active gullied channels running across transect regions was computed based on average morphometric parameters (length, width, depth) calculated by use of the measure tool in ArcGIS software. Change in length, depth and width determined from the initial time (2000/2001) to the current (2021) position and gully volume computed were used to assess gully growth rate (m /yr), calculated by dividing the growth rate and volume by the period of the observed period.

4.6.8 Gully threshold estimation

Gully initiation threshold for 31 gully head points was used to determine the threshold factor for gully initiation using topographic threshold models of drainage area contributing surface overland flow to the gully (*A)* and gradient at the gully head (S). The appropriate $S - A$ relation for the environment to evaluate the possible threat of gully initiation on a slope. The relationship is described by the power function, using the equation Vandaele *et al.* (1996), and expressed as:

$S = {}_aA^b$ 16

Where;

S = local slope in m/m,

A =is the up-slope drainage area (ha) from the head cut position,

Coefficient, *a* and exponent *b* values, have diverse values based on the state of the local slope under different environments. The values of '*a'* and '*b'* are acquired from a log-log scale plot of *'S'* versus *'A'*.

The statistics derived were used to determine the distance required by surface overland flow for gully initiation at a specified slope angle. The relationship between gully head slope and drainage area contributing to the gullies over the three-segment regions was analyzed using the Anova value b, test (Analysis of variance), to establish the significant relationship between the two variables using the regression coefficients.

y = $b_0 - b_1$ x 17

Where;

y – local slope

x – Contributing area

b_0 – Regression intercept

b_1 – Coefficient of area

4.6.9 Success of gully stabilization methods

Social-economic factors for farmers on gully rehabilitation structures and their effectiveness in the gully healing process were determined using Paired sample t-test to depict the relationship between the variables. Paired sample t-test is an excellent measure to compare two population averages in the case of two samples that are correlated. In a case-control study, a paired sample t-test is the best measure to show how effective rehabilitation structures are in gullied areas in relation to non-rehabilitated gullied areas. The analysis sets two hypotheses; the null hypothesis, assumes that the two means of paired samples are equal.

$$\mu_{gulley\ areas} = \mu_{healed\ gulley}$$

and the alternative hypothesis, which assumes that the means of two paired samples are not equal

$$\mu_{gulley\ areas} > \mu_{\ healed\ gulley}$$

Once the hypothesis was set, the level of confidence was chosen at 5% using (Goulden, (1959) formula.

$$t = \frac{\bar{d}\sqrt{n}}{s} \qquad 18$$

t-statistic above follows *t-distribution with (n – 1) d.f.,*

$\bar{d}$ =mean of the differences

$$\bar{d} = \frac{\sum d}{n} \qquad 19$$

d – the difference between paired observations is the standard deviation of the differences and is given by:

$$s = \sqrt{\frac{\sum\left(d-\bar{d}\right)^2}{n-1}} = \sqrt{\frac{\sum d^2 - n\left(\bar{d}\right)^2}{n-1}} \qquad (15)$$

and

n is the number of paired observations in the samples.

If the p-value computed correlates with the computed ‘t’ value is > 0.05 (5% significance level), the null hypothesis is accepted, otherwise rejected.

Table 4.1: Summary of study methodology

Study objective	***Data Collection Method***	***Field Activities***	***Data Analysis method***	***Unit of Analysis***	***Importance to the study***
To evaluate geomorphological factors that initiate and promote progressive development of gully erosion	-Secondary data from Landsat images GIS, remote data -Detailed field surveyed data by GPS	-Acquiring Spot image 1.5m resolution, 8m and 15m resolution satellite images -Detailed surveying of gullied areas by use of GPS - Field measurement of gully morphometric parameters	-Use of bivariate statistical approach in ArcGIS -Use of Weighted Overlay Tool ArcGIS -Kappa statistic - *Chi-squire test*	Gully	-The accuracy of predicting areas susceptible to gully erosion is valuable tool for targeting, planning and monitoring for conservation of regions sensitive to concentrated overland flow
To establish the relationship between gully morphology and rate of gully development	-Detailed direct field measurement and surveys -Landsat images	-Field measurement of gully morphometric parameters -Documenting morphological characteristics and areas most affected by geomorphic processes -Analysis of parametric changes in three gully morphologies using Landsat images over 19 years	Calculation of gully volume for each gully segment by use of cross-sectional areas -GIS - *chi-squire test*	-Gully	Establish morphologies most affected by geomorphic processes and most active gully points for effective gully stabilization - Suggesting gully stabilization structures -Soil conservation
To determine the threshold of gully development in the semi-arid environment	-Use of satellite images -Direct field measurement on gully channel -GPS points	-Measurement of areas contributing surface runoff to gully heads -Picking GPS points of the extent of the drainage area -Measurement of gully head initiation slope	-Slope-area topographic threshold for gully initiation -GPS - ANOVA	-Gully -Gully head slope -Gully drainage area	-Locating areas most susceptible to geomorphic processes for gully initiation -Locating areas most appropriate for installing conservation and rehabilitation structures -Soil conservation
To evaluate the success of different gully stabilization methods used for controlling gully erosion	Interview schedules	-Filling of interview schedules from famers ad key informers	Paired t-test	-gullies -gully stabilization structure	-Identify the most appropriate conservation structures -Gully stabilization -soil conservation

CHAPTER FIVE: RESULTS AND DISCUSSIONS

5.1 Introduction

The chapter presents the study's findings about gully erosion and stabilization in the semi-arid environment of the Wanjoga River Catchment of the Tana River Basin. Based on the study objectives, the chapter presents the effects of geomorphic factors on gully initiation and progression. It evaluates their inter-relationship with gully development in a semi-arid environment.

5.1.1 Gully erosion in the semi-arid environment of Wanjoga catchment

Digital and visual analysis of Landsat images and systematic field surveys revealed that about 4% ($8.02km^2$) of Wanjoga river catchment is affected by gully erosion (35,650 pixels out 891,271 total pixels). A total of 66 gullied areas were identified in the study area, of which 39 gullied areas were captured correctly by the use of Landsat images. In contrast, the rest were identified during field data collection and verification and included in the gully inventory map of the study area. The analysis revealed that gullies occur in a more random way across the landscape, with gullied areas on the western side (upper segment; 1200m – 1800m) shorter and tend to be discontinuous in that they terminate mid-slope, but a few continue down slope and evolve at points of junction (Figure 5.1).

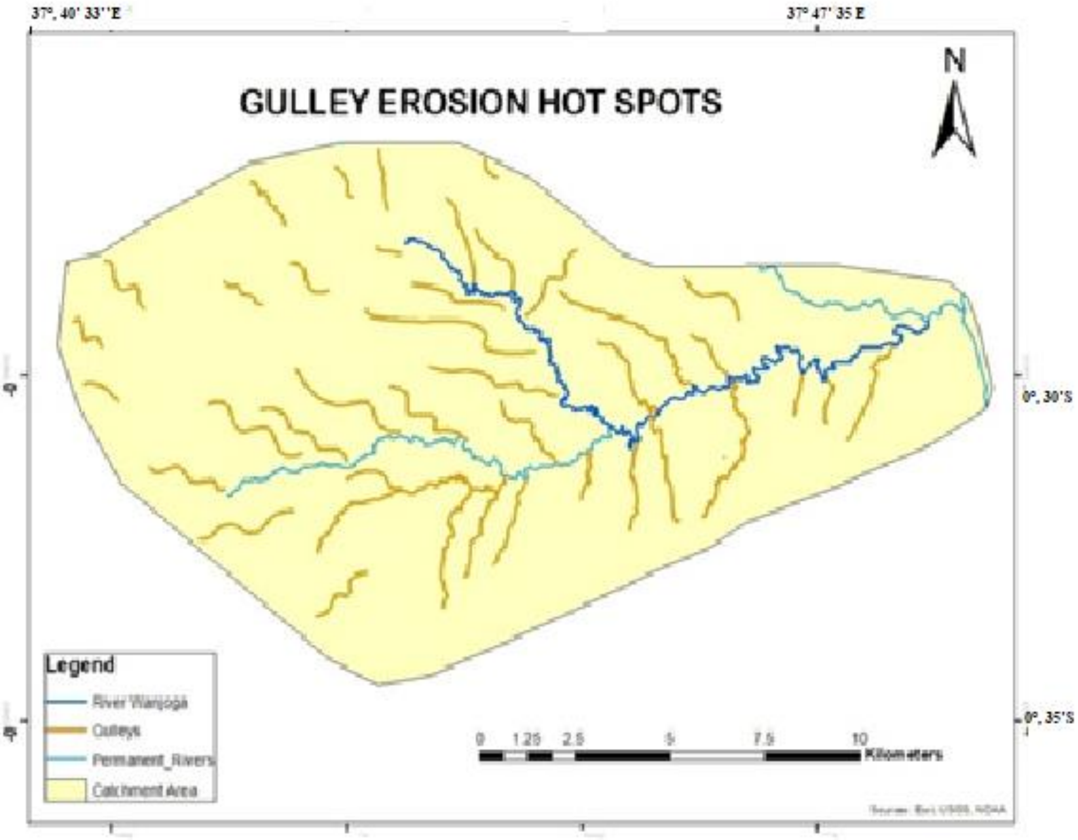


Figure 5.1: Spatial distributions of gullies in Wanjoga River catchment

In the eastward direction (lower segment; 600m – 900m), gully channels are more continuous and marked by the evolution of gully networks, increasing gully density downslope. Variables describing the geometry of gullies in the study area include; gully length, depth and width. Geometric analysis of gullies reveals a more complex characterization, with gully channels varying in the vertical incision and side-walls extension across geographical segments. Regarding gully length, the mean value for the entire study area ranges from 345m at the upper segment to 1080m at the lower segment, with a range of differentiation depending on geomorphological factors acting upon individual gullies (Table 5.1).

The depth of gully channels increases eastwards with the direction of increased elevation. The upper-segment region has a maximum incision depth ranging from 2.5m to 4.2m. On the contrary, the mid and lower segment gullies present a low incising power with depths averaging at 0.9m and 0.5m through several gullies with a maximum depth of a high of 5.6m deep (Table 5.1).

Table 5.1: Gully morphometric characteristics in Wanjoga River catchment

Segment category	Gully count	% Gully	Incision depth (m)		Extension width (m)		Length (m)		Average volume m^3	Total gully volume m^3	% Volume
			Max d	Av. d	Max. w	Av. w	Max. l	Av. l			
Upper segment (> 1200m)	33	50	2.5	1.0	4.2	0.6	1,600	345.5	450.5	14,866.5	12.1
Mid-segment (900 – 1200m)	25	37.9	5.6	0.9	7.5	1.6	2,400	620.1	3,225.6	80,640.7	65.1
Lower segment (600 – 900m)	8	12.1	1.3	0.5	7.5	2.2	5,700	1,080.0	3,319.7	26,556.9	21.8
Total	66	100								122,062.9	

The high incising depth of gully channels in the upper segment region results from continued scouring at the bed and the bank. An increased bank height decreases its stability bringing about failures under gravity, generally attributed to gully banks that are retreating most frequently by slumping and/or shallow mass failures (Valentin *et al.,* 2005). Moreover, soil sediments from cambisols (clay loam to clay), such as those occurring at the upper segment, are generally quickly evacuated within the gully channel, encouraging further increased incision (Figure 5.2). The width of the gullies varies similarly, with gullies at the upper segment comprising mainly of hillslope gullies, presenting low extension power, width averaging at 0.6m.

Figure 5.2: Retreating gully head by failures in the upper-segment region

Gullies at mid (900m – 1200m) and lower segment (600m – 900m) comprising valley gullies are generally broader and shallower. The valley gullies have a high extension power with width parameters averaging at 1.6m to 2.2m for mid and lower segments, respectively. The noted divergence in morphometric variability in the gully landforms resulted from geomorphological factors and geomorphic processes affecting gullies across the study area.

Once a gully is formed into recognizable channels, soil particle displacement within a gully system is similar to corrosion and transportation in open channels (Bull and Kirkby, 1997). The process of particle displacement in lower and mid regions is brought about by concentrated overland flow at a high velocity of water at the point of discharge (mainly at the roadside). The increased flow speed is adequate to dislodge and transport particles by increased discharge (Q) (Kirkby and Brecken, 2009). The scouring process occurs when the flow that enters macro-pores is accelerated, where hydraulic gradients are steeper in mountainous landscapes or vertical high channel heads or banks (Dunne, (1980).

The critical characteristics controlling gully erosion in such a situation are the velocity and discharge (Q), with Q proportional to the drainage area (QD), which is proportional to sediment discharge (QS) as simulated in Figure 5.3. The input into the gully (discharge) is the driving force that increases flow velocity, increasing the width, depth and length of a gully in a homogenous soil in peak discharge. As shown in Figure 5.3, at the gully head position (R1), limited discharge into the gully system ensures low geomorphic processes limiting the gully bed and head. Gully banks are inactive and stable, with most geomorphic processes confined to the bed resulting in more profound and narrower gully channels, as indicated in the upper-segment region (western side of the region), with gully head retreat more impacted by human activities and plant root system (Figure 5.3a).

The region R2 represents a semi-active character of gullies, where the walls are stable with slight geomorphic processes on the banks and beds. In contrast, the R3 region represents the most active region of the gully system, brought about by increased discharge due to the merging of gully channels. The gully banks are nearly vertical with increased geomorphic processes; undercutting, slumping and failure (Figure 5.3b). The greater the bank slope, the greater the probability of slumping, thus, more active gully channel laterally. The gullies have a high extension power with an average width of 1.6m, depth of 0.9m, and length of 620m, increasing overall volume averaging 3225.6m^3 (Table 5.1).

Figure 5.3: Increased discharge has increased headward extension channelization. (b)Active bed processes) (c) increased bank geomorphic processes(d) Stable gully heads and banks

The valley gullies R4 have the highest volume, though they have attained stable heads and banks with almost no slumping and undercutting. This could be attributed to continued erosion reaching the rock region (Figure 5.3d), increased channelization at the lower segment resulted in complete removal of topsoil, which has risen the overall amount of sediment removed from gullied areas, with volume averaging at 2936m^3 per gullied area (Table 5.2)

Table 5.2: Relationship between discharge and sediment discharge on gullies in Wanjoga catchment

Geographical segment	Average slope (*m/m*)	Average drainage area (ha)	Average gullied erosion (m^3)
Upper region	0.13	0.62	414
Mid-region	0.1	0.84	1146
Lower-region	0.07	2.59	2936

The upper segment region portrayed a low average drainage area per gullied area of 0.62ha and an average volume of 414m^3 per gullied area. Therefore, increased discharge (Q) affected by increased drainage area and/or concentrated flow from roads at peak times has increased lateral and headward gully extension commonly associated with gully banks retreating by mass movements. Excessive deep-seated failures on lower and mid-segment results in immense volumes of debris which block the gully thalweg and limit effective removal of sediments resulting in deposition (Kirkby and Brecken, 2009). Increased accumulation of sand debris on gully channels at lower the segment has contributed to increased human activities, including sand harvesting resulting in excessive bed processes across gullied areas. Sand harvesting

Activities in lower and mid-segment regions result in excessive soil loss per gullied area volume averaging at 3,225.6m^3 and 3,319.7$m^{3,}$ respectively. However, mid-segment region gullies account for 37.9%, while the lower-segment region accounts for 12.1% of the total gullied sites (Table 5.2). Increased volume per gullied area at mid and lower segments can be attributed to gullies affected by anthropogenic activities, including; sand harvesting resulting in high cumulative volume, surpassing 5,000m^3 (Figure 5.4)

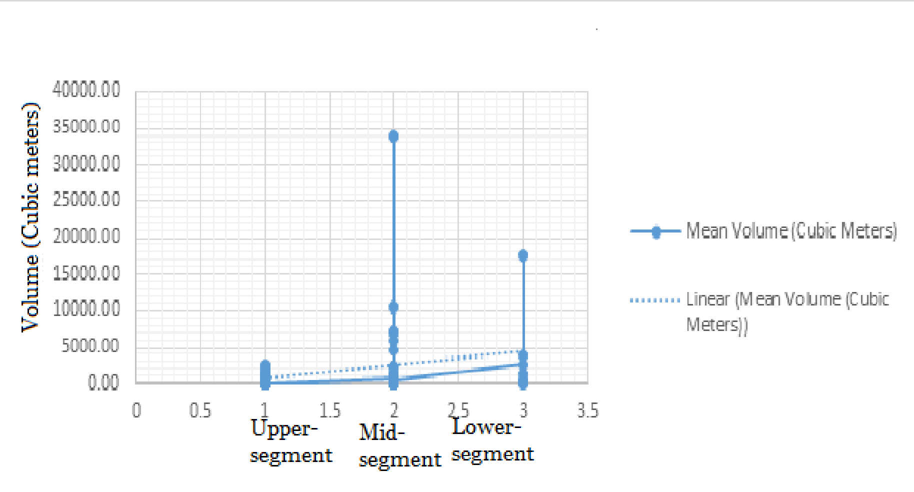


Figure 5.4: Gully volume across segment regions

Consequently, varied morphometric parameters brought about by the various effect of geomorphic processes on gully heads, beds and banks portray gullies with a more complex morphometric characteristic and organization across the study region. Gullies are more profound and narrower at high altitude regions (900*m* – 1800*m* and become winder and shallower in a down-slope direction (Figure 5.5 a, b), remaining more or less stable in a down-slope order.

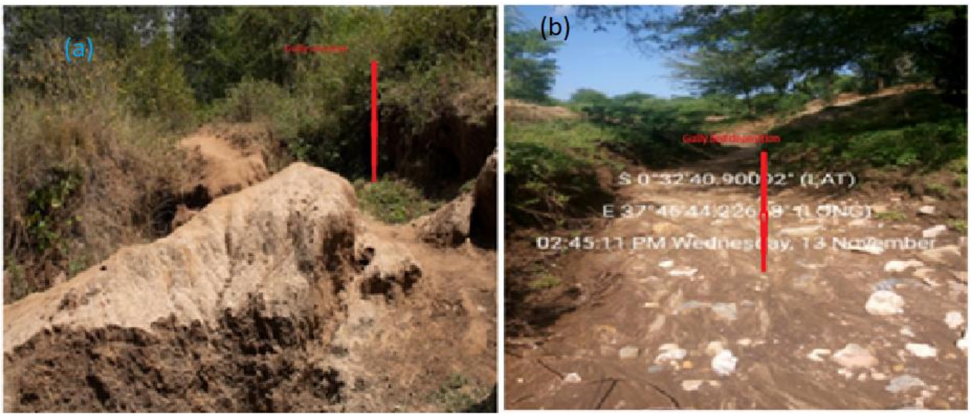


Figure 5.5: **Variation in gully erosion across segment different regions**

(a) Deep incision on gully in the upper segment (>20°) (b) Deposition on the bed on gully at the lower segment (0°-10°)

Gullies in the upper and mid-segment (Figure 5.5 a) have steeper and more vertical banks, decreasing as gullies get transformed towards the low gradient region. Similar results are portrayed by the use the of chi-square test carried out at a 0.05 significance level, showing a strong positive significant relationship between gully volume and elevation in the Wanjoga river catchment p= 0.04, which is similar to fishers' test at p = 0.05 (Table 5.3)

Table: 5.3: Chi-Square tests on gully volume and geographical segments

	Value	df	Asymp. Sig. (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)	Point Probability
Pearson Chi-Square	10.244[a]	4	.07	.04		
Likelihood Ratio	12.289	4	.05	.05		
Fisher's Exact Test	10.760			.05		
Linear-by-Linear Association	7.203[b]	1	.007	.008	.006	.003
N of Valid Cases	66					

Calculated X^2 = 14.800. 2 Significance level at 0.05

Thus, gully development is a more serious problem in higher elevation areas since gullies require limited drainage areas for initiation. Low elevated areas are more impacted by channelization, which increases gully drainage area, increasing discharge (Q), which in turn affects gully volume. The findings concur with those of Lonergan *et al.* (2013) that gullies in Gabon become increasingly dense and wider spaced in a seaward direction. Therefore, gullies on the upper segment (steeper region) are influenced by bed concentrated geomorphic processes, while those on the lower segment region (gentler slopes) are more affected by side banks processes (slumping, failures, mass movement), resulting in shallower and wider gully channels.

5.1.2 Geomorphological factors for gully development in Wanjoga River Catchment

Adequate definition and consideration of gully conditioning factors and their relationship to gully occurrence are inevitable in eval gully development in a river catchment. Gully erosion and spatial distribution of gullies in a catchment area are controlled by factors that trigger susceptibility to gully initiation and increase geomorphic processes for gully extension. Gully geomorphological factors (conditioning factors) are grouped into two; extrinsic factors, which surround a gully and contribute to the channel initiation and progressive development (rainfall variability, land cover, soil characteristics) and intrinsic factors, which act to determine the rate of lateral, headward and vertical extent of gullies.

5.1.2.1Rainfall variability and gully erosion

The annual rainfall analyzed was based on four gauging stations for the period 2000 – 2018 recorded an average value of 550*mm* per annum in the lower region and 1100*mm* in the upper region. However, rainfall averages output based on Kriging interpolation at ArcGIS 10.3 software was slightly higher, averaging 860*mm* per annum. Though the study area covers an area of approximately l0km^2, the spatial and temporal variations of rainfall are large, with the lower region's rainfall averaging at 550*mm*-800*mm* per annum while the upper region averages at 900*mm*-1294*mm* per annum. Rainfall increases eastward, with the western side recording higher rainfall than the eastern region, which covers the lower drier region (Figure 5.6).

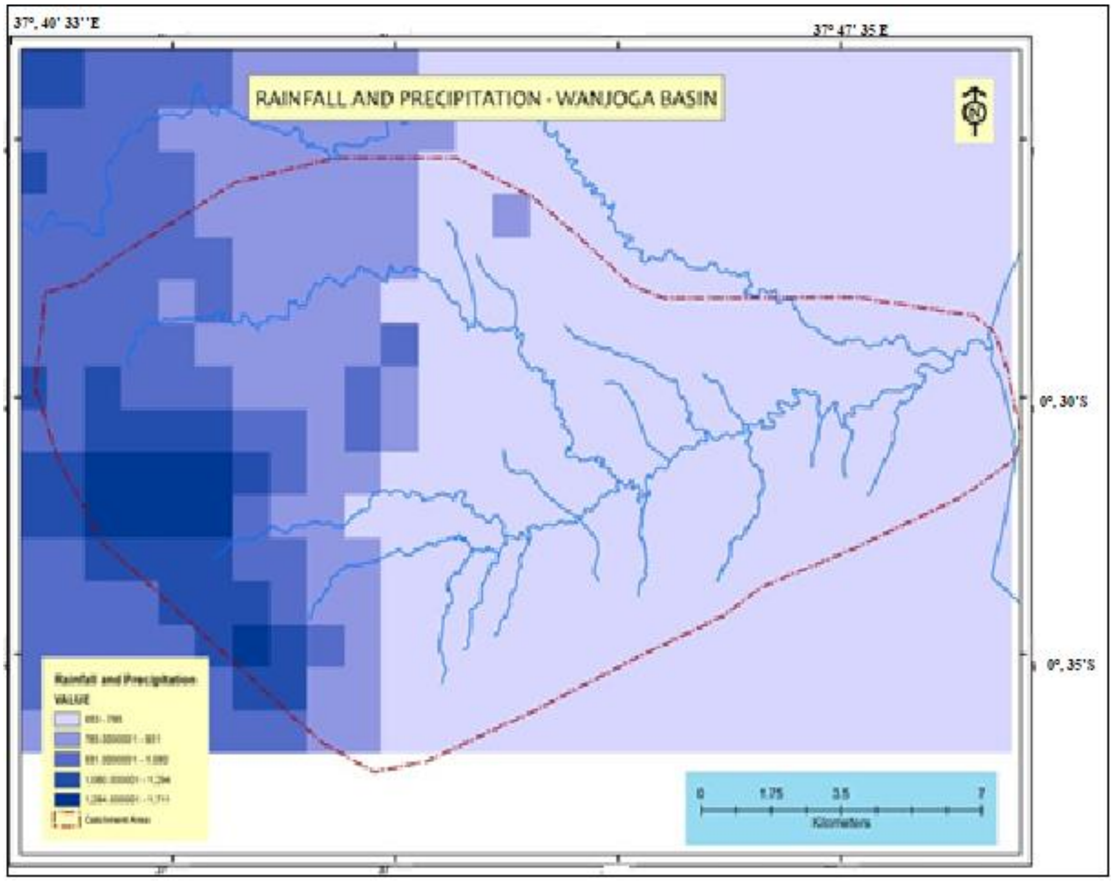


Figure 5.6: Rainfall variability in Wanjoga River catchment

Based on field data analysis of gully systems in the Wanjoga catchment, rainfall variability and seasonality play a significant role in the severity of gully erosion. Moreover, the distribution of rainfall between days and months has an impact on the soil erodibility factors. Geomorphic processes (side walls mass failure, under-cutting and slumping on gully channel) which increase gully erosion were viewed to be pronounced in months of extreme rainfall events (March to May) due to a sudden increase of daily rainfall amount after a prolonged dry period (November - February) (Figure 5.7).

Similarly, a prolonged dry period between months (November - February) results in a limited degree of land cover, increasing surface overland flow and encouraging gully initiation and expansion upon the onset of rains. Standardized annual rainfall amounts from 2000 to 2018 show high anomalies between years and months. Similarly, wide variations are exhibited in daily rainfall events, with a few days per month exceeding 20*mm* per day, while most daily rainfall events are below 3*mm* (Appendix 7).

Extreme short-duration rainfall events were considered the primary mechanism influencing surface processes resulting in gully development. Based on rainfall statistical data (Appendix 7), the lower region (eastern side) shows the highest anomalies, with several extreme daily rainfall events exceeding 40*mm* per day. Still, many days of dry conditions within a rainy season compared to the region of higher rainfall (western side), which exhibits a more regular daily and monthly rainfall event, averaging 5 - 10*mm* per day (Figure 5.7).

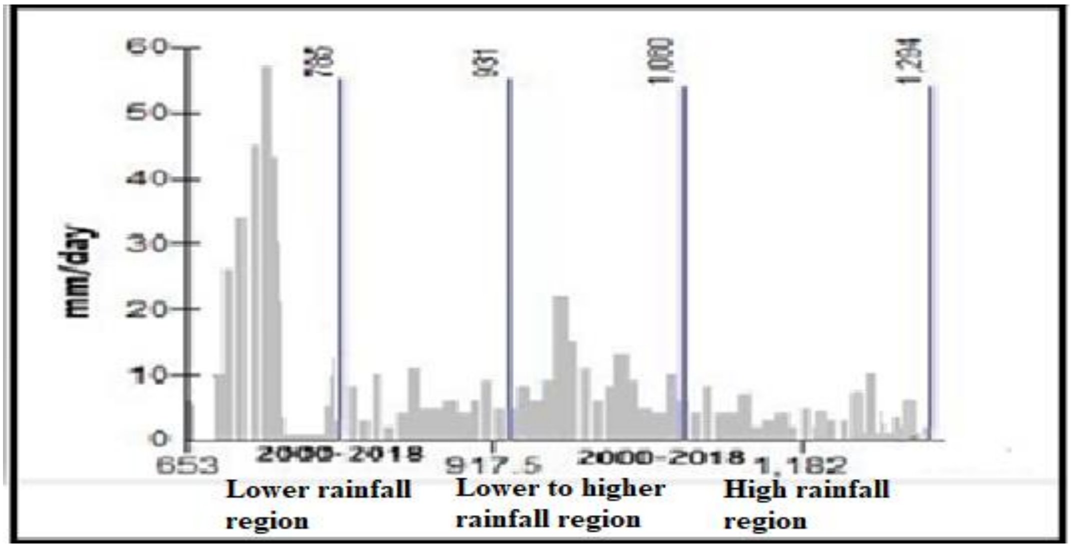


Figure 5.7: Standardized rainfall event between days 2000-2018

Extreme daily rainfall events characterized by high-intensity rainfall of short duration impact erodibility factors (soil characteristics) (Flügel *et al.*, 2003), influencing gully development. Combined with pronounced monthly extreme rainfall events; a sudden increase in monthly rainfall amount (March-May), after a prolonged dry period (November - February), an in-depth analysis of gully network systems revered gullies as more complex units whose long-term development can only be effectively analyzed by use of both short-term and long-term rainfall processes; rainfall seasonality between months and years and long-term rainfall variability between regions. Inevitably, parts of lower and more extreme rainfall regions account for 83.3% of gullied areas. The higher rainfall region exhibits a steadier daily and monthly rainfall event (around King'ombe hills), accounting for 16.7% of total gullied areas (Table 5.4).

Gullies can be actively eroding where erosion is retreating upwards in the landscape at the gully head position and lateral extension at the banks or in-active if a gully channel has ceased actively eroding its head, banks, and bed. A morphometrical analysis of gullies (gully length, width and depth parameters) in Wanjoga Catchment reveals that gully channels at the upper segment have a trend of shorter and narrower parameters. The maximum incision depth of gully channels at 4.2m with a total width of 2.5m. This compares to a maximum incising depth of 5.6m and width of 7.5m in low rainfall regions.

Table 5.4: Rainfall variability and gully morphometric characteristics

Rainfall category regions	**Total Gullies**	**% Gully**	**Max width (m)**	**Max. incision depth (m)**	**Max. length (m)**	**Average volume per gully m^3**	**% Gullied volume m^3**	**V-shape**
High rainfall region (1200mm - 700mm)	11	16.7	4.2	2.5	1,600	563.6	5.1	17
Lower rainfall region (530mm - 785mm)	55	83.3	7.5	5.6	5,500	2,106.6	94.9	10
Total	66	100						

Low length, depth and width of gully parameters at high rainfall region has contributed to low average volume per gullied as observed (563.6m^3) compared to low rainfall regions (2106.6.6m^3). Low gully parameter averages lead to narrower channel features, indicating an active dissection stage. Of all narrow V-shaped features in the Wanjoga river catchment, 63% were observed in regions of high rainfall, with 37% in low average rainfall. Consequently, only 4.5% of high volumes gullies were observed in the area since gully channels are limited in side walls geomorphic processes, which limit lateral extension capabilities. The low extension capability of gullies could be attributed to increased land cover, which increases with the increase in rainfall amounts (Canovas *et al.*, 2017)

In contrast, 82.3% of gully channels affected by excessive bank geomorphic processes (wall slumping, undercutting and mass failure) were observed in low rainfall regions, which results in high cumulative gully volume (V >1000m^3) (Table 5.5). Mass failures mainly tend to dominate head and side walls during storm periods since an increase in water increases bank material weight and decreases its strength (Harvey, 1994). As shown in Table 5.5, of the six very deep, actively eroding assed gullies, the average extension per gully for the surveyed period was 35.2m. Eight deep active gullies extended at an average of 34.8m per gullied area, while shallow active gullies' average increase was by 25.9m on morphometric parameters (length, width and depth).

Table 5.5: Spatial distribution of gullies of excessive geomorphic processes

Volume category	Low rainfall		High rainfall		Excessive Geomorphic Processes	Average extension rate per gully 2000-2021 (m^2)	%
	Gully count	%	Gully count	%			
Shallow gullies (<1m deep)	38	57.6	8	12.1	3	25.9	17.6
Deep gullies (1-2m deep)	11	16.7	3	4.5	8	34.8	47.0
Very deep gullies (>2m)	6	9.1	0	0	6	35.2	35.3
Total	55		11		17		
Excessive geomorphic processes	14	82.3	3	17.6	17		100

Deep gullies were more impacted by undercutting processes resulting in gully channel bank slumping and failures mainly at regions of branches merge and/or areas roadside drainage concentrate flow gullies discharge on farms; a few meters from the discharge point (Figure 5.8). Channel bank instability in low rainfall regions has impacted an excessive increase in gullies' gully volume (Figure 5.8).

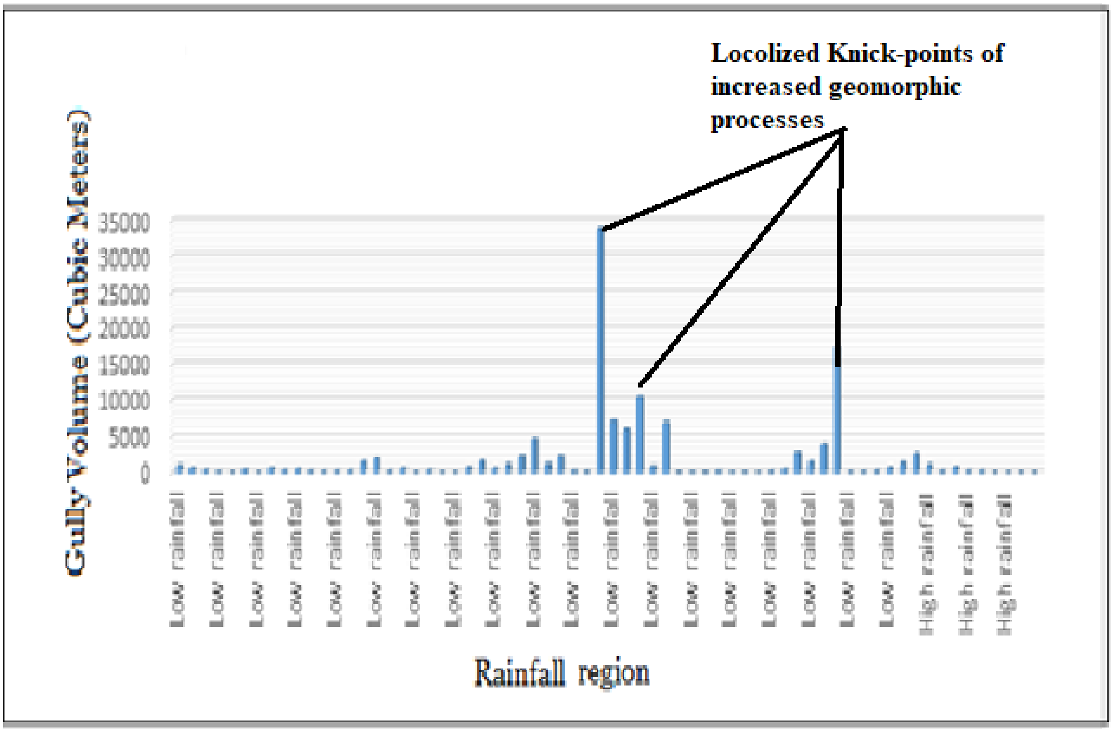


Figure 5.8: Gully volume and rainfall variability

Excessive geomorphic processes at low rainfall regions could be attributed to high rainfall anomalies with extreme rainfall events between days and months, adversely affecting soil structure, texture and vegetation cover, increasing gully banks, bed and head processes. The saturation by excess overland flow increases bank failure by undercutting and increasing lateral dimensions, resulting in material weight, hence slumping (Kumar *et al.*, 2013). Concentrate excess overland flow, which prevails in semi-arid areas of Wanjoga catchment, is localized along with the convergence of flow; animal tracks, footpaths, roadsides and sand mining regions, over periods of extreme short rain bursts, characteristic of the area of lower rainfall regions (530*mm* -930*mm*). The studies match those of Tebebu *et al.* (2010), which conclude that gullies are more actively retreating at the head and widening at banks by up to 20m during a single rainy season.

The generation of concentrated overland flow over a larger area is majorly dependent on short periods of rain bursts and localized on knick-points (Figure 5.9). These knick-points are created by both natural factors (convergence of slopes, steep slopes) and increased anthropogenic activities; road and paths, animal tracks and sand mining, which concentrate overland flow, thus, increased undercutting and slumping (Figure 5.9).

Figure 5.9: Enhanced geomorphic processes at knick-point

Undercutting due to more accelerated flow generated by short storm periods enters micro-pores removing materials underneath in regions of increased hydraulic gradients (Kirkby and Brecken, 2009), creating localized knick-points resulting in slumping and failures. To establish the degree of association between gullied volume areas and rainfall variability, used data in Table 5.1 to compute a chi- squire Correlation Coefficient at a significance level of p= 0.05. The study hypothesis (H_0) postulates; that rainfall variability does not influence gully initiation and progressive development in the semi-arid region, as summarized in Table 5.6.

Table 5.6: Chi-Square Test on rainfall variability and gully volume

	Value	df	Asymp. Sig. (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)	Point Probability
Pearson Chi-Square	19.143[a]	2	. 0.485	p = 0.604		
Likelihood Ratio	21.981	2	.000	.000		
Fisher's Exact Test	19.566			.300		
Linear-by-Linear Association	.255[b]	1	.614	.801	.398	.174
N of Valid Cases	66					

Calculated X^2 = 19.143 Significance level at 0.05 (Source: Field data 2021)

Using 2-sided exact significance, the results indicate no association between gully erosion and rainfall variability in Wanjoga river catchment ($p = 0.604$). Thus, rather than rainfall variability, regions of extreme rainfall bursts are more vulnerable to gully extension since its impacts on erodibility factor such as initial soil conditions (texture and structure) and land cover, which affect material shear strength. These concur with findings of Luffman and Nandi (2020) in Southeastern USA, which concludes that gully erosion is more intense during summer and driven by convectional storms, which influence head and side wall geomorphic processes.

5.1.2.2 Land cover and gully erosion

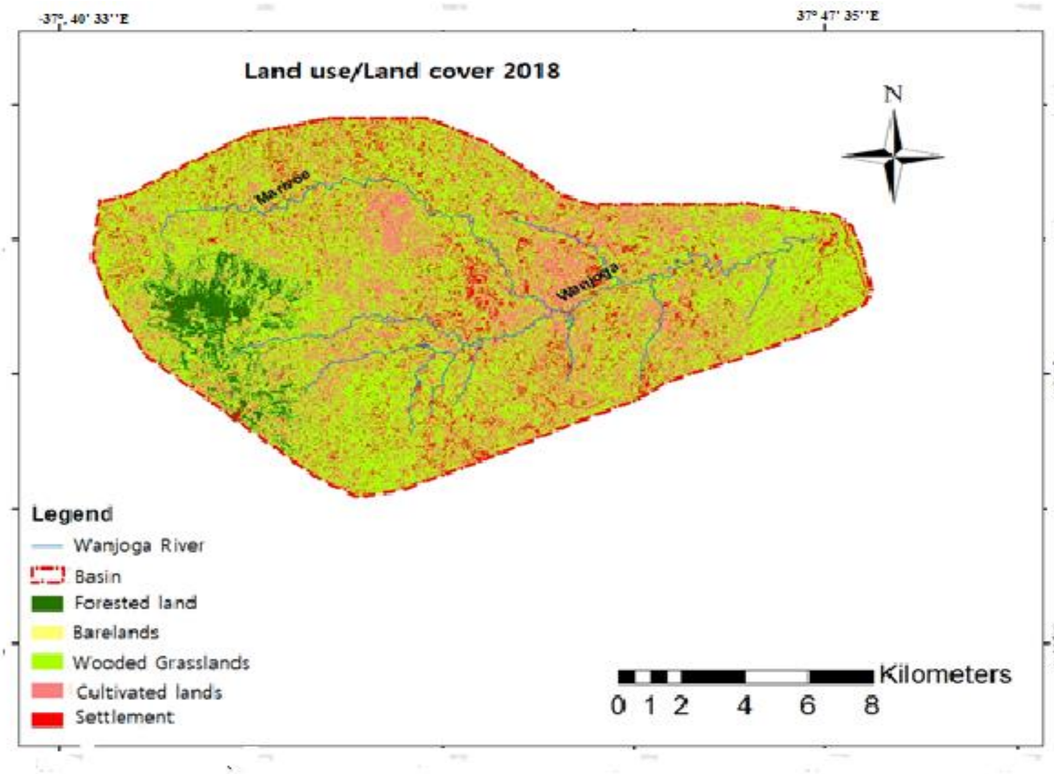
Understanding gully erosion dynamics under changing land cover conditions is essential for gully rehabilitation in a river catchment. Land cover changes were analyzed over 19 years using land cover maps generated from Landsat 8 Images and supervised classification carried out in Arc Map. The supervised classification interpretation of the Wanjoga River catchment for the years 2000, 2009 and 2018 revealed four major land cover types; Forest cover (wooded vegetation with little undergrowth, mainly predominantly evergreen at Kiang'ombe hills), wooded grassland (open grasslands with scattered shrubs, thickets and uncultivated bushes), cultivation (farmlands, abandoned lands), settlements (built-up areas both rural and urban) bare land (non-vegetated land, road surfaces and rocky outcrops), and water surface (permanent and seasonal rivers, swampy areas, water pans).

The results revered that in the year 2000, water bodies covered 0.078 km^2 (0.039%), wooded grasslands 103.3km^2 (51.52%), forest cover 37.9km^2 (18.9%), bare land 5.6km^2 (2.8%), cultivated land 48.74km^2 and 4.87km^2 of settlements land. A shift in land cover/land use occurred from 2000 to 2018 with water bodies, wooded grasslands and forest cover decreasing to 0.001Km^2(0.005%), 52.3Km^2 (26.1%) and 9.02km^2 (4.5%) respectively. Contrary, in same period an increase in cultivated land to 88.8km^2 (44.3%), settlements 24.3km^2 (12.1%) and bare land increased to 24.3Km^2 (13.0%) (Table 5.7)

Table 5.7: Land use/ land cover in Wanjoga River catchment 2000-2018

Land cover	Area (*Km*^{2})			Area %			% Relative change in land use
	2000	**2009**	**2018**	**2000**	**2009**	**2018**	**2000-2018**
Water Body	0.078	0.068	0.01	0.039	0.034	0.005	⁻50
Wooded Grassland	103.3	87.6	52.3	51.52	43.7	26.1	–49.4
Forest Cover	37.9	25.5	9.02	18.9	12.7	4.5	–76.2
Cultivated land	48.74	60.8	88.8	24.31	30.3	44.3	82.2
Settlements	4.87	14.4	24.3	2.43	7.2	12.1	398
Bare land	5.6	12.2	26.1	2.8	6.1	13.0	366
Total area *Km*^{2}	**200.5**	**200.5**	**200.5**	**100**	**100**	**100**	

Spatial changes of land cover over time for the period 2000 to 2018 revealed negative relative change for forest cover, wooded grasslands and water bodies at –76.2%, –49.4% and –50%, respectively. Contrary, cultivated land increased by 82.2%, settlement areas by 398% and bare lands by 388%. Regions originally under forest cover and wooded grasslands were converted to cultivated lands by 2018, while more vegetated land was converted to barer ground (Figure 5.10 a, b, c).


37°, 40' 33''E
37° 47' 35''E
Land use/Land cover 2018
N
Wanjoga
0°,30'S
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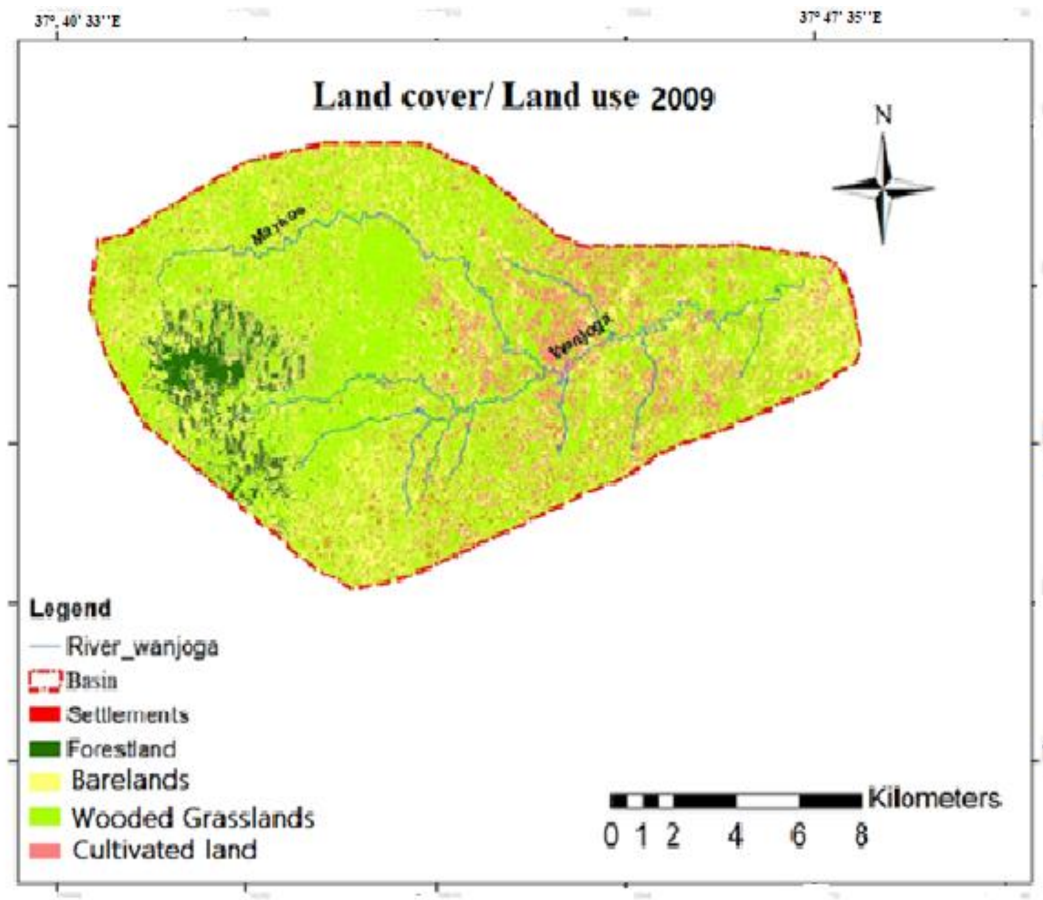
Legend
Wanjoga River
Basin
Forested land
Barelands
Wooded Grasslands
Cultivated lands
Settlement
Kilometers
0 1 2 4 6 8


37°, 40' 33''E
37° 47' 35''E
Land cover/ Land use 2009
N
Wanjoga
0°,30'S
0°,35'S
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Basin
Settlements
Forestland
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Wooded Grasslands
Cultivated land
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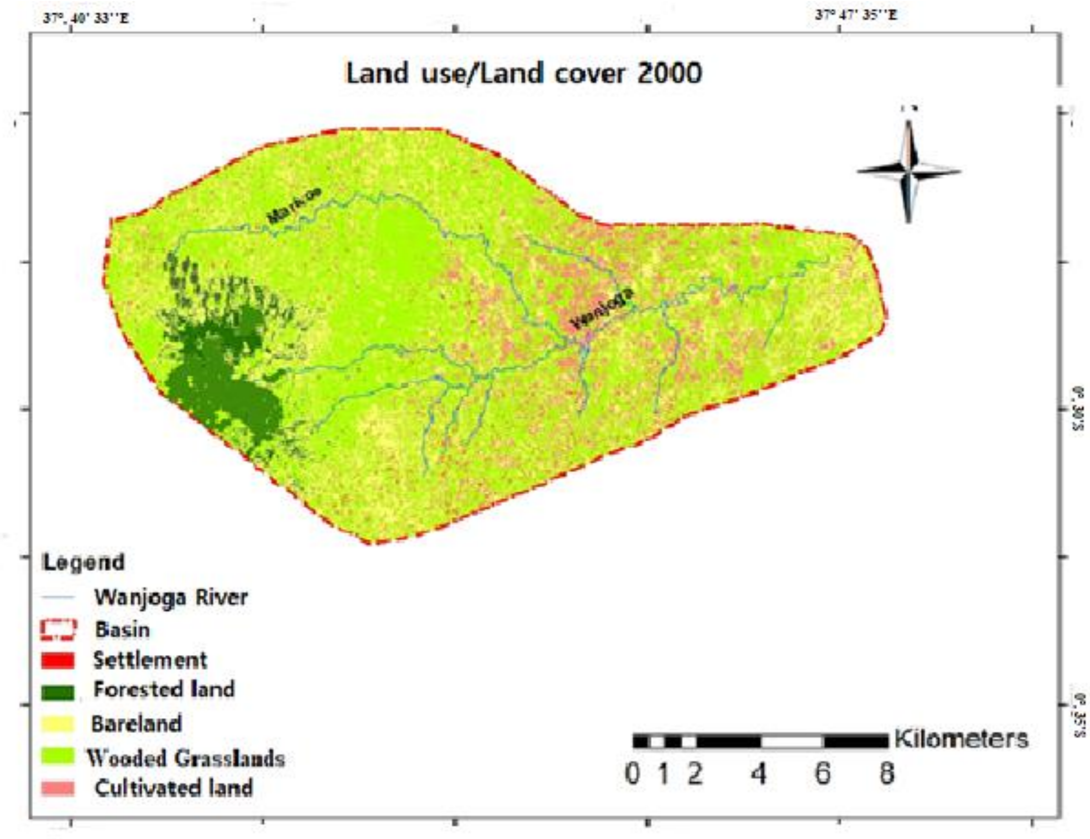


Figure 5.10: Land use/land cover changes in Wanjoga River catchment; (a) 2000, (b) 2009 and (c) 2018)

Conversion of vegetated land to barer lands could be attributed to the influx of population in the Wanjoga catchment occasioned by overpopulation in high potential surrounding regions (Kisaka *et al.*, 2014). According to KNBS (2019), Mbeere North Sub-County, the study area, saw a population increase from 89,035 in 1979 to a total population of 105,587 by 2019 (KNBS, 2019) addition to 175 persons per square kilometer from 121 persons in 1979. An influx in population in the river catchment means increased demand for food, water, forage and site selection for constructing roads and other anthropogenic structures, increasing bareness. An increase in these unsustainable human practices, incompatible with vulnerable and unstable semi-arid environments, is a causative factor in environmental hazards like gully erosion (Southgate and Hulme, 1996).

A steady increase in human activities saw a concurrent rise in gully density over the same period. An increase in gully density increases in several gullies per unit area and subsequently, greater eroded volume per gullied area. Spatial evaluation and distribution of gullies across the study area were carried out using a sequence of three Landsat images for the years 2000, 2009 and 2018. Digital analysis revealed the year 2000; gullied areas occurred in lower segment regions with sparse vegetation cover (Figure 5.11; G1). Only 6 (G1) major gullied areas were identified using satellite images for the year 2000.

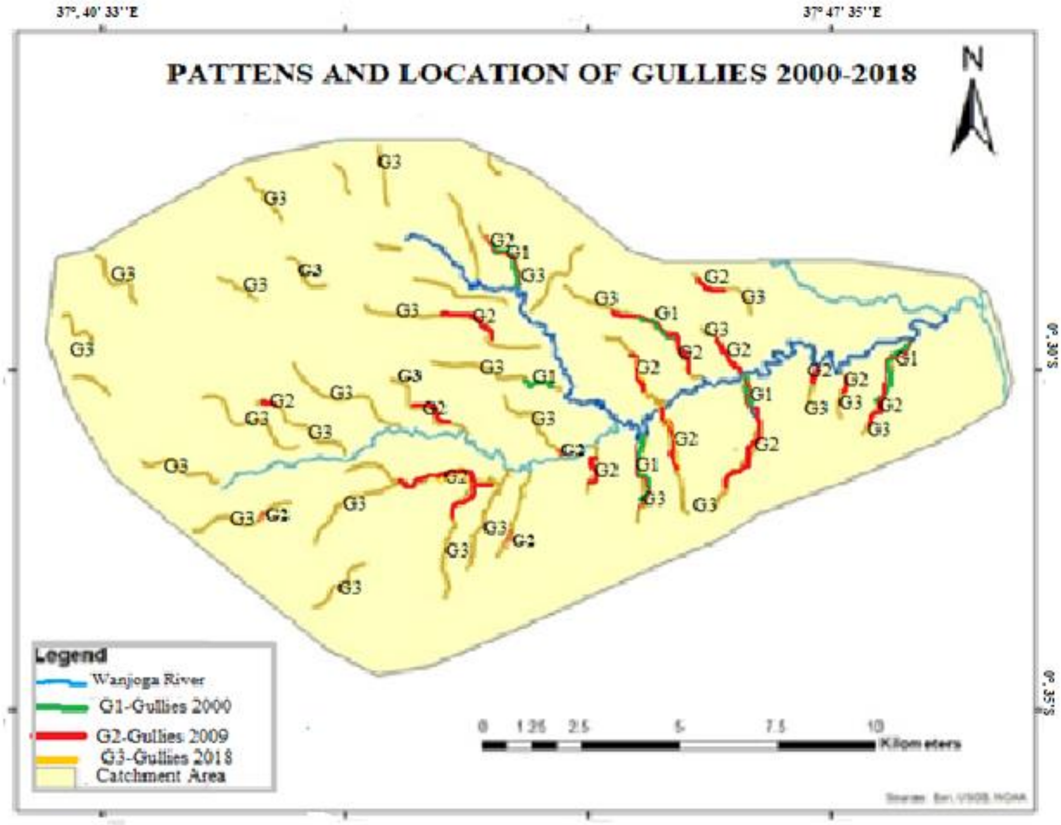


Figure 5.11: Location and patterns of gullies 2000-2018 (G1-gullied regions as observed in the year 2000; G2-gullies in 2009 and G3- gullies in 2018)

Observed gullied areas are adjacent to river valleys, suggesting likely formation brought about by overland flow accumulation and channelization at lower slope regions. No gullied areas were captured in the western, upper slope regions; the part was under thick forest cover with little or no human activities. Conversion of vegetated land to more bareness and cultivated land by 2009 brought a tremendous increase in gully density from 6 gullies in 2000 to 20 (G2) in 2009, more than three times an increase. The period had increased gullied areas in lower slope regions near river channels. Several gullies are identified further into the interfluves, indicating overland flow accumulation influenced by more factors than channelization by converging slopes and reduced slope angle. By 2018, gullies experienced a significant increase in the lower segment regions and near river valleys and more gullies were captured in the upper part, previously non-gullied regions. Gullied areas increase to 39 (G3), with an increase in gullied areas deeper into interfluves and steeper slopes. There was a more increase in gully density in the eastern direction than in the western side.

Existing gullies (G1 and G2) also evolved in structure in all directions, affecting the landscape's ruggedness. This can be attributed to increased unsuitable human practices in a semi-arid region susceptible to gully erosion, including increased anthropogenic structures, grazing and farming, which increase unstable slopes and channelization. Substantive increase in human activities was reported from 2000 to 2018, with 2009 – 2018 experiencing approximately 95% rate of gully growth compared to 2000-2009 (Figures 5.10), which saw a 233% increase. The overall gully density increase was 6.5 times, representing a 550% increase (Table 5.8).

Table 5.8: Relative change in gully density 2000 - 2018

Class	% Relative change in land use					Gully count	% Relative change in gullied areas
	Forest land	**Wooded grasslands**	**Bare land**	**Cultivated land**	**settlements**		
2000-2009	–32.7	–15.2	117.9	24.7	195.7	6	233
2009-2018	–64.6	–40.2	113.9	46.1	68.8	20	95
2000-2018	–72.2	–49.4	366	82.3	399	39	550

An increase in gully density is influenced by changes in gully erosion controlling factors, including changes in land cover/land use. The result portrayed in Table 5.8 indicates that increases in gullied areas are comparable to increases in bare lands, cultivated areas and settlements. The relative increase in gullied regions for the periods 2000-2009, 2009-2018 and 2000-2018 account for 233%, 95% and 550%, respectively, a scenario replicated in a positive increase in bare lands by (366%), cultivated lands by (82.3%) and settlements by (399%). Though the period 2000-2009 showed more increases in gullied areas, vegetated regions depleted at a slower rate of –32.7% and –15.2% for forest lands and wooded grasslands, respectively, compared to the period 2009-2018 with a more rapid recorded depletion at –72.2% for forest land and –49.4% wooded grasslands (Table 5.8).

Increased depletion of forested lands and wooded grasslands covers coincides with population increases which increase demands for food, forage and anthropogenic structures, a scenario suggesting more unsustainable human practices which trigger excessive overland flow, localized along artificially imposed convergence flow zones, impacting on gully development. Increased unsuitable human practices in the semi-arid regions such as the Wanjoga River catchment have impacted gully density and eroded volume. Wooded grasslands used as communal grazing land have more gully frequency (45.5%) than forested land (9.1%). Though bare lands account for only 20% of the study area, they account for 27.3% of gullied sites. Cultivated land and settled areas have a low impact on gully erosion accounting for 4.5% and 10.6%, respectively (Table 5.9).

Table 5.9: Relationship between land cover classes and gullied parameters

Class	Gully count		Gully parameter			Average volume m^3
	count	%	Max. Length (m)	Max Depth (m)	Max. Width (m)	
Forest land	6	9.1	900	2.23	1.5	288.8
Wooded grasslands	32	48.5	5700	7.53	7.4	1,794.8
Cultivated land	3	4.5	213	0.8	0.9	34
Settlement	7	10.6	715	1.2	1.2	312
Bare land	18	27.3	1600	4.2	1.5	532.5
Total	66	100				

Unsuitable human practices such as grazing increase eroded gully volume at wooded grasslands averaging (1,794.8m^3) per gullied area, compared to forested and cultivated lands accounting for 288.8m^3 and 34m^3, respectively. Large volumes of eroded material in wooded grasslands are attributed to an increase in animals per unit area (Tebebu *et al.* (2010), which corresponds with a reduction in vegetation cover.

Unsuitable human practices over time have resulted in a high percentage of gullies with parameters (width and depth) >3m, an indication of a relatively large portion of wooded grasslands affected by actively eroding gully channels (channel banks slumping and failures), a scenario impacted by livestock disturbance including; trampling and movement on animal trails which increase abrasion in gully channel. These results collaborated with Go´mez Gutie´rrez *et al.* (2009), concluding that areas under rangeland are highly affected by gullying.

Active gullies occur in areas where gully erosion is aggressively moving up in head cut retreat and lateral extension due to scouring, slumping and wall failures (Figure 5.12).

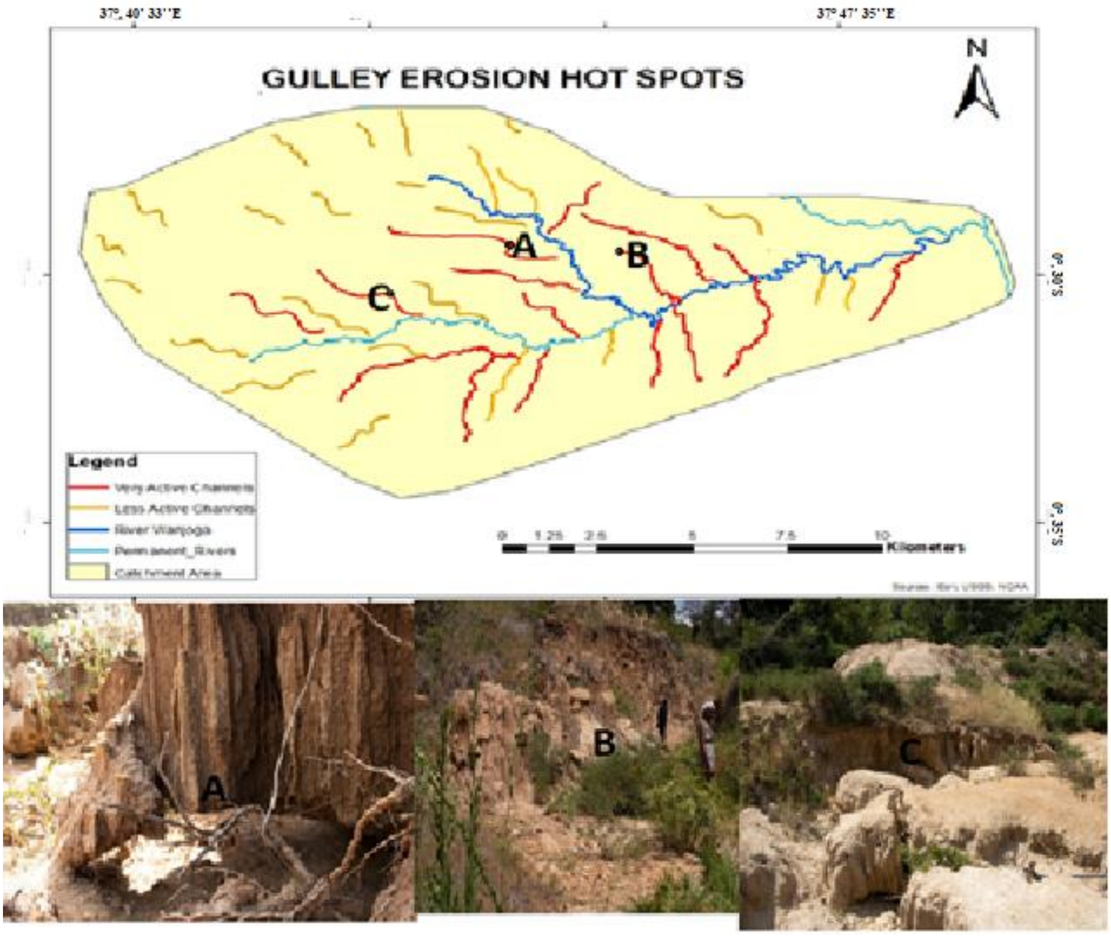


Figure 5.12: Active gully systems in Wanjoga River catchment (a,b,c; regions of increased geomorphic factors)

Gullies observed in the forested area (western region) portrayed more stable channels due to the ability of tree roots to enormously improve soil structure and reduce the erosive action by overland flow (Figure 5.12). Their length varies from a maximum of 900m and a minimum of 3m. On the contrary, some gullies in wooded grasslands and bare land exceed 5700m and 1600m in length, respectively.

Following the diverging results on gully channel morphometry and occurrence at different land cover areas, a chi-square test was performed to establish the role of land cover on gully development. Results were computed in **Appendix 3.** A 2-tailed chi-square exact value of p = 0.001, less than the probability value (p=0.05), indicates a significant positive relationship between vegetation cover and gully development. This concurs with the result of Kartz *et al.* (2013) that changes in land cover resulting from the construction of roads and other anthropogenic structures result in more creation of bare land, making an area more sensitive to formations of gullies. Also, Dai *et al.* 2002 conclude that vegetation has a decreasing effect on gully susceptibility since it reduces erosive exertion of overland flow, at the same time, bare lands are more susceptible to gullying.

The finding is further expressed in Figure 5.12, which reveals a much lower volume across gullied areas on forested land compared to the vegetated region with scattered parches of the bare ground brought about by overgrazing. Wooded grassland cover areas portray a trend of high-volume gullies ($\geq 20{,}000m^3$) and bare lands ($\geq 1000m^3$, compared to low volume gullies observed at forested, cultivated and settled land covers $\leq 1000m^3$ (Figure 5.13).

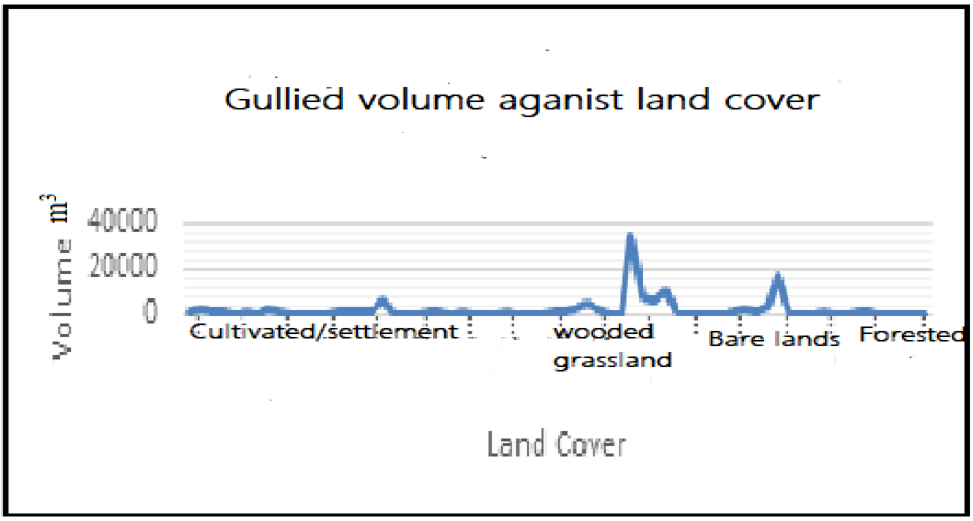


Figure 5.13: Relationship between land cover and eroded gully volume

These results further illustrate the importance of vegetation cover in controlling soil loss in the hillslope discharge areas. As observed by the study, gullied volume representing sediment discharge decreased with an increase in vegetation cover extension. The ability of vegetation cover to control gully head retreat channel bank extension can be associated with the presence of plant roots mat on more vegetated areas have the ability to hold soil particles together. Studies by Valentin *et al.* (2005), reveals that, plant roots limit gully erosion by improving the structural stability and infiltration of the soil. Further, Kendie *et al*. (2015) conclude that major causes of gully initiations are areas with increased human-induced factors such as; poor farming systems, clearing of vegetation and overgrazing, which leave the soils bare. Therefore, increased vegetation cover is essential in controlling gully density and increased volume on a river catchment. The frequency of gullies impacted by increased anthropogenic structures brought by expanded human population results in limited or non-vegetated areas that create regions of increased concentrated overland flow, thus initiating and extending gullies.

5.1.2.3 Soil lithotypes and gully development

Soil characteristics in a landscape play a dominant role in influencing the geomorphological stability of a slope (Dai et al., 2001). Soil sample analysis from the study area derived three classes of lithotype; lithosols (sandy clay loam to sandy clay), arenosols (loam sandy to loam clay), cambisols (clay loam to clay and sandy clay to loam). Results showed soils in the study area mainly belong to the cambisols class (clay loam to clay), with few samples showing locations with lithosols from the described textural classes (Figure 5.14)

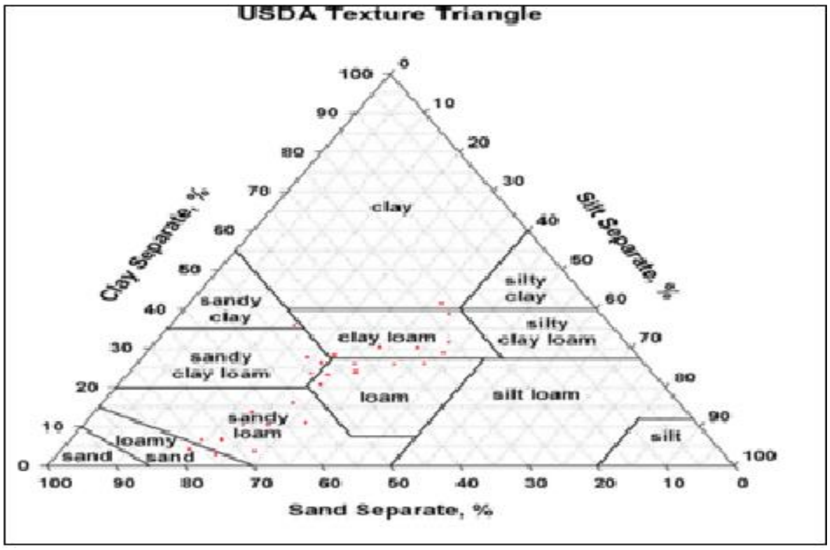


Figure 5.14: Proportions of sand, silt and clay for soil samples; sampled soils are shown on USDA Textural triangle indicates soil grain sample (red points)

Lithosols were sampled at different hilly areas with excessive erosive runoff. The soils are shallow, weakly developed, and sometimes with gravely character, containing< 15% clay. At lower slopes, soils are arenosols type, with deeply weathered layers. The soils are well-drained, containing 60% sand and 30% clay (Table 5.10).

Table 5.10: Soil texture analysis

Soil lithotype	Sand grain size (mm)	% Sand	Clay %	Gully count	% Gully
Lithosols (sandy loam to sandy clay	0.1-0.25	72	15	7	10.6
Arenosols (Loam sandy to loam clay)	0.3-0.23	60	30	12	18.2
Cambisols (Clay loam to clay).	0.25-0.90	33	50	33	50
Cambisols (Clay sandy to clay)	0.25-0.10	40	45	14	21.2

In upper to mid-segment regions, cambisols (clay loam to clay and sandy clay to loam) is most common, with weatherable primary materials of different percentages across landscapes. The soils are moderately drained and contain 50% clay to 33% sand in the same areas, while in another region, the cambisols have 45% clay to 40% sand. Further, field data analysis revealed a degree of association between gully network extension and occurrence and soil lithotypes. 71.2% of all gullied areas occur in regions under cambisols, 18.2% on arenosols, while lithosols account for 10.6 %.

Most gullied areas on cambisols (clay particles>50%) form deeper crevices during the dry season, which act as channelization points at the onset of rainfall (Nyssen *et al.*,2004). This eluviation clay character, coupled with low depth of soil profile and/or presence of weatherable primary materials, can result in scour erosion knick-point due to the capability of these weatherable materials to accelerate water scour downslope (Frankl *et al.*, 2013). Also, the presence of weatherable materials triggers undercutting through which excessive processes such as hydraulic action act upon the ground onset of rainfall which result in the creation of a thick deposit of loose weathered materials on the gully bed.

In the mid-segment region, the most spectacular landforms related to gully erosion almost exclusively developed on cambisols (clay soils with high content of sand) with channel networks mainly characterized by a parallel pattern within a segment region. The networks are most extensive in terms of cumulative sediment loss with a total volume of 82,739.6m^3 (average 2,507.3m^3 per gullied area) (Table 5.11).

Table 5.11: Soil lithotypes and gully eroded volume

Lithotypes	**Volume category**				**Total volume m^3**	**Average volume m^3**	**Slumping/collapsing activity**
	shallow	Deep	Very deep	Gully %			
Lithosols (sandy loam to sandy clay	6	1	0	10.6	1,983.0	283.3	0
Arenosols (loam sandy to loam clay)	9	4	1	21.2	29,568.2	2,112.0	2
Cambisols (45% sand).	22	6	5	50	82,739.6	2,507.3	11
Cambisols(36 % sand)	9	3	0	18.2	7,772.1	647.7	3
Total volume m^3					**122,062.9**		

These gully channels are most impacted by side wall geomorphic processes with severe collapsing and slumping. About 68.8% of gullies mainly affected by gully head and side wall collapsing occur in this region of cambisols, where soils form cracks during the dry season and slumping during wet seasons due to expansion and contraction dynamics of clay minerals. These study outcomes are comparable to those of Pulice *et al.* (2009) who concludes that, falls and topples are enhanced by the existence of desiccation crevices in expandable clays developed during dry seasons.

The trend is replicated in areas of cambisols (50% clay) lithotypes where the impact of collapsing gully head and side slopes is reported in three major gullies accounting for 18%. Sandy lithotypes are least affected by head and side walls geomorphic processes explaining their low average volume at 283.3m^3 (Figure 5.15).

Figure 5.15: Gullied surfaces on different lithotypes (a)gully on Lithosols with minimal side wall geomorphic processes (b) cambisols adversely affected banks collapsing

The adverse geomorphic processes on gullies' side walls and gully head-on cambisols enhance the overall extension of gullies laterally and in length resulting in high sediment loss. Slumping and slight mass movement on gully side walls and vertical incisions dissect a landscape resulting in a more rugged landscape. This relationship is further expressed using the chi-test in Table 5.12 to show the relationship between soil lithotype grouped against gully volume and frequency. The result reveals a strong association between soil characteristics and gullied volume(p=0.000).

Table 5.12: Chi-test on soil lithotype against gullied volume and frequency

N	66
Median	2.0000
Chi-Square	17.173[b]
df	3
Asymp. Sig.	.001
Exact Sig.	.000
Point Probability	.000

Significance level p=0.05

Thus, there is a positive relationship between frequency and volume and soil lithotypes, with poorly developed cambisols with a tendency to experience higher sediment loss rates than Lithosols and arenosols lithotypes. In conclusion, as observed in the study area, large portions of land are characterized by highly erodible soils, forming cracks and increasing slumping, falls and topples, resulting in gully development. Cambisols with weatherable materials can accelerate run-off discharged around the weatherable materials, playing a pivotal role in determining gully initiation and expansion. These findings resemble those of Pulice *et al.*, 2009 concluding that concentrated falls and topples are intensified by desiccation cracks during dry seasons. Also, Frankl *et al. (*2012) reveal that, gully head cut retreat is more vulnerable in areas of vertisols which makes them highly pulverized, resulting in the formation of deep, wide cracks when dry, which act as points of concentrate flow that turn into large gullies after collapsing. Therefore, gully erosion increases in regions of erosion-prone conditions, including erodible soils and soft lithologies.

5.1.2.4 Slope characteristics and gully development

The landscape of the Wanjoga river catchment is significantly controlled by the topographic setting, with the western side characterized by steep slopes (>18°). The high local relief with a limited flow area results in abrupt channeling of surface overland from the western side, resulting in severe drainage down-cutting on the eastern side. To analyze the role of slope angle in gully development, slope analysis was derived from Digital Elevation Model (DEM) at 30M resolution from Shuttle Radar Topography Mission (SRTM) satellite and reclassified into three categories; < 10°, 19°-20°, and > 20° (Figure 5.16)

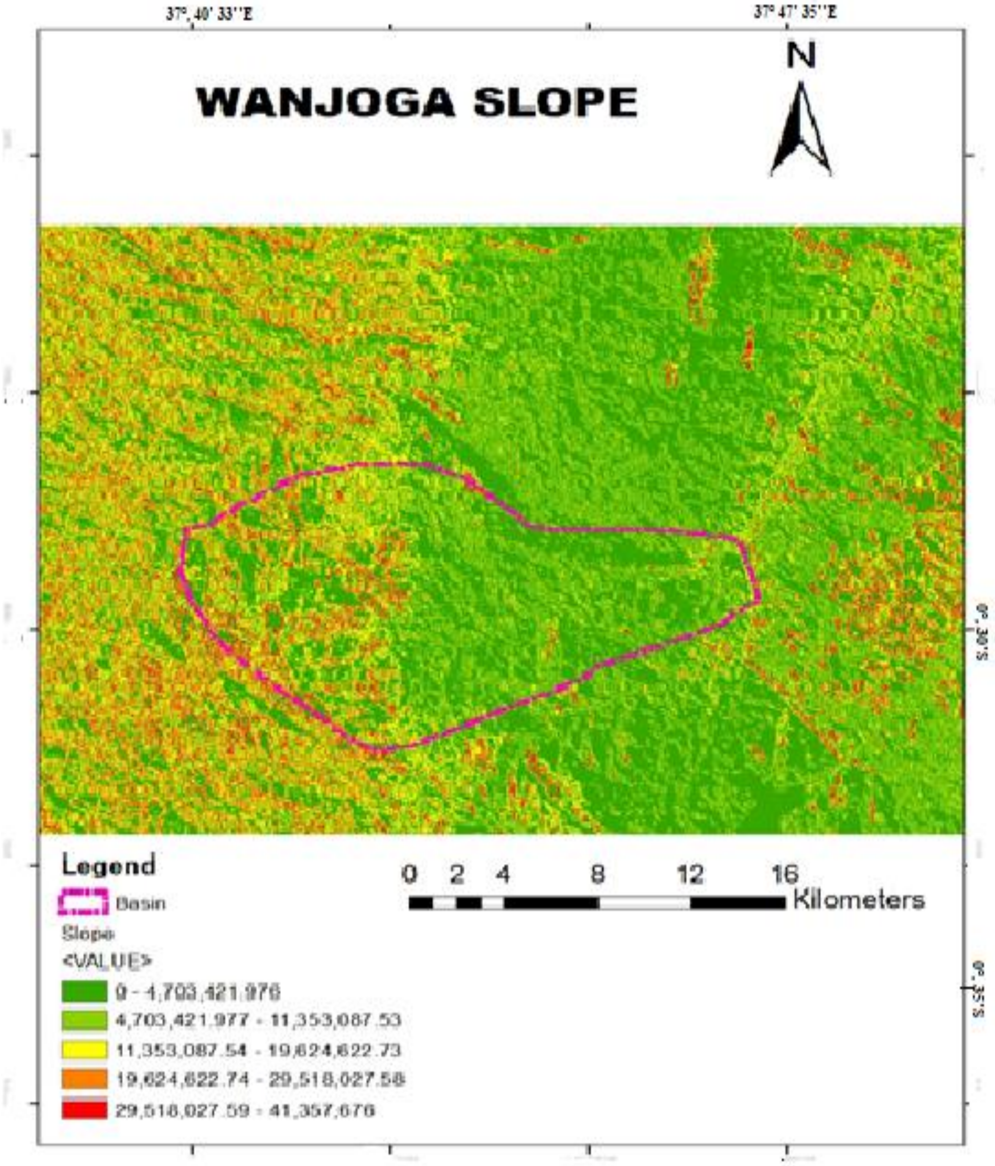


Figure 5.16: Slope classification in Wanjoga catchment

An analysis of 66 gullied areas depicts a high frequency of gully on steep slopes (> 20°), accounting for 36% compared to medium (11° - 20°) and lower slopes (< 11°) which account for 31.1% and 33.3% respectively (Table 5.13)

Table 5.13: Gully morphometry and slope angle

Slope segment	Slope category	Gully count	Gully %	length (m)	Average w (m)	Average d (m)	Gully total V (m^3)	Average volume (m^3)
Upper segment	0º–10°	4	9.1	4155	0.8	1.0	2,889.8	722
	11º–20º	7	10.6	5036	0.8	0.7	3,067.8	438
	>20º	22	33.3	10,143	1.0	0.5	8,908.9	405
Mid-segment	0º–10°	9	13.6	12,015	2.7	1.4	64,942.8	7327
	11º–20º	13	19.7	9,906	1.1	0.7	15,394.6	1100
	>20º	2	3	692	0.4	0.3	103.9	52
Lower segment	0º–10°	7	10.6	1,531	2.5	0.4	25,671.1	3769
	11º–20º	2	3	530	0.4	0.5	83.5	530
	>20º	0	0	0	0	0	0	0
Total		66					122,062.9	

The trend of eroded gully volume estimates increases with a decrease in slope angle. Areas of high gully density (> 20°), depicts low average volume, compared to slopes <10°, showing higher average volume per gullied area. Despite the high density of gullies per unit area (36.3%), gully channels on steep slopes have a low average volume averaging 228.5m^3. Cumulatively, gully channels on gentle slope accounts for 93,503.7$m^3$of eroded volume, which accounts for 77.2% of the total gullied volume areas, though they represent only 30.3% of the gullied area. High volume per gullied area in the gentle sloping region can be attributed to a high mean width of gullies (2.7m) and extensive gullies length. The results concur with those of Kumar *et al.* (2015), which suggests that, topographical factors play a crucial role in gully occurrence and eroded volume in West Bengal, India.

Further, gully channels were categorized into three; Shallow gulley (0 to 1000m^3), deep gulley (1001 – 5000m^3), and very deep gulley (> 5000m^3). Shallow gullies dominate the area accounting for 69.7%of all gullied regions, of which, 45.7%occurred on slopes steep slopes (> 20°), 36.9% on medium slopes and 17% on slopes gentle slopes (< 11°). Deep gullies account for 21.2% of total gullied areas, of which 50% occur in gentle slope areas. 83% of very deep gullies occur on gentle slopes (Table 5.14)

Table 5.14: Relationship between Slope and gully eroded volume

Slope category	Volume category			Total gullies	Volume m^3	
	Shallow gulley	Deep gulley	Very deep gulley		Total	Average
Gentle slope (0 º - 10 º)	8	7	5	20	96,306.0	4,765.3
Moderate slope (11 º - 20 º)	17	4	1	22	17,744.2	806.6
Steep slope (> 20 º)	21	3	0	24	9,012.6	375.5
Total Gullies	46	14	6	66		
% Gullies	69.7	21.2	9.0	100		
Total Volume m^3	9,732.5	29,515.9	82,814.5		122,062.9	

The analysis illustrates gradient and slope angle have a strong spatial relationship on both gully development and gully occurrence. Gullies on gentle slopes (0º–10º) have the highest cumulative volume (95,306m^3), accounting for 78% of total gullied sediment though they account for only 30% of the gullied areas. Moderate slopes account for 14.5% of gullied volume with a very high average per gullied area (4,765.3m^3). Though steep slopes (>20º), have the highest gully frequency (36%), gullies portrayed very low total volume accounting for only 7.4%. The high average volume of gullies on gentle slopes is attributed to channelization impacting the amount of sediment loss with severe gully channels exceeding35,000 sub-total volume (Figure 5.17).

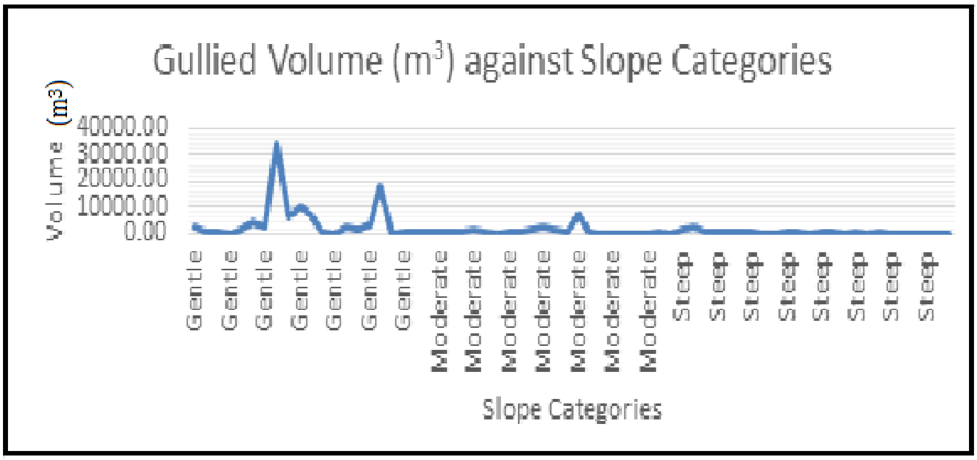


Figure 5.17: Relationship between slope angle and gully volume

On gentle slopes, gullies depict a character of wider, shallower and longer parameters; thus, they are more susceptible to gully extension compared to gullied areas on steeper slopes, which portrays a narrower, steeper and shorter gullies. The results concur with those of Frankl *et al.* (2013), which conclude large volume gullies are best observed when considering lower slopes on large catchments > $45km^2$. Increased catchment area coupled with reduced slope result in cut and fill process on gully bed which in turn encourage human activities such as sand harvesting increasing overall gully volume.

The relationships were confirmed by the use of computed Chi-square and fisher's Rank Correlation Coefficient, which established the degree of association existing between slope angle and gullied volume and expressed in Table 5.15. The study hypothesis of analysis (H0) postulates that; the 'slope characteristic does not influence gully initiation and progression in semi-arid environment of Wanjoga River catchment in Tana Basin.

Table 5.15: Chi-Square Test and gully volume

	Value	df	Asymp. Sig. (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)	Point Probability
Pearson Chi-Square	14.800[a]	4	.005	.002		
Likelihood Ratio	15.512	4	.004	.006		
Fisher's Exact Test	13.097			.005		
Linear-by-Linear Association	12.983[b]	1	.000	.000	.000	.000
N of Valid Cases	66					

$x^2 = 14.800$, Significance test p= 0.05

The chi-square value p=0.004 and fisher's test p=0.005 are less than the probability value (p>0.05). The results indicate correlation has positive significance to gully development, implying that gullies in most slope locations were prone to more erosion irrespective of the contribution of other geomorphic factors. This relationship is further expressed in Table 5.15, which shows gully density increases with increases in slope angle while the volume parameter increases with a decrease in slope angle. The results resemble those of Arabameri *et al.* 2018 who conclude, elevated that slope are highly related to gully erosion susceptibility. Similarly, studies by Dube *et al.* (2014), conclude gully density increases with increasing slope.

In conclusion, slope accelerates surface overland flow playing a critical role in determining gully development. The results show a positive correlation between the gully frequency, eroded volume, and slope gradient. This implies that steeper slopes have a greater proneness to gully initiation than gentle slopes. Inversely, lower slopes and unstable road discharge points recorded higher gully volume than steep slope areas. This was attributed to a more continuous discharge in gentler slopes determined by longer slopes and the confluence of gullies' downslope. Studies by Wemple *et al.* (1996) concluded that, the chances of gully formation on more inclined regions were significantly higher than on gentle slopes since steeper slopes have a lower infiltration rate hence the risk of gullying

5.1.2.5 Gully erosion susceptibility assessment in Wanjoga catchment

To evaluate gully erosion susceptibility in the Wanjoga River catchment, all data were analyzed in a single platform in a GIS environment using a bivariate statistical method. The calculations were based on relationships between each gully conditioning factor in relation to the location of gullied areas as mapped by satellite imagery and by the Global Positioning System (GPS) during comprehensive field surveys. Maps generated for each conditioning factor were transformed into raster format through ArcGIS software. Gully conditioning factors included; land cover, rainfall variability, slope, elevation and soil lithotypes (Figure 5.18)

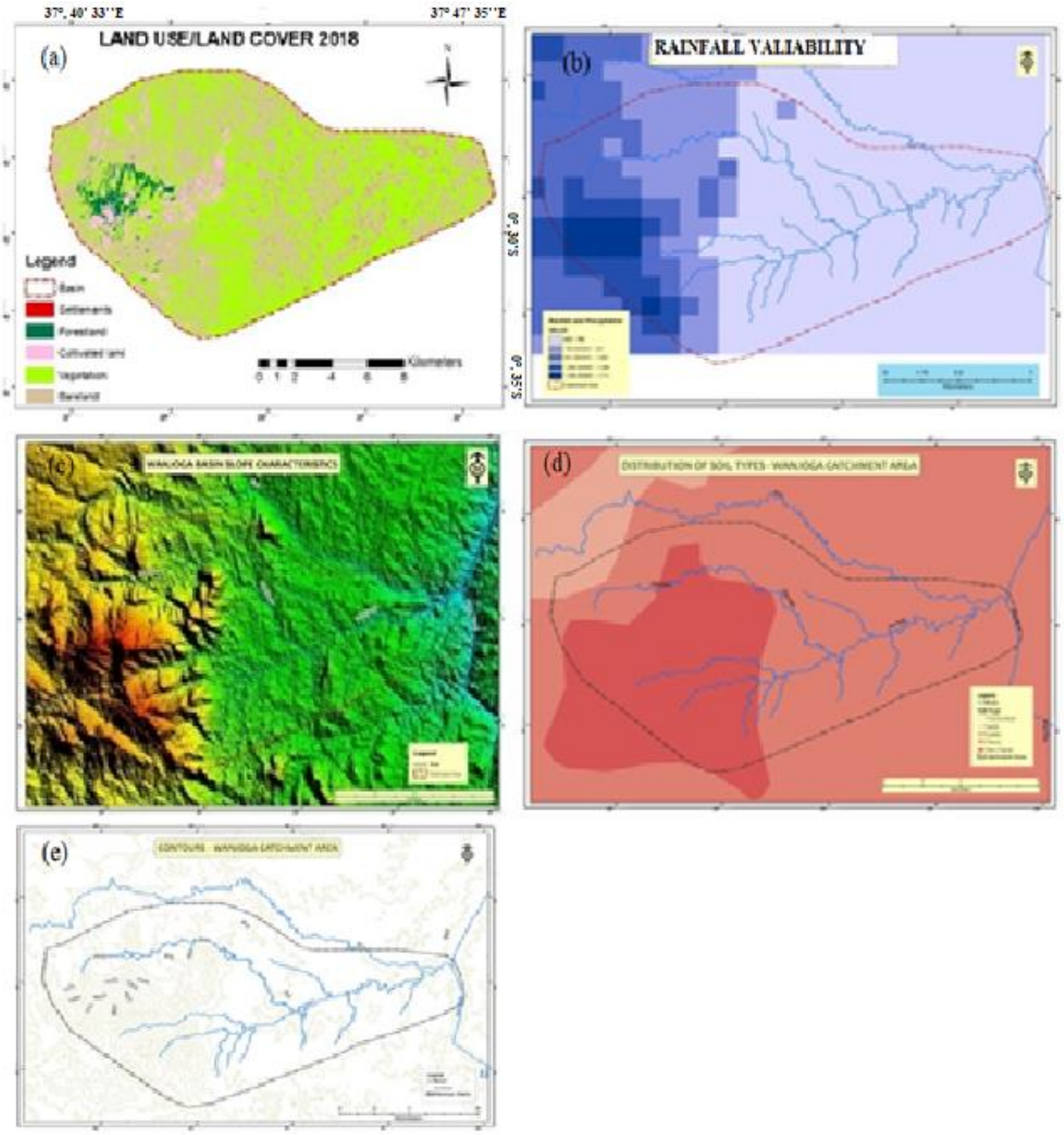


Figure 5.18: Gully erosion conditioning factor layers (a) land cover (b) rainfall variability (c) slope (d) soil lithotype(e) elevation

Based on gully conditioning factor layers, the gully density for each factor was computed, symbolizing the weighted level for each factor class and their importance in reference to each other using a pixel size of 15 m. Positive weighted values indicated a positive correlation between evaluated gully conditioning factors and gully erosion in the study area. The density of gullied areas and weighted values reported (Table 5.16) indicate about 4% ($8.02km^2$) of Wanjoga river catchment is affected by gully erosion (35,650 pixels out of 891,271 total pixels). The slope factor is imperative in gully development, specifically slopes > 20° (Wi= 2.82). Areas of slope 11° - 20° recorded values Wi = 1.00. This region is affected by increased gully volume and velocity brought about by the merging gullies (Table 5.16). Thus slope > 20° is positively associated with gully erosion.

Table 5.16: Spatial relations on gully conditioning factors and gully location

Conditioning factors	Class factors	Gully count	Gullies %	NpixNi	NpixSi	Wi
Rainfall	653- 900	55	83.3	681,681	22,449	0.83
	90 1-1,200	11	16.7	209,590	13,201	1.57
Slope	< 10°	20	30.3	574,530	16,695	0.73
	10° - 20°	22	33.3	238,215	11,764	1.0
	>20°	24	36.4	78,530	8,834	2.82
Elevation	600-900m	8	12.1	629,420	17,825	0.7
	900-1200m	25	37.9	135,893	13,511	2.49
	1200-1800m	33	50.0	125,959	4,314	0.86
LC	Waterbody	0	0	4,456	0	0
	Cultivated	3	4.5	312,836	25	0.1
	Wooded grasslands	34	51.5	359,182	23,170	0.7
	Forest cover	8	12.1	40,731	325	0.1
	Bare lands	21	31.8	174,066	12,130	1.7
Soils lithotype	Lithosols (Sandy)	7	10.6	67,630	2783	0.8
	Arenosols (Loamy)	14	21.2	138,532	7,559	1.47
	Cambisols (clay 51 %)	33	50.0	470,012	18,825	1.0
	Cambisols (clay 47 %)	12	18.2	215,097	6,483	7.53
Total				PNpixNi=891,271	PNpixSi=35,650.8	

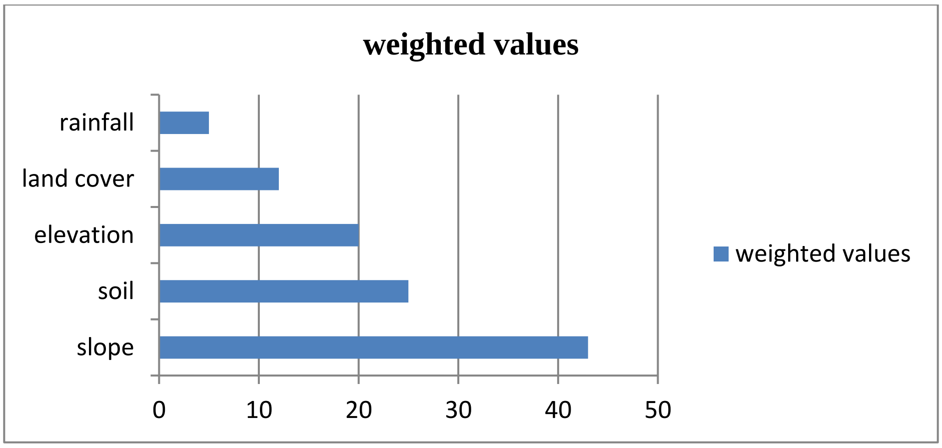
Gentles lopes (< 10°) are the least influential gully susceptibility since most small gullies have merged at the confluence point. The results march those of Termeh *et al.* (2020), which conclude that the number of gullies increases with an increased slope. Similarly, soil factor plays a crucial role in influencing gully susceptibility based on the high weighted values recorded. Soils with high clay content (Cambisols (51% clay) recorded the highest weighted values Wi=7.53 followed by Arenosols at Wi = 1.47. Lithosols were least affected by gully susceptibility (Wi = 0.8), since this zone has numerous rock outcrops thus less gully erosion.

The land cover factor also plays a significant role in increasing geomorphic processes (undercutting, slumping, failure and scouring) that influence gully formation. Bare land most impacted by gully erosion with weighted value Wi = 1.7, since the surface is exposed to raindrop impact and a possibility of flow concentrating and accelerating. Wooded grasslands used as grazing land is highly impacted by gully erosion (Wi = 0.7). Contrarily, gully density-weighted Wi = 0.1 and 0.1, respectively, forested and cultivated land is the least affected. The presence of thick forest reduces the possibility of gully erosion, since plant roots and leaves decrease the erosive action of surface runoff by protecting the soil from overland flow and raindrop impact. Kiang'ombe forested hills have a lower impact on gully occurrence (Wi=0.1) compared to lower areas under vegetation cover and bare land; thus, weighted values decreased with increasing vegetation cover. A positive contrast value of Wi = 1.7 on bare land and a low positive value in areas covered by thick forest (WI=0.1) reveals, that vegetation plays a significant role in prohibiting gully occurrence. Valentin *et al. (*2005) concludes that, gully erosion is accelerated by land cover changes.

Gully erosion is higher impacted by lower rainfall (Wi = 1.57) compared to areas of higher rainfall with weighted W= 0.082. Similar patterns are witnessed in the lower elevation class, where higher weighted values estimated are associated with lower elevation (Wi = 2.49) compared to upper elevation areas (Wi = 0.7) since rainfall and vegetation cover in the study area increases with altitude increases.

5.1.2.6 Multi-evaluation ranking factors for gully susceptibility

Once weighted evaluation for each class factor was determined, a multi-evaluation ranking for gully erosion conditioning classes was determined against each other. The results indicate slope and soil lithotype impacted most on gully susceptibility accounting for 43% and 25%, respectively. High susceptible areas are in slope >20° under cambisols (clay >51%). The region covers the upper segment (1200m – 1800m) most impacted by land cover changes (conversion from forest cover and wooded grassland to more settlement and bare lands) due to encroachment. The finding concurs with Conoscenti *et al.* (2014), that degree of steepness is a major factor in influencing gully susceptibility. Land cover and rainfall variability have the least effect on gully susceptibility at 12% and 5%, respectively (Figure 5.19).



Consistency Ratio (CR) = 0.097

Figure 5.19: Evaluations for gully erosion susceptibility

Thus, there is a higher probability of gully initiation on slopes > 20° with cambisols (clay 51%) lithotype and higher rainfall compared to slopes < 11° under arenosols (loam soils) and lower rainfall (Figure 5.19). The impact of individual variables on gully susceptibility is further emphasized by calculating the consistency ratio (CR), a measure of the consistency of judgment about large samples of purely random conclusions. If CR is greater than 0.1, then, the judgments should be considered un-trustworthy and the procedure should be repeated until the preferred value of CR of < 0.1 is obtained. The calculated consistency value CR =0.097, which is < 0.1, indicates that individual variables have a relative importance in influencing gully erosion in the study area.

Lastly, an overlay analysis was executed to determine the overall summation of the weight of each contributing fact. The bivariate statistical (Figure 5.20) shows that 12.73% of the area has high susceptibility, 36.32% is in moderate susceptibility while low susceptibility accounts for 46.95%. The increased susceptibility areas are located in a high elevated region on a slope > 20°.

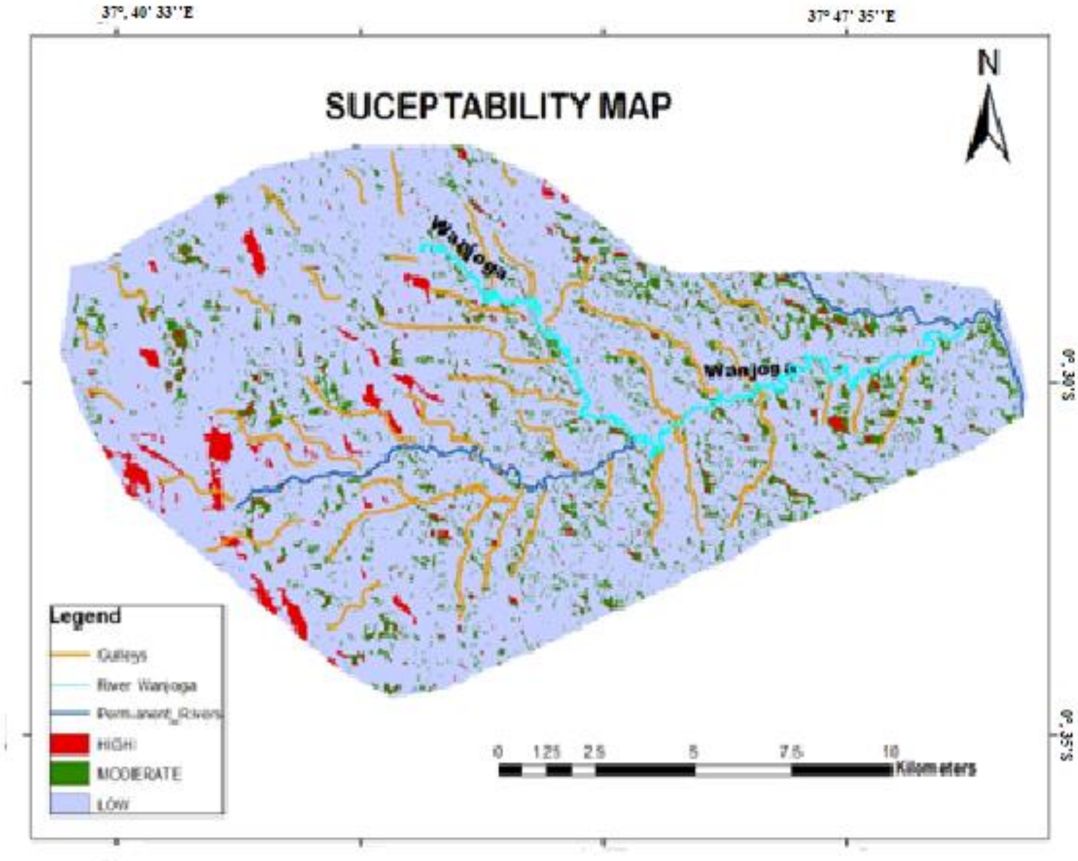


Figure 5.20: **Gully erosion susceptibility in Wanjoga River catchment**

High susceptibility areas for gully erosion at the upper segment of Wanjoga river catchment could partly be linked to geomorphological characteristics, including steep slopes coupled with weakly developed soil structures, generally cambisols with distinct higher weatherable materials in the subsoil. This finding concurs with the results of field data analysis, which concluded that about 51.2% of gullies were observed on slopes > 20°, mainly dominated by cambisols.

Table 5.17: Gully occurrence and gully conditioning factors

Segment category	Total gullies	Gullied area (%)	Main lithotypes	Slope (°)	Elevation (m)
Upper segment	21	51.2	Cambisols (clay loam to clay)	>20°	1,200 -1,800
Mid-segment	12	29.3	Cambisols (sandy clay to loam	11° - 20°	900 – 1,200
Lower segment	8	12.1	Arenosols (loam sandy to loam clay loam)	0° - 10°	600 -900
Total	66	100			

Moderate risk areas are slopes mainly 11° - 20°, accounting for 29.3% of gullied areas, while low-risk areas had 21% gullied areas observed. Therefore, there is a higher probability of gully initiation to occur in areas influenced by two or more gully conditioning factors such as bare land on steep slopes > 20° with Cambisols.

5.1.2.7 Testing and Verification of the gully image

Test verification on satellite images was carried out using an accuracy assessment test, assessing the degree of error in the output images produced. An error array is a standard accuracy reporting mechanism that shows a cross-tabulation of the class labels in the classified map versus those in the ground truth reference data. Error array was employed to calculate user accuracy, overall accuracy, producer accuracy and the kappa statistic using equation 12. The verification was carried out using 120 pixels of known gully presence or absence to produce an error array based on comparing actual outcomes to the predicted results developed. The accuracy of the susceptibility image was approximately 76.2%, with a false positive value of 4% and a false-negative value of 7% (Table 5.18).

Table 5.18: Kappa statistic Error Matrix

	Actual absence	Predicted presence
Actual absence	110	5 (expected gullies)
Actual presence	4 (actual gullies present)	1 (absent)

The kappa statistic susceptibility map was at 0.42 representing a low, moderate level of agreement, indicating some errors are still occurring which could be due to paths appearing on more vegetated areas identified as gullies and/or gullies not identified in Landsat images resulting in a lower kappa statistic. However, the current prediction produces fewer false positives.

In conclusion, the study reveals that gully erosion is the worst degradation, aggravated by unsustainable human practices, which impact climate change leading to more erodible soils, unstable slopes and changes in land cover. There is a significant relationship between the regions where gully occurs and the surrounding gully conditioning factors based on the bivariate statistical method. A combination of two gully conditioning is an essential factor for gully susceptibility, such as steep slopes with Cambisols (clay loam to clay), accounting for high gully susceptibility compared to gentle slopes of Arenosols (loam sandy to loam clay) under cultivation. Moreover, the successful performance of bivariate statistical methods can be linked to the use of enhanced spatial resolution image that allows precise recognition, visualization of the spatial distribution and delineation of areas affected by gully erosion, which can be problematic in the use of traditional methods. These results concur with Frankl *et al.* (2013), who concluded that gully networks in Northern Ethiopia could be accurately mapped using remotely sensed data and GIS technologies.

5.2 Relationship between gully morphology and rate of gully development

Morphological characteristics (gully typology) for gully development were determined by detailed field study through field surveying, repeatedly measurement of gully geometry, and documenting geomorphological factors around different gully cross-sections since they majorly influence gully development. Three types of gullies identified in the study area included; V, U, and T-shaped (trapezium) gullies.

V-shaped channels are broader at the top with a thinned-out bed since they occur in areas often affected by pipping or cracking brought about by bed geomorphic processes accelerated by plant roots. V-shaped channels are deepened by runoff velocity at maximum, indicating that erosion processes predominate in the upper reaches of the slopes where the gradient is higher. They account for 33.4% of total gullied surface brought about by concentrated runoff along pipped areas and accelerated by steep slopes (> 18°).

The features have similar dimensions across slope segments where they occur in that their sidewalls and gully heads are less prone to erosional processes but more dynamic beds. They tend to be shorter, with the longest gully extending 1600m and the shortest extending approximately 3m. The channels have deeper incision rates with a maximum depth of 2.5m but are limited in lateral extension, with widths ranging from 0.2m to 2.3m (Table 5.19).

Table 5.19: Gully Morphological characteristics

Segment category	Gully shape	Gully count		Max width (m)	Max depth (m)	Max length (m)
		Number	%			
Upper segment	V	12	18.2	2.3	2.5	541
	U	20	30.3	4	2.4	1600
Mid-segment	V	7	10.6	0.63	0.52	940
	U	16	24.2	5.46	2.63	7,500
	T	2	3.0	7.53	5.62	1,400
Lower segment	V	3	4.6	0.4	1.3	750
	U	5	7.6	6.53	0.8	5,700
	T	1	1.5	4	0.8	700
Total		66				

They tend to occur in regions of lithotypes of high clay content, which forms cracks during drought periods, through which channelization occurs during storms resulting in V-shaped features. These landforms tend to be discontinuous in that, they terminate after running for a short distance (average length 450m), with few managing to continue down slope and joining more enormous gullies at the confluence junction.

V-shaped features showed limited evidence of active gully channel banks and heads, discounting the possibility of feature development triggered by slope failure events. Once initiated, the process of deepening and extension on V-shaped gully features appears to be influenced by individual narrow turbidity currents restricted to a single gully channel. Despite the significant similarity in morphological characteristics (gully channel shape V, U, T), the channels depict more random occurrence across the study area (upper segment 18.2%, mid-segment 10.6%, and lower segment 4.6%), a factor probably influenced by surface geomorphic processes controlled by a combination of geomorphological factors (slope, land cover, soil type and rainfall characteristics), rather than a single element.

U-shaped morphologies document enormous diversity in gully morphometry and organization than V-shaped gullies. They account for 62.1% of the total gullies in the study area. Long-term erosional processes influence them in that channel banks block materials crumple due to tension cracks along the gully's steep walls and deepening due to accumulated runoff flow, which keeps gully banks bare and unstable. They are characterized by the width and depth parameters being more or less equal, with the gully channel featuring further growth downstream depending on the erosive capacity of the flow through the gully. Their width ranges from a maximum of 6.53m to a minimum of 1.5m. Their highest width and depth occur after individual channels confluence, which increases discharge downslope, an indication of peak bed and side slopes geomorphic processes (i.e., undercutting and slumping) brought about by higher erosive power of increased runoff.

They depict a higher incision ability at medium slopes (11° -20°) and lower slopes (<11°), with a maximum depth of 2.6m. In these sections, the channels mainly occur on road discharge points and the edge of interfluves where erosive power is high due to high discharge through the gully at peak times. Once they confluence, they tend to be longer and extend to a distance ranging from 1,500m to 5,700m with more or less stable density downslope from the point of convergence. These channels are mainly affected by channelization at lower slopes more adjacent to river channels resulting in higher flow velocities due to higher discharge. Since they tend to be more permanent gully features, the long-term scouring activity on gully cross-section is responsible for high volume on U-shaped channels averaging at $2011m^3$ per gullied area, cumulating to $71{,}396.9m^3$, which represents 59.3% of total gullied sediments. Once formed, these channels showed morphologies that responded more to long-term erosional processes with less short-term erosional geomorphic processes evident at the banks (Figure 5.21c). These studies concur with Rasmussen (1997), concluding that U-shaped channels occur from the Miocene period to recent times in southern Gabon.

Figure 5.21: Bank's geomorphic processes on different gully morphology

The long-term geomorphic processes result in the presence of a coarser apron developed at the gully's bed, an indication of long-term scouring activity at the bed and side walls (Figure 5.21c). This suggests that the turbidity currents responsible for U-shaped gully development were dominated by coarse-grained sediments that simultaneously scoured on gully bed and side walls. The long-term geomorphic processes affecting the gully channel has attributed to their permanent nature with high cumulative volume. Permanent gullies act as channel points connecting river channels and interfluves during wet periods.

At lower (<10°) and medium slopes (11°-20°), another set of gullies occur more irregular in form (T- shaped (Trapezium). T-shaped features are broad, with their bed undergoing both erosion and deposition processes alternately, thus shaped like a double trapezium in the middle and lower section. They account for 4.5% of the total gullied surface in the study area. In some instances, T-shaped gullies are very wide-ranging, between 7.53m to 4m at the top, while their bottom width ranges from 2m to 4m. Their depth is small, averaging (< 0.2m), especially at the lower slopes. They occur on slopes 5° - 12° and in some instances, are filled with sand sediments resulting from low flow velocity (Figure 5.21b), which encourages human activities such as sand mining, which increases the overall total width parameters. The finding concurs with those of Lonergan *et al.* (2013), which conclude that gullies become more profound and broader in a down-slope direction. T-channel shapes are more active channels with evidence of massive slumping and mass failure on their banks (Figure 5.21b). The gully head is responsible for its enormous extension, high volume parameters and unique features. The presence of slumping and mass failures reveals a possibility of sediment gravity flow triggered by slope failure events. These gully channels respond to short-term geomorphic processes making them most active, especially during rainy seasons (Figure 5.21b). On average, T-shaped gullies have the highest average volume (14,123.1m^3), with a cumulative volume of 42,369.4m^3 accounting for 35% of total gullied volume. However, they represent only 4.5% of the gullied areas. The excessive slumping and mass wasting on gully side walls and headward slopes is due to their dynamic nature; in the long-term, suggesting a possibility of slope failure events triggered by more factors than gravity flow necessitated by slope angle (Table 5.20).

Table 5.20: Gully morphology and volume characteristics

Gully Morphology	**Gully volume**			**Gully (%)**	**Total volume (m^3)**	**Average volume (m^3)**	**% Volume**	**Actively eroding**
	Shallow	Deep	Very deep					
V	27	0	0	40.9	7296.3	270.2	6	2
U	19	13	4	54.5	72,396.4	2,011	59.3	11
T	0	1	2	4.5	42,369.4	14,123.1	35	3
Total	69.7	21.2	9.1		122,062.9			

V-shaped channels are shallower with low cumulative volume (7,296.3m^3), though they account for 40.9% of all gullied areas. This low average volume is attributed to their shallow nature (V < 1000m^3), compared to T-shaped gullies, which account for a high volume of >20,000m^3 (Figure 5.22).

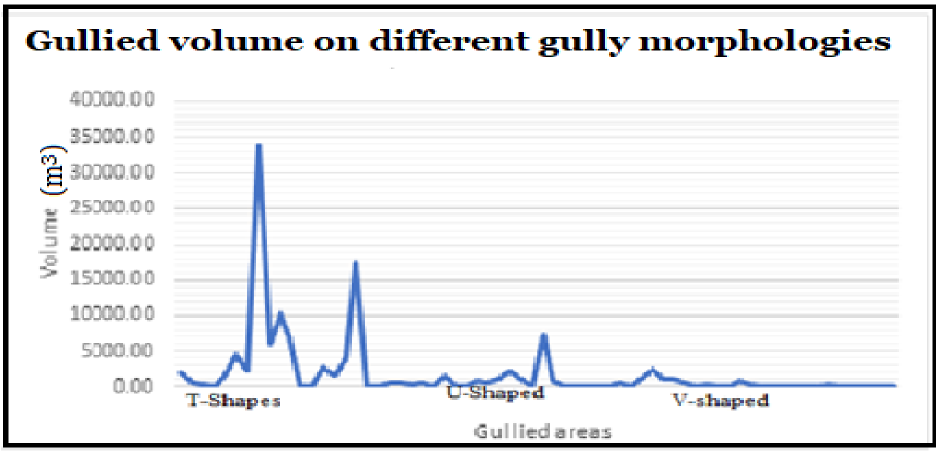


Figure 5.22: Relationship between gully type and eroded volume

The relationship is further emphasized by computed Pearson's moment correlation coefficients and Spearman's Correlation as summarized in Appendix 6. 2 tailed Pearson's computation reveals the value p =0.004 and Spearman Correlation p=0.002 at p=0.05 significance level, thus a significant relationship between the predicting factor and gully development. Thus, the prostrated hypothesis (Ho) 'Gully morphological characteristic does not influence the rate of gully development in semi-arid environment' is rejected while upholding the alternative hypothesis (H1). Therefore, gullies with particular shapes and in specific slope locations were more prone to erosion irrespective of geomorphological actors surrounding them.

5.2.1 Gully morphology and rate gully development

Different gully morphological characteristics respond differently to long-term gully erosional processes. Three gullies to evaluate were identified and monitored from 2000-2021 long-term effect of different geomorphic processes along the gully channel. The channels were monitored using a sequence of two Landsat images for the period (2000/2009) to determine the rate of gully growth over time in the study region. The results indicated that the most active channels are T-shaped morphology, with the length evolving from 963m in 2000 to 1,140m and finally to a total length of 1700. The channel system's highest extension rate was experienced between 2009- 2021compared to 2000 – 2009, with gully extension at a rate of 46.7m/yr. In contrast, the V-shaped channel had the lowest extension rate with the period 2000 – 2009 extending from 87m to 118m and further to 630m by 2021.

U-shaped experienced a steadier extension during the observed period from 540m to 950 from 2000 -2009 and further to 1250 by 2021. Cumulatively, from 2000 – 2021, T-shaped channels extended at a rate of 1421.3m/y, U-shaped channels at a rate of 33.8m/y, while V-shaped features grew at a rate of 25.9m/y (Table 5.21).

Table 5.21: Long-term gully dynamics

Gully category	**Gully parameter**	**Initial survey (2000)**	**Second survey (2009)**	**Third survey (2021)**	**Rate of gully growth (m)**		
					2000-2009	2009-2021	2000-2021
U	Width (m)	1.5	2.6	4.9	0.11	0.2	0.2
	Depth (m)	1.0	1.5	1.9	0.05	0.03	0.05
	Length (m)	540	950	1,250	41	25	33.8
Gully volume m^3		810	3,705	11,637	289.5	661	515.6
T	Width (m)	3.6	4.2	5.5	0.06	0.1	0.09
	Depth (m)	1.1	2.1	3.6	0.1	0.13	0.12
	Length (m)	963	1,140	1,700	17.7	46.7	35.1
Gully volume m^3		3,813	10,054	33,660	624.1	1,967.2	1421.3
V	Width (m)	0.4	0.7	0.9	0.03	0.02	0.02
	Depth (m)	1.2	1.4	1.7	0.02	0.03	0.02
	Length (m)	87	118	630	3.1	42.7	25.9
Gully volume m^3		41.8	115.6	963.9	7.4	70.7	43.0

The same period revealed that the T-shaped gully experienced the highest growth in width parameters over the 21-year period from 3.6m to 5.5m from 2000-2021, while the depth parameters tripled over the same period from 1.1m to 3.6m. On the contrary, V-shaped features, width extended at a limited rate within the same period from 0.4m to 0.9 from 2000 -2021, with incision rate at a much higher rate ranging from 1.2m to 1.7m. This indicates that V-shaped banks and gully heads are less prone to geomorphic erosional processes but more dynamic to bed processes.

Increases in parametric characteristics result in an equal increase in gully volume within the three main channels over the 21 periods. Due to the high rate of increase in gully length, width and depth parameters, the T-shaped channel experienced the highest volume growth from 624m/yr in 2000 to 1,967m/yr in 2009 to 1,421m/yr in 2021, representing 2.3 times increase. This is consistent with field data analysis which indicated that the channels were most active on the head and side walls geomorphic processes. Contrary, the V-shaped channel experienced the lowest increase rate at 7.4m/y in 2000 to 43.3m/y in 2021, and a two-times increase.

The computed rate of gully growth reveals the period 2000 to 2009 experienced the least growth at a rate of 624m/yr for T-shaped gullies, 289m/yr for U-shape gullies and 7.4m/yr for V-shaped gullies, with the period 2009 to 2021 experiencing the higher growth rate (Table 5.21). The period from 2009-2021 shows the lowest growth rate for all the channel types, with T-shaped gullies increasing at a rate of 1421m/yr, U-channels at 515m/yr, while V-shaped features indicated a 2.9m/yr growth rate. These rates compare with those of Romania at 366m^2/yr as reported by Rădoane and Rădoane (2017). The high extension rate observed on T-shaped gullies can be attributed to their active eroding nature, with 100% of observed channels actively eroding. This compared to 31.4% and 7.4% of active U-shaped and V-shaped channels, respectively (Table 5.21).

Therefore, a systematic study of different morphological and morphometric characteristics of gullies reveals a strong relationship between rates of gully growth and morphological characteristics in the study area with computed 2-tailed Pearson's computation reveals the value p=0.002 at a p=0.05 significance level (Appendix 6). T-shaped channels increased rapidly over the 21 years due to raised gully channel bank geomorphic processes such as slumping and failures, increasing the overall width and length parameters. V-shaped landforms tend to be discontinuous in that they terminate after running for a short distance since they are limited in head and side wall geomorphic processes, which increase the overall length and width parameters of gully channels resulting in deeper and shorter gullies. The results are compared with those of Hayas *et al.* (2017), which conclude that V-shaped channels retreat at a slower rate of 39.7 m/yr than U-shaped channels, which retreat at a rate of 49.7 m/yr in southwestern Spain.

These results are compared to those derived from the sediment delivery ratio for the sub-catchment as calculated by the Rusle model. Very low derived values were established with sediment yield ranging from 0.65 t/ha/yr in cultivated and forested land-cover in Kiangombe hills to 14.57 *t/ha/yr* on bare lands and 30.61 *t/ha/yr* vegetated covers. The low sediment removal by sheet and rill erosion confirms that land degradation by gullying was more severe in the Wanjoga River catchment for 21 years. Therefore, more efforts in environmental rehabilitation and conservation need to be undertaken by farmers to stabilize the most active gullies and conserve gully drainage areas which increase discharge into the gullies, increasing soil loss.

5.3 Thresholds for gully development

Understanding a local slope's topographic threshold is critical in gully erosion control. To analyze the threshold factor for gully initiation and expansion, 31 gully head sites were mapped in different geographical regions of Wanjoga River catchment: eleven (11) were sampled in the upper segment (slopes mainly >20º), 14 in the mid-segment (11º-20º) and six (6) in the lower segments (slopes mainly <11°), and used to assess resistance to gully initiation. The 31 gully heads sites for most dynamic gully channels were examined to determine the gully soil slope at the head and drainage area contributing to overland flow to the initiation points. An assessment of geomorphological variability around the gully head, including; soil and land cover characteristics and rainfall variability, was carried out. An assessment of these factors was necessary since the threshold exponent value is dependent on them.

The summary statistics for the 31 initiation points at the gully heads in the Wanjoga River catchment are analyzed in Table 5.22. The average drainage area of gully head cuts in Wanjoga River catchment was 0.0064 ha – 2.59 ha. The slopes for the three-segment regions ranged from 0.067m/m – 0.36m/m (Table 5.22).

Table 5.22: Characteristics of the major gullied area

Characteristics (units)	Upper-segment [n=11]	Mid-segment [n=14]	Lower segment [n=6]
Elevation (m)	1200m -1800m	900m-1200m	600m-900m
Average slope [°]	20.6°	8.4°	4°
Average head slope (m/m)	0.36	0.15	0.067
Area (km^2)	36.1	112.3	52.1
Main lithotype	Cambisols to lithosols	Cambisols (clay >=45%)	Arenosols
Mainland cover	Forest, wooded grasslands, cultivated	Wooded grasslands, bare lands	Cultivation, wooded grasslands, Bare lands
Average gully head width (m)	1.3	1.5	2.3
Average gully head depth (m)	0.6	0.8	0.3
Average gully volume m3	455	1554	1740
Average drainage areas (ha)	0.064	0.84	2.59

The average gully head width increases with an increase in gully drainage area. The upper-segment width parameters averages at 1.3m, 1.5m at the mid-segment and lower-segment at 2.3m. On the contrary, the lower-segment area recorded minimum mean depth of 0.3m compared to 0.6m depth for the upper-segment and 0.8m for the mid-segment region. Increased gully head depth could be attributed to increased overland flow velocity attributed to steeper slopes.

Average gullied volume is estimated at 455m^3 for the upper segment, 1554 m^3 in the mid-segment region and 1740m^3 for the lower segment region. These values indicate the presence of steeper slopes which permits faster movement of surface materials, facilitating the quicker formation of gullies. The relationship estimates upper-segment region had the smallest average drainage area for gully initiation (0.064ha) at a maximum average slope of 0.36m/m, compared to gullies in the mid-segment and lower segment region. In the mid-segment region, the estimated average drainage area for gully initiation is 0.84ha at a minimum slope of 1.15m/m. The lower segment requires the largest drainage area averaging 2.59ha at a minimum slope of 0.067m/m. Consequently, the steeper the slope, the larger the drainage area required for gully initiation and vice vasa. The results concur with Sun *et al.* (2013) concluding that, regions of slopes ranging from 0.035–0.088 m/m have increased gully initiation compared to the gentler region under agriculture in European.

5.4 Slope-drainage area threshold for gully development

Computed gully head slopes (S) and drainage areas (A) relation for 31gullies in the Wanjoga catchment was achieved by empirically computing power regression which was considered as the threshold for gully initiation in the Wanloga River catchment. In the three geographical segments, gully head slopes are positively correlated with R^2= 0.0321 and a p-value of 0.59 for the upper-segment, R^2 =0.498 and p-value at 0.005 for mid-segment and R^2 = 0.088 and p-value of 0.04 for the lower-segments.

As computed in Table 5.23, the upper-segment determination coefficient of R^2 = 0.032, indicates that 3.2% of changes in slope are accredited to the shift in the contributing area, as shown by the linear regression model. Thus, 3.2% changes in slope are explained by varied drainage areas for gully initiation. This indicates a weak association between slope and initiation catchment area for a gully. Thus, other than slope and drainage area, a possibility of different geomorphic factors (a shift in land cover and soil and rainfall characteristics) plays a significant role in gully initiation in Wanjoga catchment.

Table5.23: Regression statistic output in different geographical regions

Regression statistic	Upper-segment	Mid-segment	Lower- segment
Regression Multiple R	0.1791	0.7055	0.3859
R^2	0.0321	0.4977	0.0885
Adjusted R^2	-0.0755	0.4559	-0.0638
Standard Error	0.1544	0.0247	0.0328
Observations	11	14	6

At the lower segment, the R^2 value = 0.089, indicating an 8.9% chance that changes in slope resulted in a difference in the catchment area according to the linear regression model. This shows a weak association between gully head slope and drainage area for gully development. This indicates that 8.9% variation changes in slope are explained by variation in drainage area for gully development. Therefore, though slope and drainage are responsible for a reasonable number of gully initiation, varied geomorphological factors (soil and rainfall characteristics and a shift in land cover) play a significant role in gully initiation in this region.

The determination coefficient of R^2 in the mid-segment is 0.49, showing that 4.98% of changes in slope are attributed to the difference in the area based on the linear regression model. This indicates a strong association between slope and drainage area for gully initiation. Thus, 49.8% of variation changes in slope are explained by variation changes in drainage area for gully development. The coefficient of multiple R= 0.705 (70.5%) indicates a strong association linking gully initiation and development to variation in slope and drainage area in the mid-segment region. Thus, to a more significant extent, slope and drainage are the major factors that influence gully initiation in the mid-segment area.

The result indicates that though slope and drainage area play a vital role in determining gully initiation mid-segment, the establishment of anthropogenic structures (paths and roads) could have contributed to the reduction and/or enlargement of gully catchment area attributed to changes in the direction of overland flow affected by the artificially created channels on roads and paths resulting in gully development.

5.4.1 Initiation threshold for gully heads

The relationship between soil slope and gully head catchment area is shown on the linear regression line in Figures 5.23, 5.24 and 5.25. Visual observation on the regression line revealed an inverse relationship between gully head soil slope and catchment area on the upper-segment. Therefore, the slope reduces with an increase in the drainage area. The direction of correlation as seen from the slope coefficient $^{-}0.3977$ in the regression equation, indicates a negative correlation between slope and drainage area size (Figure 5.23). This implies that, in ($y=0.3835-0.3977x$), a marginal (unit) increase in area (ha) leads to a decrease in the slope of 0.3977 with all other factors constant, thus gully initiation.

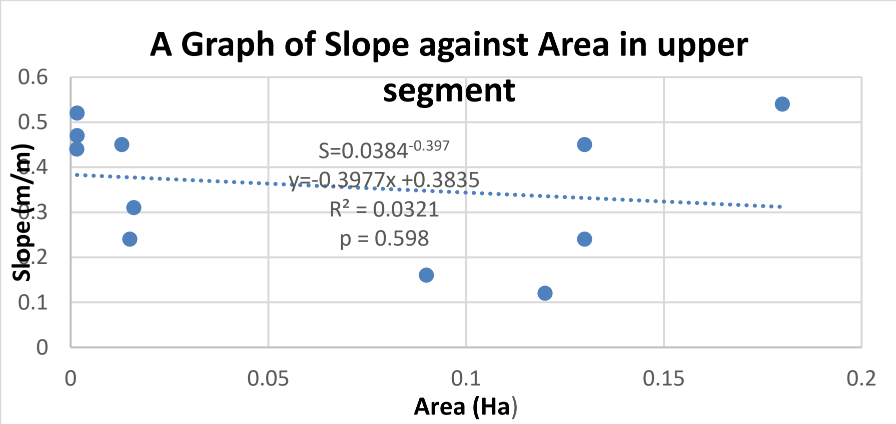


Figure 5.23: Relationship between gully head slope gradient (S) and drainage area (A) in the upper segment

In the mid-segment region, visual interpretation of the linear regression line between slopes of the gully head and drainage area indicates drainage area for gully initiation increases with an increase in gradient. The negative correlation value indicates an inverse relationship between slope and catchment area. The slope direction is seen from the slope coefficient of x in the regression equation {x= ¯0.032), which indicates a negative correlation between slope and area (Figure 5.24). This implies that (y=0.1743-0.03231x), a marginal (unit) increase in area (ha), leads to a decrease in the slope of 0.03231 with other factors constant, which forms a basis for channelization increasing proneness to gully initiation at mid-segment region.

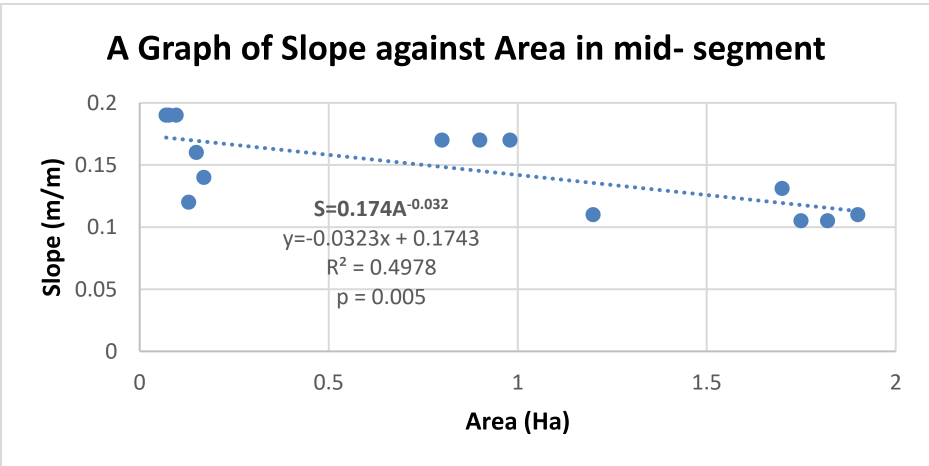


Figure 5.24: Relationship between gully head slope gradient (S) and drainage area in mid-segment

In the lower segment, the visual interpretation of the linear regression line (line of best fit) displays an inverse relationship between the slope of the gully head and gully catchment area. Consequently, the gully catchment area increases with a decrease in slope. The direction of correlation is viewed from the slope coefficient of x (x= ¯0.0203) in the regression equation, indicating a negative correlation between the slope and drainage area. This implies that (y=0.05916–0.02383x), a marginal (unit) increase in area (ha), leads to a decrease in the slope of 0.003283 in slope with all other factors constant, forms the basis for channelization and much prone to gully initiation at lower-segment region (Figure 5.25).

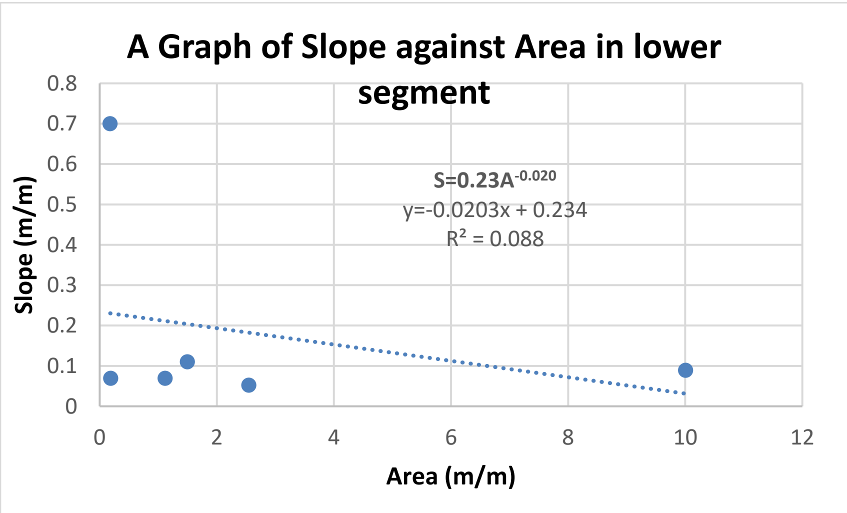


Figure 5.25: **Relationship between gully head slope (S) and drainage area in lower segments**

The derived gully head slope and catchment area values (*S-A)* relation is $S=0.0384^{-0.397}$, with R^2 =0.0321 for the gully initiation area in the upper-segment, $S=0.174A^{-0.032}$, with R^2 value at 0.498 for gully initiation area in mid-segment and at lower-segment $S=0.23A^{-0.020}$, with the value of R^2=0.088, for gully initiation area for the lower segment, represents approximate region for gully initiation and increased proneness to gully development in Wanjoga River catchment (Figure5.23, 5.24 and 5.25). This means that any site gullied or un-gullied below the critical values in the specific landscapes at upper, mid and lower segments, is highly prone to gully erosion.

A comparison of the three graphically derived *S-A* relations indicates the upper-section sites for gully initiation require a higher topographical threshold, shown by exponent values of *b*=¯0.397, compared to mid-segment exponent value *b*=¯0.032 and the least value at the lower segment at *b* = ⁻0.020. Generally, negative exponent values for *b,* if less than 0.2, are considered to deduce areas of dominant overland flow over sub-surface processes in a study area (Vandekerckhove *et al.,* 1998). The studies concur with those by Vandaele *et al.* (1996) that, the slope and drainage area exponent value is approximately ⁻0·4, in an environment influenced by a variety of environmental factors, land uses, and climate variations.

The observed *b* negative exponent values of topography threshold ⁻0.397 at the upper segment, ⁻0.032 at mid-segment and ⁻0.020 in Wanjoga river catchment is an indication that geomorphological factors such as (land cover, soil lithotypes and rainfall variability), increase overland flow since the *S-A* threshold line near ⁻0·4, which Montgomery and Dietrich (1994), associated with similar values of *b* to landscapes with common channel initiation processes which includes channelization and shallow land sliding.

The topographic threshold for gully initiation in the Wanjoga River catchment was lower than those reported by Vandekerckhov *et al.* (2000) in Mediterranean Europe. The different levels could be related to lithological and environmental factors variations in different geographical regions; soil lithotype, rainfall variability and land cover, showing differences in erosion soil resistance (Table 5.24). The high threshold level for gully initiation in the lower-segment compared to the upper-segment attributed to high resistance to gullying in the lower segment, increased by reduced slope, nature of soil lithotypes (arenosols), and land under cultivation with different conservation structures installed by farmers.

Table 5.24: Geomorphological differentiation across geographical regions

Segment class	**Soil lithotype**	**Textural characteristics**	**Land use/land cover**	**Gully %**
Upper-segment	Cambisols (clay > 51%)	clay loam to clay.	Forest cover	50
Mid-segment	Cambisols (clay > 45%)	clay sandy to clay	Wooded grasslands	37.9
Lower-segment	Arenosols	loam sandy to loam clay	Cultivated land	12.1

Regions of cambisols (clay >51%) were mainly in the upper-segment with weatherable materials, unlike the lower segment covered by arenosols. Lithotypes of higher clay content, cambisols, form crevices during dry seasons, which act as fissures through which overland flow concentrates. Soil lithotypes with stony weatherable materials that appear in lower and mid-segment regions may trigger sliding over the bedrock and accelerated over the surface. The presence of weatherable materials triggers accelerated flow over the course material on lower sections of the channel, which triggers bed scouring and bank slumping and failures.

The relationship was further emphasized using Anova to test the relationship between slope and drainage areas across landscapes at a significance level of p = 0.05 and displayed in Table 5.25. The null hypothesis for the test was that 'critical slope and drainage area do not influence gully development in a semi-arid environment.' The results observed revealed p-value at the upper-segment (p=0.598) is much higher than the significance level of p=0.05. Therefore, the relationship is insignificant. Thus, there is no significant linear relationship between slope and drainage area for gully initiation.

Table 5.25: Anova test of significance

Upper-slope	***df***	***SS***	***MS***	***F***	***Significance F***
Regression	1	0.007108	0.007108	0.298278	0.59824
Residual	9	0.214456	0.023828		
Total	10	0.221564			
Mid-segment	***df***	***SS***	***MS***	***F***	***Significance F***
Regression	1	0.007268	0.007268	11.89301	0.004817
Residual	12	0.007334	0.000611		
Total	13	0.014602			
Lower-segment	***df***	***SS***	***MS***	***F***	***Significance F***
Regression	1	0.000754	0.000754	0.700057	0.449838
Residual	4	0.004309	0.001077		
Total	5	0.005063			

In the mid-segment region, value p significance = 0.004 shows significant relation for predicting gully initiation between gully head slope and drainage area. Therefore, the study rejects the null hypothesis. At the lower-segment, the p-value significance =0.4498, which is above the significance level of 0.05 (5%); thus, the gully head slope and gully catchment area are not statistically significant in predicting gully initiation areas in Wanjoga river catchment at 0.05 (5%) level of significance. Therefore, the there is no significant relationship between independent and dependent variables at a 5% significance level.

Though *S-A* relations influence gully initiation at upper and lower segment regions, other geomorphological factors play a significant role in increasing gully development since they influence overland flow dynamics. Using gullies on roadsides, brought about by increased road discharge, requires a lower critical slope for a given gully catchment area for gully initiation and expansion. This gullied channel initiates a few meters from the road, as analyzed in Table 26, using four main gullied areas on the roadside. The gully's initiation catchment area ranged from 0.0017ha at a slope of 0.47m/m in Kiang'ombe hill. In lower-segments areas such as Ngose, a maximum gully catchment area required for gully initiation to start is 0.19ha and a lower limit slope of 0.069m/m for gully head initiation and lateral channel progression (Table 26).

Table 5.26: Influence of drainage area and slope on roadside gullies

Major gullied areas	Drainage areas (ha)	Slope (m/m)	Gully length (m)	Soil lithotype
Kiangombe	0.002	0.47 (27°)	1500	Lithosols (sandy)
Kathera	0.013	0.145 (7.2°)	800	Cambisols(51% clay)
Kerie	0.08	0.19 (11°)	1000	Cambisols (51% clay)
Ngose	0.2	0.39 (3°)	1340	Arenosols (loam)
Iriatune	0.097	0.019 (4°)	1660	Cambisols (Clay 47%)

Channelization onto roadsides has increased gully drainage areas. Thus, gullies exhibit broader and longer characters, lengths ranging from 800m at Kathera in the upper segment to 1660m at Iriaitune in the lower-segment. However, initiation sites have a gentler initiation slope of 0.019m/m. These results compare with those of Kartz *et al*. (2013), which conclude lower slope critical values and gully catchment areas are required for gully formation in areas associated with roads.

Based on soil lithotypes, areas of weakly developed clay lithotypes, characterized by soils with weatherable materials in the top layers, require a low drainage area for gully initiation ($S = 0.383A^{-0.397}$) for the upper segment. This is due to the physical property of these soils to form crevices during dry seasons, which act as points of overland flow concentrates during wet periods. The very cracking nature of clay lithotypes in the upper- segment led to the concentration of overland flow along the minute cracks, increasing gully development in the area even though the site is under forest and thick vegetation cover (Figure 5.10). A high susceptibility can further explain this to gully erosion on higher elevation grounds (Figure 5.20). The studies concur with Torri and Bryan's (1997) conclusions that the clay lithotypes areas created concentrated flows that resulted in gully system formation. Also, Vandaele *et al.* (1996) concluded that places associated with steeper slopes and sliding require lower drainage areas for gully initiation compared to regions of gentler slopes. After determining critical slope and drainage areas for gullying in a landscape unit, an elaborated and effective strategy for gully rehabilitation and conservation can be effectively put in place.

Therefore, gully head slope and catchment area contributing to the gully have statistically significant effects on the overall gully initiation and extension at the mid-segment of Wanjoga river catchment. From the results, an increase in slope requires a limited area for gully initiation, while a large slope requires a large drainage area for gully initiation. Large drainage areas, as observed in mid and lower segments regions, generate an enormous volume of overland flow with high erosive power, capable of producing elaborate gullies and vice versa (Fu *et al.,* 2009). Croke and Mockler (2001) demonstrated that a reduction in gully contributing area through a decrease in the catchment area reduced gully erosion at roads, particularly on steep slopes.

5.5 Social-economic factors on gully erosion stabilization

The study objective engaged in analyzing the elements of social-economic factors of gully stabilization in the Wanjoga River catchment. Most sites are under extensive land cover shift despite the steeply inclined slopes, putting most regions at high risk of gully development. The effectiveness of gully stabilization methods in an area depends upon a thorough understanding of the localized mechanics of the gully erosion processes. This involves a proper understanding of both natural and artificially induced factors that increase gully erosion. This includes; elaborate geomorphic processes, channelization which results in increased gully initiation sites and extension of already formed gully channels. The areas covered in this analysis were those farmlands that had gullied areas large enough to pose a threat to livelihood loss.

5.5.1Farmers interview schedule respondents

The study region was divided into three geographical segments to enable the study to capture various views of land owners in the Wanjoga River catchment, a part of differentiation in elevation and rainfall variability. Of the respondents interviewed, 39.8% were drawn from the upper-segment, 32% from the mid-segment, while the lower segment had 28% respondents. The response rate in the upper-segment was 30.5%, mid-segment 27.1% and 26.3% for the lower segment region; the overall response rate at 83.1%. Studies by Johnson and Owens (2003) concluded that a response rate of at least 60% was sufficient in social science surveys (Table 5.27).

Table 5.27: Distribution of respondents across geographical segments

Geographical category		Frequency	Percent	Expected count	Percent
	Upper segment	36	30.5	47	39.8
	Mid-segment	32	27.1	38	32
	Lower segment	31	26.3	33	28
	Total	98	83.1	118	100

As indicated in Table 5.27, the respondents were equally distributed across the three geographical segment regions. This helped to determine regions and eliminated bias in making conclusions on gulley formation across regions in the area.

5.5.2 Farmers' level of education

The outcomes reveal that 5% of the farmers were of university-level education, 20% were of college-level, 66.6 were of 0-level education and 7.0 % were below 0- level (Table5.28).

Table 5.28: Education levels of the respondents

Education level		Frequency	Percent	Cumulative Percent
	Below 0- level	7	7.0	7.0
	0-Level	67	66.6	73.6
	College	20	20.2	93.8
	University	5	5.0	100.0
	Total	98	100.0	100.0

The results indicated that most of the respondents (91.8%) had attained a reasonable level of education to A-levels, while a small minority (7%) had no formal education. Thus, the respondent had the requisite knowledge to give the required information regarding gulley formation in their respective farmlands.

5.5.3 Land cover influence on gully formation

A Survey of areas with gullies indicated a relationship between land cover/land use and the frequency of gullied sites in the Wanjoga River catchment (Table 5.29).

Table 5.29: Gully frequency and land cover

Land cover		Frequency	Valid Percent
Valid	Crop growing	5	5.1
	Animal grazing/vegetated	69	70.4
	Roadsides	15	15.3
	Near river	9	9.2
	Total	99	100.0

Of all the surveyed gullies on farmlands, most of the gullies occurred on vegetated land used as grazing land accounting for 70.4% of the total gullied area, 5.1% on cultivated land, and 15.3% on roadsides and footpaths, while 9.2% on land near rivers. The study concurs with that of Zucca *et al.* (2006), which indicates, that excessive grazing weakens soil structure resulting in gully initiation and progression

5.5.4 Farmland size holding

The distribution of land in the Wanjoga River catchment is summarized in Table 5.30 Majority of farmers owned land between 5-10 acres accounting for 61.6%, while a small percentage owned land larger than 10 acres (16.2%).

Table 5.30: Farmland size holding

Farm holding		Frequency	Percent	Cumulative Percent
Valid	> 5 acres	22	22.2	22.2
	5-10 acres	61	61.6	83.8
	>10 acres	16	16.2	
	Total	99	100.0	100.0

The remaining respondents (22.2%) owned less than 5 acres of land. Given that most of the respondents in Table 5.30 had more than one gullied channel on their respective farmlands, most of the farmlands are at increased risk of gully development.

5.5.5 Gully frequency on farms

Even though most farm holding is < 10 acres, the respondent indicated a high frequency of gullies on their farms. The findings showed that most farms had between 1 and 5 gullies accounting for 86%, while only 4% of farms had gullies of more than 5, accounting for 4% (Table 5.31)

Table 5.31: Gully frequency on farmlands

Gully count	Respondents count	% Respondent
1 to 2	68.0	68.7
3 to 5	27.0	27.3
Above 5	4.0	4
Total	99.0	100

A high number of gullies on farmlands indicated that farmers had not viewed gullies as a threat to loss of livelihood. Of all observed gullies on the farm, only 28.8% of gullies had any form of conservation structures applied to them. Small landholders were more concerned with conservation against gullies, with 58.3% of the gullies having recorded a form of conservation structure compared to34.8% of conservation structures applied on gullies on farmlands > 10 acres (Table 5.32)

Table 5.32: Frequency of rehabilitation structures on farmland

Farm holding	Gully frequency	Gully count	Conservation Structures on farmlands	%
> 5 acres	22	24	14	58.3
5-10 acres	61	46	16	34.8
>10 acres	16	86	16	18.6
Total	99	156	45	

Farmers holding large pieces of land did not view gullies as a threat to their farms, with only 18.8% conservation structures on these farms. These farms (>10 acres) were under communal grazing, therefore at higher risk of gully formation.

5.5.6 Role of elevation on gully formation

Farmers recognized the role played by elevation in gully formation since it leads to intensive overland flow concentration. Farmers' responses on the perception of the role played by elevation on gully erosion are depicted in Table 5.33. The findings of respondents indicate that, out of 156 regions along gully channels identified to require rehabilitation on farmland, 90 gullies (56.7%) were on steeper slopes, and 46 gullied sites (29.5%) were on medium slopes. In contrast, 20 gullied sites (12.8%) occurred in gentle slope regions.

Table 5.33: Perceived slope steepness and gully occurrence

Steepness	Gully Number	Percentage
Steep slopes	90	56.7
Medium slopes	46	29.5
Gentle slopes	20	12.8
Total	156	100

The steep slope regions had more frequency of gully occurrence compared to medium and gentle areas. The results reveal that land steepness plays a significant role in gully formation.

5.5.7 Gully rehabilitation methods in the study

In gully control and rehabilitation, the principle used by farmers was mainly to create new conditions which would decrease overland flow since the farmers could not determine the real cause of the gully initiation and development. Several farmers were aware that extreme overland flow was the leading cause of gully development, as they took the effective approach of slope reduction by use of methods such as terracing, while most gullied regions on the roadside used an alternate principle of gully restoration by use of gabions and 'channel filling,' an approach is aimed at restoring the original hydraulic balance of a landscape and protected the gullied scar area very well.

All the gullied areas identified on farmlands with or without a form of conservation structure were analyzed during the study to establish the magnitude of soil loss change once the rehabilitation structure was installed. The revelation on the erosion control approaches assed and recorded in Table 5.34 indicates that fill-up with stones/stone barriers (12.8%) was the most preferred method for gully rehabilitation in the study area while using vegetation and filling with soil was least used at 5.1% and 1.9% respectively. Gabion's rehabilitation methods mainly were used on roadsides accounting for 6.4%. Several farmers saw the need to use a combination of rehabilitation methods for maximum control of gull erosion on their farmlands. 12.8% of the respondents applied the use of both vegetation and stone barriers, while 10.3% used gabion structures and filling with soil. However, a high proportion of farmers (48.7%) ignored the threat of gully occurrence on their farms since the area lacked installed rehabilitation structures across gullied areas.

Table 5.34: Installed rehabilitation structures on gullied areas in Wanjoga catchment

Gulley conservation method	Upper-segment		Mid-segment		Lower-segment		Total gullied areas	%
	Gullied areas conserved	%	Gullied areas conserved	%	Gullied areas conserved	%		
Filling with stone/stone barrier	11	12.2	9	19.6	-	-	20	12.8
Filling with soil	1	1.1	1	2.2	-	-	2	1.3
Use of Vegetation	2	2.2	6	13.0	5	25	8	5.1
Gabions	2	2.2	3	6.5	4	20	10	6.4
Vegetation and use of stone barriers	13	14.4	7	15.2	-	-	20	12.8
Gabions and filling with soil	9	10	5	10.9	2	10	16	10.3
Conserved regions	38	42.2	22	47.8	11	55	80	51.3
Non-conserved regions	52	57.8	15	32.6	9	45	76	48.7
Total	90	100	46	100	20		156	100

Upper-segment region had the least number of rehabilitation structures (57.8%). This indicates that farmers in this region did not view gullies as threatening sediment removal. The most preferred gully rehabilitation structures were stone barriers/filling with stones accounting for 12.2%. In the mid-segment region, 32.6% of gullied areas were not rehabilitated and only 25% of respondents prefer using vegetation rehabilitation. Gabions were mainly used to rehabilitate roadsides gullies in the lower segment region, accounting for about 30% of all structures established in this section. Since the local authority constructs most structures on roadsides, the lower region has the least number of farmers carrying out gully rehabilitation.

Preference for conservation structures is portrayed in appendix 3, with results showing a significant association (Chi = 32.739, p-value = 0.001 < 0.05) between the gulley prevention measures and the topographical segment. For instance, stone barriers are mostly preferred in the upper and mid-segment regions compared to the lower segments where gabions are preferred.

5.5.8 Success of gully rehabilitation methods

Based on interview responses, once conservation structures were installed on regions of increased erosion (Increased Erosion; IE), the structure could heal the gully (Gullied Healing areas; GHA) and/or increase gullying and no healing effect downslope (Gullied Non-Healing Areas; GNA). The use of a combination of rehabilitation methods was more effective in the rehabilitation of gullies. Most farmers in Wanjoga catchment used only one rehabilitation structure per gullied area to limit soil removal. Thus, used structures did not limit and/or prevent banks and bed gully erosion downslope. Only 20.5% of observed installed structures showed healing processes (GHA) or completely healed gullied areas after installation of the structure, while 30.8% (GNA) modified gully channel and increased instances of soil removal downslope after rehabilitation structure was installed (Table 5.35)

Table 5.35: Effectiveness of rehabilitation structures on gullied areas

Gulley conservation method	Upper segment		Mid-segment		Lower segment		Total GHA	GNA	Total	%
	IE	GHA	IE	GHA	IE	GHA				
Filling with stone/stone barrier	11	7	9	5	-	-	12(37.5%)	9 (18.8%)	21	26.3
Filling with soil	1	1	1	-	-	-	0	2 (4.2%)	2	2.5
Use of Vegetation	2	1	6	4	5	5	5(15.6%)	8(16.7%)	13	16.3
Gabions	2	-	3	1	4	1	-	9(18.8%)	9	11.3
Vegetation and stone barriers	13	12	7	1	-	-	13(40.6%)	7(14.6%)	20	25
Gabions and filling with soil	9	4	5	-	2	1	3(9.4%)	13(27.1)	16	20
Total Conservation structures	38	27	31	13	11	7	32	48	80	
Percentage %							**20.5**	**30.8**	**51.3**	

Most methods preferred rehabilitation structure; filling with stone was ineffective in healing or limiting erosion downslope after installation. Only 37.5% of gully channels rehabilitated by filling with stones had limited erosion downslope. In comparison, 15.6% of those which used vegetation showed signs of slight deterioration after the conservation structure was installed. This could be explained by the fact that additional coarse materials can ensure incision cut around the introduced structure or accelerate flow downslope. The conclusions concur with Kirkby and Brecken (2009), who conclude that rehabilitation structures limit the drainage area a gully system can exploit, and then erosion becomes self-limiting.

Combining rehabilitation structures in gully rehabilitation was the most effective form of gully restoration since the two methods could discourage flows by by-passing the threat areas to other sites surrounding the gully. 40.6% of channels rehabilitated by use of a combination method of vegetation and stone barriers had limited erosion downslope. In comparison, 9.4% of those who used gabions and filling with soil had limited erosion after the conservation structure was installed. Vegetation treatment on gullied areas increases soil shear strength by providing additional resistance against gully head and bank slumping and mass failure (Simon *et al.,* 2000)

Gabions were the most preferred roadside gully rehabilitation methods, though it was the least effective in limiting erosion downslope since no gully rehabilitated using this method showed decreased erosion downslope. Figure 5.26 shows changes in gully width after installation of gabion as a rehabilitation structure. At the degraded gully bank and downslope, there is maximum retreat observed. The roadside gully system had evolved downslope, causing further growth around the original gully channel in all directions, which affected the ruggedness of the landscape (Figure 5.26).

Figure 5.26: Excessive erosion downslope over rehabilitation structure

After installing the gabion across the gully channel, the width had doubled in size.

Thus, introducing gully rehabilitation structures (gabions and filling with stones) reduces the gradient at which flood events carry materials. However, additional coarse materials must be done with caution since incision can cut around the introduced structure and scouring by the movement of the added materials downslope.

5.5.9 Citing of conservation structures

Despite limited knowledge of factors that increase gully erosion in the local environment, farmers were responsible for designing and placing rehabilitation structures in the affected areas. Interviews based on site selection for installing rehabilitation and conservation structures revealed, that 84% of respondents' site choice for the location of rehabilitation structures was informed by perceived areas of excessive soil loss, ignoring the threat posed by catchment areas' overland flow accumulation potential. Similarly, 12% of respondents installed rehabilitation structures randomly, while only 2.1% sought advice from agricultural extensional officers (Table 5.36).

Table 5.36: Choice of conservation structures placement

	Gully Frequency	%	Structure frequency	
			Use of one structure	Use of more than one structure
Randomly	12	12.2	83.3	16.7
Use of agricultural officer	2	2.1	100	0
Areas most affected by gullies	84	84.7	94.1	5.9
Total	98	100.0		

While citing rehabilitation structure, farmers ignored impacts of the area contributing to the gully and gully length at the point of conservation. Irrespective of the size, width and length of the gullied area, most farmers used one rehabilitation structure for rehabilitation. Farmers assumed that a single rehabilitation structure installed over any cut channel was effective enough to reduce the impact of surface overland flow over the affected area. 94.1% of respondents who sited their structures based on excess erosion points used one structure per gullied area. 16.7% of those who sited their structures randomly had one structure over the gullied area, while none sited more than one structure though they sought advice from agricultural extension officers.

Using one structure such as a gabion or stone barrier to control concentrated overland flow over a wide gully catchment area resulted in acceleration of flow on the lower sections or/and in the diverted direction (Figure 5.27). Coarse rehabilitation structure can result in an increasing gradient at which storm regimes carry coarse materials increasing incision around the introduced structure (Kirkby and Brecken, 2009).

Figure 5.27: Accelerated downslope gully erosion

Accelerating flow on the lower section or/and the diverted section increases erosion in a downslope direction. Thus, the most effective rehabilitation methods for a gully channel are those most suited for causing filling of gullies and providing necessary maintenance of the hydraulic balance. Geyik (986) concluded that management methods for the reduction of drainage areas for runoff control and erosion must be well designed and laid out for effective rehabilitation. In addition, all farmers expressed challenges in gully rehabilitation due to minimum government engagement in conservation action, with the local authorities viewing the most significant threat of gullies as roadside sites of increased geomorphic processes since they pose a threat to transport networks cut-off (Table 5.37).

Table 5.37: Perception of threat to gully erosion

	Respondent Frequency	**%**
Grazing land	7	7.1
Cultivation land	15	15.3
Roadsides	72	73.5
forest	4	4.1
Total	98	100

Gullies act as channelization points through which gully discharge is increased, thus, they dictate planned, more frequent and complex rehabilitation structures for gully initiation control. Contrary, only 7.1% of farmers viewed gullies on grazing land as a threat to soil loss threatening their livelihood since they did not affect the net production output. These areas are used as communal grazing land; thus, farmers had no direct responsibility for gully rehabilitation.

Following the diverging results on gully rehabilitation in different segment regions, a paired t-test was used to establish the success of rehabilitation structures as portrayed in Table 5.37and results computed in Table 5.38a and b. The calculated 2-tailed significance observed p-value is 0.000, which is less than 0.05 hence accepting the null hypothesis and concluding that gulley rehabilitation and conservation measures used by farmers have not healed a significant number of gullies across all segments.

Table 5.38: Paired t-test statistics for three segments

a. Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	Gully count	23.31	156	20.616	1.651
	Healing gullies	2.45	156	3.667	.294

b. Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	Gully count - healing gully	20.859	22.412	1.794	17.314	24.404	11.624	155	.000

Moreover, most farmers cited a challenge in gully rehabilitation, with 36.7% citing financial difficulties, 4.1%lack of technical knowhow, 16.3% lack of equipment while lack of materials for use in gully rehabilitation accounted for 18.4% (Table 5.39). This is despite most gully rehabilitation structures constructed by filling with stones and vegetation, materials available within the local environment.

Table 5.39: Challenges to gully rehabilitation

Respondent challenges	Frequency	Percentage
Lack of technical know-how	4	4.1
Lack of equipment	16	16.3
Lack of Capital	36	36.7
Choice of materials to use	18	18.4
Not available	24	24.5
Total	98	100

However, 24.5% of farmers did not see the need for rehabilitating gullies on their respective farms. Of major concern,96% of farmers assumed they had technical know-how on gully structure establishment, though their structure design and placement proved ineffective in compacting gully erosion. This assumption resulted in increased gully development in the catchment.

Numerous uses of inappropriate, poorly constructed and installed gully rehabilitation structures have increased the chances of gullies bypassing the threat areas by cutting a new channel at the side and /or lower gradient area. Therefore, the most effective rehabilitation structures appropriate for the study region would be those designed and appropriately sited to reduce slope, properly manage upland drainage area and maintain vegetation cover to reduce surface overland flow (Figure 5.28).

Figure 5.28: Degraded areas versus conserved lands in Wanjoga River Catchment; (a and b) degraded gullied areas in Kathera and Kirie (c and d) Rehabilitated lands by different grass varieties.

Installation of effective rehabilitation structures such as the use of grass may take longer and sometimes be costly to install but minimizes overland flow and flow concentration aimed at minimizing the erosive power of overland flow. The comparison results of treated gully head (c and d) and untreated gullied areas (a and b) show tremendous soil loss reduction over time. Eventually, the downstream part of the gully becomes inactive and discontinuous due to a decrease in discharge. In areas of increased channelization, infiltration capacity of soil can be ensured by increasing vegetative cover and, if it’s proven a challenge due to a semi-arid environment, increased alternate beams of stone structures. Such beams would increase sediment deposit behind the check dam, eventually encouraging naturally growing grasses to establish. As observed in Ethiopia by Kraaijvanger and Veldkamp (2015), such measures efficiently trapped sediment due to raped gully heads.

Gully development in the study area results from human-induced activities resulting in land cover changes; in established gullied areas, conservation against gullies can be achieved by reducing drainage area into the gully head by constructing a stone barrier at the gully's edge. The upstream region of the gully should then be filled with soil and/or trapped with stones, and after, plant fast-growing grass in the upstream direction of the gully channel (Figure 5.28c). Consequently, the introduction of conservation structures should start at the upstream edge of the gully to reduce drainage area, which increases discharge (Q) into the gully system. Subsequently, more rehabilitation and conservation structures should be designed and appropriately sited to minimize slope and overland flow accumulation (Figure 5.29).

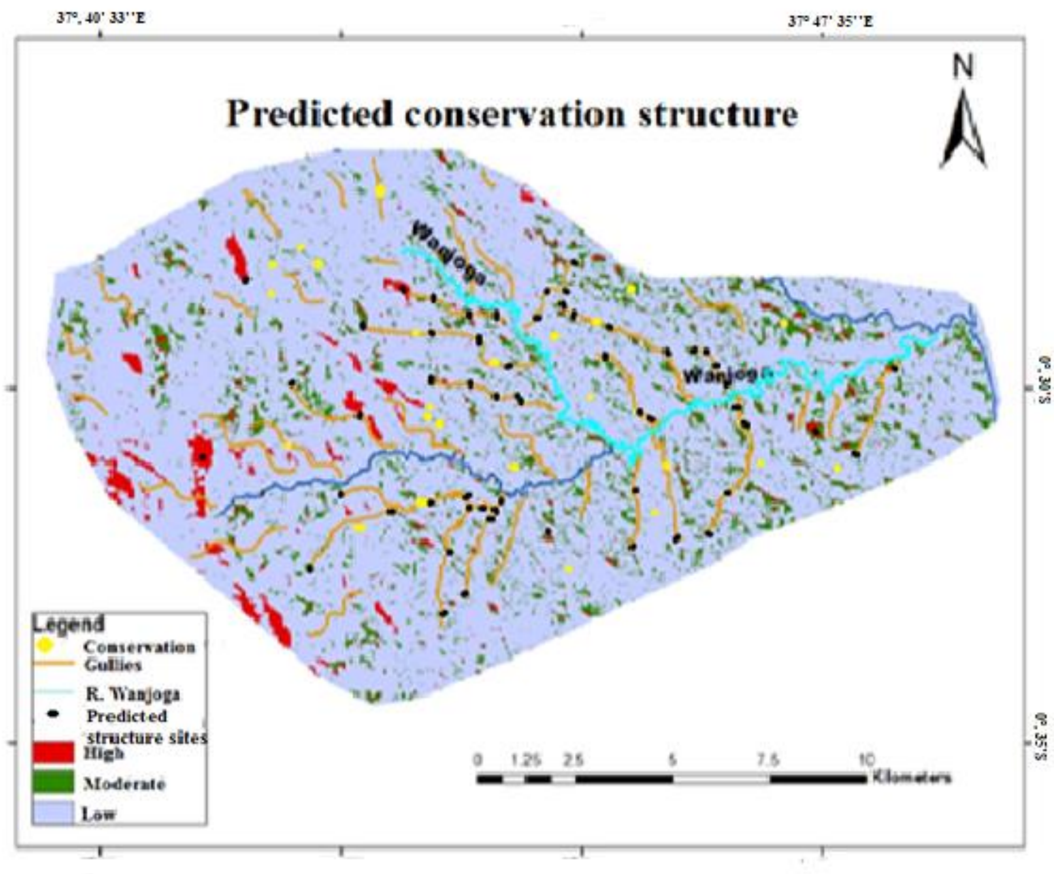


Figure 5.29: Predicted areas for gully rehabilitation

Increased conservation structures increase channel roughness which reduces overland flow velocity and evacuates bed load, increasing effective bedload fraction. Vanwalleghem *et al*. (2008) revealed that, the increased slope is the most critical factor in predicting incidences of permanent gullies. Less pronounced gully channels can be rehabilitated by limiting human activities in gullied regions which allows for natural vegetation growth within the gullied channel, thus, continued natural regeneration. Subsequently, in instances of land cover changes, farmers and road planners should be careful not to initiate gullying by increasing slope gradients which encourage gully development.

CHAPTER SIX: SUMMARY, CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

This chapter summarizes the study's findings on gully development and rehabilitation in a semi-arid environment of the Wanjoga River catchment of the upper Tana River Basin. The study evaluates geomorphological and morphological gully threshold factors that promote gully initiation and progression across different geographical regions. The summarized findings are based on the objectives that guided the study. In addition, the chapter makes conclusive remarks concerning the achievements of conducting this study, given the overriding purpose. Finally, implications and recommendations are presented to mitigate the gully erosion problem in the Wanjoga River catchment. The approaches suggested include actions and feasible research gaps that need to be filled to address the magnitude of the problem, even in other vulnerable semi-arid regions of similar characteristics.

6.2 Summary of the findings

The first objective sought to evaluate geomorphological factors that initiate and promote the progressive development of gully erosion in a semi-arid environment. The objective is examined against the null hypothesis that geomorphological characteristics do not affect gully initiation and progression in semi-arid environments. The study rejected the null hypothesis by revealing a significant positive relationship between gully occurrence and geomorphological factors (Appendix 6). The geomorphological factors examined against gully development were; land cover/land cover, slope, rainfall variability and seasonality and soil lithotype. All these factors were confirmed to have a significant positive effect ($CR = 0.097$, which is < 0.1) on geomorphic processes. Accelerated incidences of gully erosion were related to areas of extreme combination factors (steep slopes and land cover) increasing gully susceptibility.

Increased gradient creates concentrated flow points for surface overland flow is critical in determining gully erosion. Slopes>20° are more prone to gully erosion than slopes < 10°. More importantly, areas of increased slope (> 20°) had cambisols (clay>50%); clay minerals tend to form cavities during prolonged dry periods, which act as zones of concentrated overland flow, creating gullies during storms. Therefore, gullies that occur on slopes < 10° should be approached differently regarding rehabilitation. They differ from appearing at> 20° since geomorphic processes acting upon them vary depending on various geomorphological factors.

Increased rainfall is also inverse to gully erosion since increased vegetation limits surface overland flow. The lower the amount and seasonality of rain, the less the ground cover, hence increased surface overland flow on rainfall onset. Also, increases in human activities tend to clear vegetated areas to pave the way for more anthropogenic activities, influencing head and side wall geomorphic processes.

Implementation of rehabilitation measures successfully, more so in semi-arid regions (Wanjoga catchment) requires understanding erosion process dynamics and using an integrated localized approach that accounts for both sub-surface and surface drainage processes determined by geomorphological processes. Similarly, the use of GIS technology to analyze satellite images provides an effective and timely means of obtaining useful information on the spatial distribution and extent of gully erosion susceptibility in a river catchment, which is valuable information in short and long-term gully erosion management.

The second objective established the relationship between gully morphology and the rate of gully development in the semi-arid environment. This objective was examined against the null hypothesis that gully morphology does not influence the rate of gully development in a semi-arid climate. The study rejected the null hypothesis by revealing that there is a thus a strong relationship between the predicting factor and gully development. Therefore, gullies with particular shapes are more prone to gully extension, irrespective of the surrounding geomorphological actors.

V-shaped landforms tend to form discontinuous features that terminate after running for a short distance (450m), with few growing downslopes and joining more enormous gullies at the confluence junction. The absence of slumping and failures at gully side walls and headwalls of these features revealed their initiation, deepening and/or extension are influenced by individual narrow turbidity currents restricted to a single gully channel.

U-shaped morphologies document a great variety of gully morphometry and organization. They are influenced more by long-term erosional processes, in that side walls blocks of materials slide due to tension cracks along steep gully banks, deepening the gully channel due to accumulated overland flow, which keeps the side walls of the gully bare and unstable. The long-term activity process results in morphometric parameters which are more or less equal, with downstream growth of features dependent on the erosive power of the water flowing through the gully. They portrayed high volume, more dependent on individual channels' confluence with other channels, which increases discharge downslope. This indicates long-term bed and side slopes geomorphic processes (i.e., undercutting) brought about by higher erosive power of increased runoff.

T-shaped gullies showed evidence of massive slumping and mass failure on the banks and head, a factor responsible for their enormous extension, high volume parameters and unique features. The presence of slumping and mass failures reveals a possibility of sediment gravity flows over a short period, making them most active, especially during rainy seasons. Over 21 years, the channels increased from 3.6m to 5.5m in width while the length parameter doubled from 624m to 1,421m. Since T-shaped structures are the most dynamic channels and evolve rapidly, the channels dictate more frequent elaborate planned structures for effective rehabilitation and soil conservation.

The third objective sought to determine the threshold of gully development in the semi-arid environment of the Wanjoga River catchment. This objective was examined against the null hypothesis that critical slope and drainage area conditions do not influence gully development in the Wanjoga River catchment. The direction of correlation from the coefficient of x indicated a negative correlation between slope and drainage area, which implies that a marginal (unit) increase in size (ha) leads to a decrease in slope, thus, gully initiation. Therefore, drainage area contributing and gully head slope of gullied sites ($p=0.000$) have statistically significant implications for gully erosion in the study area. Regions of increased slope (> 20°) require a limited contributing area for gully initiation to occur since raised terrain and bare ground enhance concentrated overland flow leading to increased gully density. Gentle slopes require large drainage areas for gully initiation, which in turn generate larger volumes of overland flow with high erosive power, creating large gullies and vice versa. Therefore, the increased drainage area per gullied area in gentle slopes regions makes features with more profound, more comprehensive and widely spread characters. As the drainage area reduces, infilling migrates upslope brought about by lower discharge contributing to the gully channel, which plays a critical role in determining the characteristics of the gully downslope.

Similarly, other than gully catchment area and gully head soil slope, geomorphological factors play a significant role in determining gully development. Roadsides gullies, for instance, require a lowers critical slope for a given gully catchment area for initiation. In such gullies, initiation points appear only a few meters from the road due to accelerated large volumes of water from artificially created channels. Such artificial induced initiation points provide the basis for determining the threshold for gully development which dictates more frequent and elaborate methods of designing and siting conservation structures that provide clues to improve conservation and rehabilitation of semi-arid environments.

The fourth objective evaluated the success of different gully stabilization and conservation methods in gullied areas. The aim was examined against the null hypothesis that gully stabilization methods have not succeeded in controlling gully development in the semi-arid environment. The study concludes that, rehabilitation structures on gullied areas as sited by farmers have not healed a significant number of gullies across all segments ($p=0.000$). The most effective gully rehabilitation structures are those designed to reduce slope, manage upland drainage area properly and maintain vegetation cover, which reduces increased overland flow. Methods most suited to stabilize and cause filling of the gullies and provided for necessary maintenance of the hydraulic balance were; the use of gabions, stone barriers and vegetation for the upper regions, stone barriers and filling with stones for the mid-segment area and use of vegetation for lower segment region. However, care must be taken in the use of rehabilitation structures such as filling with stones, stone barriers and gabions, since added coarse materials on gullied channels can ensure incision cut around the introduced structures and/or scour more by shifting of the added materials downslope as illustrated in figure 5.26.

Since road sides act as channelization points and increase gully discharge, more elaborate and frequently spaced planned structures would be more effective for gully rehabilitation. Moreover, use of calculated slope - area threshold relation line ($S = 0.358A^{-0.3977}$for the upper segment, $S= 0.147A^{-0.023}$ $f$or mid-segment and $S= 0.0.0676A^{-0.020}$ for lower segment), for locating suitable areas for citing conservation structures is an inevitable tool as a topographical threshold predictor, for the semi-arid region of Wanjoga river catchment.

6.3 Conclusions

In conclusion, the study reveals that gully erosion is the worst form of degradation, aggravated by unsustainable human practices, which impact climate change leading to more erodible soils, unstable slopes and changes in land cover. These altered factors become sensitive to increased overland flow and extreme geomorphic processes, increasing susceptibility to gully erosion in semi-arid regions such as Wanjoga river catchment, as predicted by bivariate statistical methodology. Differences in gully morphometric characteristics also trigger gully wall instability, which must be noted as prerequisite failures and slumping, increasing immense gully extension.

Both U and T- shaped channels exhibit higher erosional rates, attributed to the nature of the channel, rainfall seasonality and uncontrolled human activities, which increase banks and head geomorphic processes such as slumping and failure. Attempt to rehabilitate these gully channels with inappropriate structures not suited to specific areas acted to increase gully progression locally in slopes that would otherwise be stable.

In gully rehabilitation, using a combination of conservation and rehabilitation structures such as gabion filled with stones and/or soils and vegetation may be costly to install and take longer to achieve, but it minimizes overland flow eventually. In steeper regions with increased surface channelization, soil infiltration capacity can be increased by increasing vegetative cover and, if it proves to be a challenge due to the area's aridity, growing alternate beams of stone cover. In regions of increased drainage area brought about by increased anthropogenic structures, gully rehabilitation can be achieved by constructing conservation structures such as terracing, which ensures reduced overland flow draining into a gully system; building a stone barrier at the edge of a gully. At the upstream region of the gully, channels should then be filled with soil and/or stones and after, plant fast-growing grass in the upper part, which increases channel roughness by reducing flow velocity. Alternatively, in land cover changes, farmers and road planners should be careful to avoid increasing slope gradients which may encourage gully development

Lastly, for erosion management, established slope – area threshold relation line (S = $0.358A^{-0.3977}$), with R^2 of -0.0321 for upper segment, mid-segment values of S= $0.147A^{-0.023}$), with R^2 of 0.498 and lower-segment values at S= $0.0.0676A^{-0.020}$, with R^2 value of 0.088, should be applied in the semi-arid environments of Kenya to locate sites of increased vulnerability to gully erosion and to pinpoint dominant geomorphic processes intensifies gully erosion to be checked fundamentally.

6.4 Recommendations

In order to reduce and/or mitigate against gully erosion in the study area, the study gave recommendations geared toward reducing both nature and human-induced incidences associated with increased geomorphic processes in Wanjoga River catchments or other semi-arid environments. Some recommended strategies have been used in different regions of the world with success in addressing the problem.

6.4.1 Short-term mitigation strategies for both farmers and local government

Short-term gully rehabilitation structures include;

1. Most urgently, the government should put in place early warning systems that guild against gully erosion. This would help identify areas with visible indicators of soil loss due to gully erosion. The immediate response should be to design and site appropriate conservation structures.
2. Areas with visible cut gully channels should be stabilized by the farmers using designed structures with locally available materials or vegetation; (use of a combination of rehabilitation measures such as; gabion sand vegetation for the upper regions, stone barriers and filling with stones for the mid-segment area and use of vegetation for lower segment region) for effective gully rehabilitation.
3. Once areas susceptible to gully erosion are identified, there is a need to educate famers on factors that increase proneness to gully erosion for soil conservation.
4. With the help of agricultural extension officers, farmers should be guided to design specific conservation structures suited for localized knick-points in hydraulic gradients for an effective gully hearing process.
5. Farmers should be guided on the use of calculated slope - area threshold relation line to locate the most suitable points for siting conservation structures and increase conservation sites based on threshold and susceptibility factors
6. Using threshold to gully initiation, farmers should be guided on targeting more gullied or/and un-gullied areas for conservation to decrease susceptibility to gully erosion
7. Since the problem of gully erosion in Wanjoga River catchment has been aggravated by use of inappropriate land-use practices and soil conservation structures increased by population pressure on land. Therefore, farmers should be sensitized to the need for gully rehabilitation and conservation.
8. County government, through local leaders, should sensitize farmers on appropriate land-use practices to mitigate against soil loss through gully erosion associated

with land use activities. For instance, terracing (in the gully drainage region) should be emphasized since it helps reduce gully erosion by reducing drainage area and slope.

9. Laws governing the conservation of forested areas should be enforced to ensure the regeneration of forests and protect areas near rivers and excessively steepened regions which are more susceptible to soil erosion.

6.4.2 Long-term conservation strategies for National government

1. Intensive agroforestry should be promoted in areas susceptible to gully erosion. This should involve growing exotic fast-growing trees and grass to provide stability in regions of shifting soil particles.
2. The created DEMs can be used in future research for small-scale catchment response analysis. These results could lead to upscaling research concerning erosion rates in the broader areas of the country.
3. The government can improve people's living standards by introducing alternative means of livelihood not focused on land use that can help farmers rely less on cultivating susceptible areas (i.e. encouraging the rich cultural activities and conservation of the Kiang'ombe hill can promote tourism for local community benefit).
4. Knowledge acquired in this study is an essential tool for decision-makers at local and national levels in devising appropriate by-laws, plans and policies governing land degradation for gully erosion in semi-arid regions.

6.5 Suggestions for further research

Based on the findings of the study, the following suggestions were provided for further research

1. Since the use of bivariate statistical methodology is an effective tool in predicting gully susceptibility in arid areas, more areas in the region should be analyzed by use of the model to assess the vulnerability levels for proper conservation.
2. Roadside gullies can be modeled by use of bivariate statistical methodology to assess their vulnerability levels to soil loss for proper conservation

3. This study used genialized soil data. Thus, further studies are needed on each soil property, including; soil texture, structure and depth, in predicting susceptibility to gully erosion confirm its relevance using a similar model.
4. The study used a few geomorphological factors on their effect on gully; further studies are suggested to analyze the effect of roads and stream power on gully erosion using similar models.

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APPENDICES

Appendix 1: Questionnaire for the farmers

Date

1. Gender: male □ Female□
2. Educational level; below A level□ A level□ university□
3. Slope position of land holding (tick the appropriate).
   (a) Upper slope □
   (b) Middle slope □
   (c) Lower slope □
4. Land use activity/activities practiced by the land user (tick the appropriate).
   Crop growing □ animal rearing □
   Settlement □ Forestry □ Transport □
   Others (specify) ……………………………………………………………
5. Do you think it is necessary to carry out land modifications or adjustments on your farmland?
   (a) Yes□ (b) No need□ (c) Already done □
6. In case you do, indicate the form/forms of modification or adjustment in land that you would be willing to undertake
   Restricting construction□ reducing drainage area□
   Reduction of slopes angle□ Limit creation of artificial slopes □
   Protect artificial slopes whenever they are created
7. Why do you choose those methods modification against others?______________________________
8. In your opinion, is gully erosion a natural occurrence or a man made?__________________________
   Give reasons for your answer____
9. Which major gully rehabilitation and conservation methods used
   Check dams □ Vegetation□
   Gabions□ Stone barriers □
   Terracing□
10. How do you choose the point in the farm where to place conservation structures?
    Randomly□ Areas with most gullies□
    With help from agricultural field officers□ Use of slope angle□
11. What are the challenges of gully rehabilitation in the area?
    Materials for use□ Capital□
    Lack of knowledge□ don't see the need to conserve□
12. When did the gullies in the farm start occurring?
    More than 15 years ago□ 8 years ago□
    5 years ago□ have no idea□

13 Did you try any form of gully rehabilitation? Yes □ No □

Vegetation □ Gabions□

Filling□ Terracing□ did not try□

14. If there was no attempt of conservation, what were the reasons?

Lack of finances □ lack of advice□

lack of materials□ lack of equipment □

15 What help would you require in gully conservation?________________________________

16. What has been the reaction of local and national government on gully erosion experienced in this area?____

Appendix 2: Interview schedule

Date

Gender: male □ Female□

Date

1. Gender: male □ Female□
2. Highest Educational level; ____________
3. What is the notable change land cover in the area in the last 10 years

More crop land□ More roads□

More grazing□ More forests□

4. What are the major causes of gully erosion in the area? Rank the causes based on severity

Lack of conservation structures□

Steep land without conservation structures□ Damaged conservation structures□

More agricultural activities□

If not, what advice do the officers give to the farmers on gully rehabilitation? _____________________

Do the farmers take these advices given? Yes □ No □

If not what reasons do they give for not implementing the advice given_________________________?

In public areas like road sides, who does conservation?

Local government □Mps □Community members □ NGOS □

What type of help do farmers ask for when advised on gully conservation? Financial □ equipment □ materials □

Appendix 3: Correlation test Summary Results

Table 2.1: Summary of Pearson's Chi-Square Test and Fishers Exact Test Results

*All Cramer's V have the same *Exact p – values* as Chi-square (χ^2).

N=66	Slope angle (a)	Segment (b)	Soil type (c)	Land cover (d)	Gulley type (e)	Rainfall amount (f)	Gulley volume (g)
Slope angle		$\chi^2(4)$ = 35.627, Exact p = 0.000; Fisher's = 33.374, Exact p = 0.000; *Cramer's V = 0.52	$\chi^2(6)$ = 20.426, Exact p = 0.02; Fisher's = 17.805, Exact p = 0.03; Cramer's V = 0.39	$\chi^2(4)$ =19.048, Exact p = 0.01; Fisher's = 17.773, Exact p = 0.01; Cramer's V = 0.38	$\chi^2(4)$ =11.334, Exact p = 0.012; Fisher's = 11.798, Exact p = 0.007; Cramer's V = 0.29	$\chi^2(2)$ =17.160, Exact p = 0.000; Fisher's = 15.633, Exact p = 0.000; Cramer's V = 0.51	$\chi^2(4)$ =14.800, Exact p = 0.004; Fisher's = 13.097, Exact p = 0.005; Cramer's V = 0.34
Elevation			$\chi^2(6)$ = 52.208, Exact p = 0.000; Fisher's = 41.625, Exact p = 0.000; Cramer's V = 0.63	$\chi^2(4)$ = 18.723, Exact p = 0.001; Fisher's = 18.003, Exact p = 0.000; Cramer's V = 0.38	$\chi^2(4)$ = 3.626, Exact p = 0.553; Fisher's = 3.980, Exact p = 0.383; Cramer's V = 0.17	$\chi^2(2)$ = 13.200, Exact p = 0.003; Fisher's = 12.910, Exact p = 0.001; Cramer's V = 0.447	$\chi^2(4)$ = 10.244, Exact p = 0.037; Fisher's = 10.760, Exact p = 0.016; Cramer's V = 0.279
Soil type				$\chi^2(6)$ = 20.645, Exact p = 0.002; Fisher's = 22.099, Exact p = 0.000; Cramer's V = 0.40	$\chi^2(6)$ = 10.771, Exact p = 0.088; Fisher's = 10.005, Exact p = 0.073; Cramer's V = 0.29	$\chi^2(3)$ = 14.79, Exact p = 0.02; Fisher's = 13.676, Exact p = 0.01; Cramer's V = 0.473	$\chi^2(6)$ = 4.267, Exact p = 0.671; Fisher's = 3.231, Exact p = 0.815; Cramer's V = 0.18
Land cover					$\chi^2(4)$ = 17.190, Exact p = 0.002; Fisher's = 17.753, Exact p = 0.000; Cramer's V = 0.36	$\chi^2(2)$ = 19.143, Exact p = 0.000; Fisher's = 19.566, Exact p = 0.000; Cramer's V = 0.54	$\chi^2(4)$ = 6.013, Exact p = 0.188; Fisher's = 4.953, Exact p = 0.252; Cramer's V = 0.21
Gulley type						$\chi^2(2)$ = 8.245, Exact p = 0.033;	$\chi^2(4)$ = 23.560,

	Fisher's = 8.652, Exact p = 0.009; Cramer's V = 0.35	Exact p = 0.001; Fisher's = 25.377, Exact p = 0.000; Cramer's V = 0.42
Rainfall amount		$\chi^2(2)$ = 1.446, Exact p = 0.604; Fisher's = 1.054, Exact p = 0.665; Cramer's V = 0.148
Gulley volume		

Appendix 4: Kruskal-Wallis Test Results

Table 2.2: Summary of Kruskal-Wallis Test Results

N=66	Slope angle (a)	Segment (b)	Soil type (c)	Land cover (d)	Gulley type (e)	Rainfall amount (f)	Gulley volume (g)
Slope angle		Asymp. P = 0.000, Exact P = 0.000	Asymp. P = 0.001, Exact P = 0.001	Asymp. P = 0.000, Exact P = 0.000	Asymp. P = 0.006, Exact P = 0.003	Asymp. P = 0.001, Exact P = 0.000	Asymp. P = 0.002, Exact P = 0.001
Segment			Asymp. P = 0.000, Exact P = 0.000	Asymp. P = 0.000, Exact P = 0.000	Asymp. P = 0.288, Exact P = 0.313	Asymp. P = 0.001, Exact P = 0.000	Asymp. P = 0.016, Exact P = 0.013
Soil type				Asymp. P = 0.315, Exact P = 0.326	Asymp. P = 0.589, Exact P = 0.615	Asymp. P = 0.197, Exact P = 0.202	Asymp. P = 0.995, Exact P = 0.995
Land cover					Asymp. P = 0.261, Exact P = 0.274	Asymp. P = 0.886, Exact P = 0.831	Asymp. P = 0.313, Exact P = 0.314
Gulley type						Asymp. P = 0.005, Exact P = 0.005	Asymp. P = 0.006, Exact P = 0.004
Rainfall amount							Asymp. P = 0.491, Exact P = 0.604
Gulley volume							

Table 2.3: Summary of Median Test Results

N=66	Slope angle (a)	Segment (b)	Soil type (c)	Land cover (d)	Gulley type (e)	Rainfall amount (f)	Gulley volume (g)
Slope angle		Asymp. P = 0.000, Exact P = 0.000	Asymp. P = 0.001, Exact P = 0.001	Asymp. P = 0.000, Exact P = 0.000	Asymp. P = 0.019, Exact P = 0.012	Asymp. P = 0.000, Exact P = 0.000	Asymp. P = 0.039, Exact P = 0.036

Segment			Asymp. P = 0.000, Exact P = 0.000	Asymp. P = 0.000, Exact P = 0.000	Asymp. P = 0.208, Exact P = 0.224	Asymp. P = 0.000, Exact P = 0.000	Asymp. P = 0.009, Exact P = 0.008
Soil type				Asymp. P = 0.014, Exact P = 0.016	Asymp. P = 0.124, Exact P = 0.129	Asymp. P = 0.003, Exact P = 0.003	Asymp. P = 0.474, Exact P = 0.565
Land cover					Asymp. P = 0.001, Exact P = 0.004	Asymp. P = 0.004, Exact P = 0.005	Asymp. P = 0.104, Exact P = 0.082
Gulley type						Asymp. P = 0.015, Exact P = 0.008	Asymp. P = 0.001, Exact P = 0.000
Rainfall amount							Asymp. P = 0.485, Exact P = 0.604
Gulley volume							

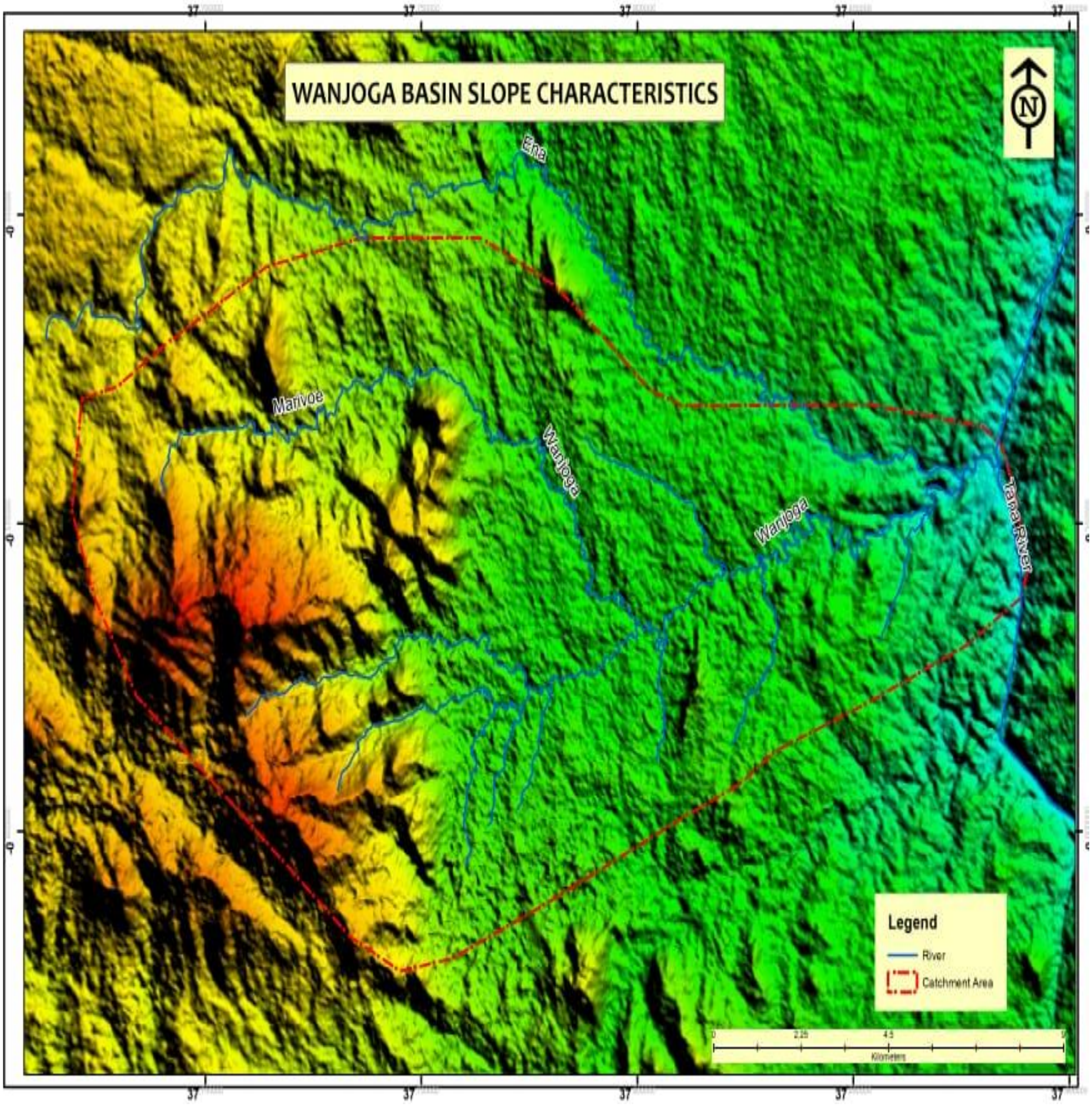
Table 2.4: Summary of Jonckheere-Terpstra Test Results

N=66	Slope angle (a)	Segment (b)	Soil type (c)	Land cover (d)	Gulley type (e)	Rainfall amount (f)	Gulley volume (g)
Slope angle		Asymp. P = 0.000, Exact P = 0.000	Asymp. P = 0.401, Exact P = 0.404	Asymp. P = 0.782, Exact P = 0.788	Asymp. P = 0.003, Exact P = 0.002	Asymp. P = 0.001, Exact P = 0.000	Asymp. P = 0.000, Exact P = 0.000
Segment			Asymp. P = 0.001, Exact P = 0.001	Asymp. P = 0.978, Exact P = 0.979	Asymp. P = 0.127, Exact P = 0.135	Asymp. P = 0.001, Exact P = 0.000	Asymp. P = 0.006, Exact P = 0.005
Soil type				Asymp. P = 0.470, Exact P = 0.476	Asymp. P = 0.879, Exact P = 0.885	Asymp. P = 0.197, Exact P = 0.202	Asymp. P = 0.917, Exact P = 0.920
Land cover					Asymp. P = 0.239, Exact P = 0.250	Asymp. P = 0.886, Exact P = 0.831	Asymp. P = 0.293, Exact P = 0.293
Gulley type						Asymp. P = 0.005, Exact P = 0.005	Asymp. P = 0.002, Exact P = 0.002
Rainfall amount							Asymp. P = 0.670, Exact P = 0.762
Gulley volume							

Appendix 5: Paired T-Tests on conservation method used and geographical regions

	Value	df	p-value	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	32.739[a]	12	.001	.[b]	
Likelihood Ratio	35.057	12	.000	.[b]	
Fisher's Exact Test	.[b]			.[b]	
Linear-by-Linear Association	3.031[c]	1	.082	.085	.045
N of Valid Cases	156				

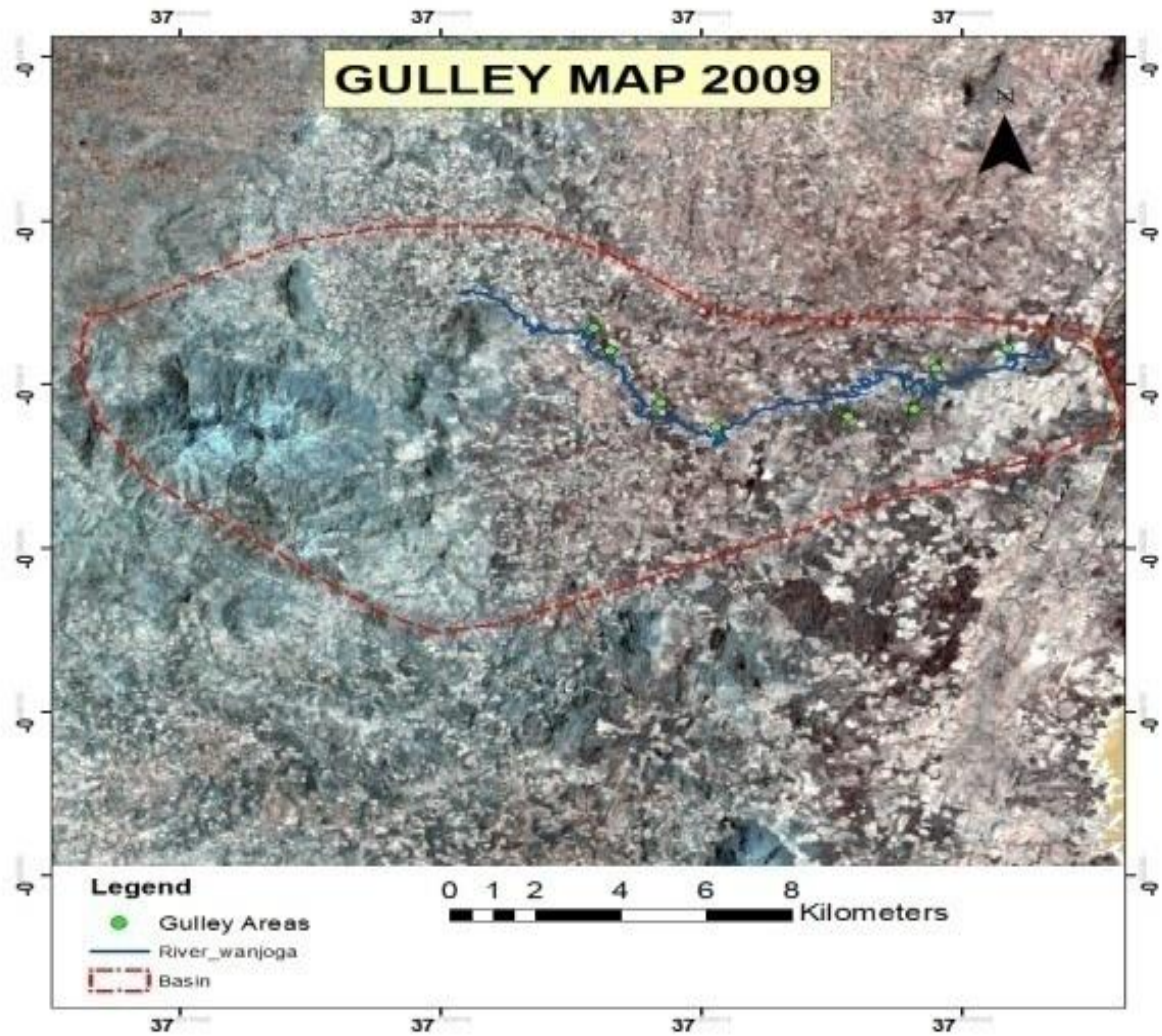
Appendix 6: Slope classification DEM

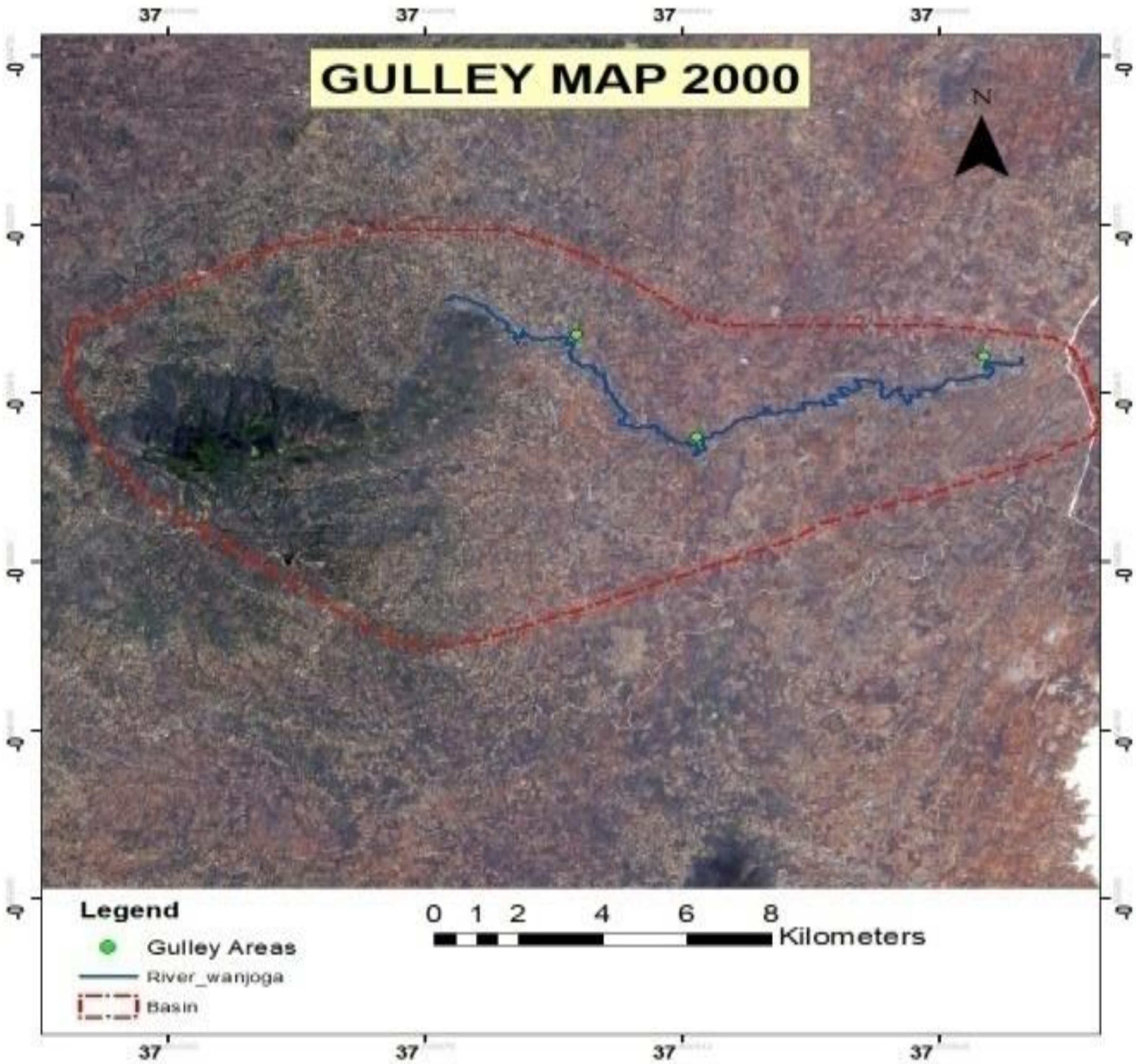


Appendix 7: Geo referenced Rainfall average Data of Wanjoga river catchment

Station_ID	Station_N	Element_I	Year	Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	ISHIARA A	Precipitat	2009	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20.4	15.9	0	0	0	0	0	0	0	0	0	0	0	0	20.5	0	
9037161	ISHIARA A	Precipitat	2009	2	0	0	0	0	0	0	0	0	8.6	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0			25.7
9037161	ISHIARA A	Precipitat	2009	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21.8	31.6	20.1	0	0
9037161	ISHIARA A	Precipitat	2009	4	0	0	0	58	6.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	47.7	6.8	10.1	0	0	2	16	0	17.2	0	0	0
9037161	ISHIARA A	Precipitat	2009	5	0.5	0	0	9.8	0	0	0	0	0	15.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9037161	ISHIARA A	Precipitat	2009	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9037161	ISHIARA A	Precipitat	2009	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9037161	ISHIARA A	Precipitat	2009	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9037161	ISHIARA A	Precipitat	2009	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9037161	ISHIARA A	Precipitat	2009	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	17	25	0	17	0	0	0	0	0	0	0	0	2.5	40.1	10.3	0
9037187	CHIAKARI(	Precipitat	1999	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9037187	CHIAKARI(	Precipitat	1999	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0.9	0.4	0	0	0	0	0	0	0	0	0	0	0			
9037187	CHIAKARI(	Precipitat	1999	3	0	0	0	0	0	0	0	0	5	0	4.5	0	1.5	4	29.4	0	0	3	0	0	0	0	0	0	21.3	0	3	3.6	70.3	70	0
9037187	CHIAKARI(	Precipitat	1999	4	39.6	0	69.8	0	30.6	0	0	10.5	1.7	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	9.9	21.6	0	0
9037187	CHIAKARI(	Precipitat	1999	5	8	0	3.1	3.8	0	0	0	0	0	0	0	1.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9037187	CHIAKARI(	Precipitat	1999	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.2
9037187	CHIAKARI(	Precipitat	1999	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9037187	CHIAKARI(	Precipitat	1999	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9037187	CHIAKARI(	Precipitat	1999	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9037187	CHIAKARI(	Precipitat	1999	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.4	32.8	0	0	0	0
9037187	CHIAKARI(	Precipitat	1999	11	0	5.4	0	3.4	13.1	0	0	4.9	0	0	10.7	10.1	35.9	8.9	12.3	2.1	22.7	6.2	11.2	5	15.4	10.2	12.5	14.6	27.1	20	38.4	32.7	36	101.8	0.6
9037187	CHIAKARI(	Precipitat	1999	12	10.5	0	0	19.4	0	51	12	6	0.5	0	0.6	0	0	0	0	0	15.3	0	33.5	2.5	0	0	10	0	0	0	73.2	0	0	0	
9037161	ISHIARA A	Precipitat	2001	1	0	0	0	2	1.1	0	0	0	0	27.1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
9037161	ISHIARA A	Precipitat	2001	2	0	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
9037161	ISHIARA A	Precipitat	2001	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0	7.5	0	12	26.2	1.6
9037161	ISHIARA A	Precipitat	2001	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.7	0	0	0	0	0	0	0	0
9037161	ISHIARA A	Precipitat	2001	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9037161	ISHIARA A	Precipitat	2001	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25.7
9037161	ISHIARA A	Precipitat	2001	8	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9037161	ISHIARA A	Precipitat	2001	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
9037161	ISHIARA A	Precipitat	2001	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.1	4	0
9037161	ISHIARA A	Precipitat	2001	11	103.8	20.4	16.9	20	16.8	0	0	10.5	0	0	3.1	6.9	3.2	6.3	0	0	0	0	0	0	0	0	0	20.1	31.3	0	0	13	0	0	0
9037161	ISHIARA A	Precipitat	2001	12	0	0	0	0	0	0	0	0	0	0	0	12	4.7	0	4.6	0	6.1	0	4.4	0	0	0	1.5	0	0	0	0	0	0	0	
																											0	0	0	0	0	0	0	0	0
																																			0
																																			0

Appendix 8: Frequency of gullied areas in Wanjoga Catchment 2000-2018


GULLEY MAP 2009
N
Legend
Gulley Areas
River_wanjoga
Basin
0 1 2 4 6 8
Kilometers
37
37
37
37



GULLEY MAP 2000
N
Legend
Gulley Areas
River_wanjoga
Basin
0 1 2 4 6 8
Kilometers
37
37
37
37
37
37
37
37

Appendix 9: Gully erosion morphological and morphometric characteristics in Wanjoga catchment

#		Segment	Length (m)	Max Width (m)	Min Width (m)	Average Width (m)	Max Depth (m)	Min Depth (m)	Average Depth (m)	Volume (M^3)	Slope Angle	Rainfall Amount (mm)	Soil Type
1		UPPER	700	4	1	2.5	1	0.75	0.75	1313	27	1200	1
2		UPPER	1600	2.65	0.85	1.75	1	0.4	0.915	2562	31	1200	4
3		UPPER	1000	3.45	0.5	1.98	0	0.75	0.535	1057	26	1200	4
4		UPPER	900	3.2	0.5	1.85	3	0.24	1.375	2289	25	1200	3
5		UPPER	600	4.2	0.4	2.3	1	0.2	0.4	552	26	1200	1
6		UPPER	400	0.85	0.5	0.68	1	0.4	0.515	139.1	33	1200	3
7		UPPER	800	1.7	0.3	1	1	0.2	0.35	280	25	1200	3
8		UPPER	400	0.6	0.2	0.4	1	0.3	0.4	64	27	1200	3
9		UPPER	4.5	1.5	2	1.75	1	0.4	0.55	4.331	32	1200	1
10		UPPER	500	2	1	1.5	2	0.5	1	750	30	1200	4
11		UPPER	300	2	0.5	1.25	2	0.5	1	375	29	1200	4
12		UPPER	3	1.5	0.5	1	1	0.5	0.85	2.55	27	1200	1
13		UPPER	400	2.23	0.81	1.52	2	0.41	0.965	586.7	14	1200	4
14		UPPER	785	0.46	0.32	0.39	0	1.1	0.765	234.2	13	1200	3
15		UPPER	400	1.3	0.72	1.01	0	0.31	0.385	155.5	21	1200	2
16		UPPER	1500	1.54	1.23	1.39	0	0.12	0.215	446.7	14	1200	3
17		UPPER	941	0.54	0.23	0.39	1	0.24	0.435	157.6	16	1200	3
18		UPPER	541	1.2	0.51	0.86	0	0.25	0.335	155	29	1200	2
19		UPPER	800	0.7	0.3	0.5	0	0.1	0.25	100	21	850	3
20		UPPER	400	0.75	0.41	0.58	1	0.51	0.665	154.3	27	850	4
21		UPPER	20	0.75	0.45	0.6	1	0.51	0.715	8.58	26	850	1
22		UPPER	200	1.65	0.65	1.15	1	0.7	0.8	184	27	850	4
23		UPPER	600	2.12	1.75	1.94	2	0.45	1.275	1480	18	850	4
24		UPPER	1600	1.23	0.34	0.79	2	0.84	1.62	2035	7	850	3

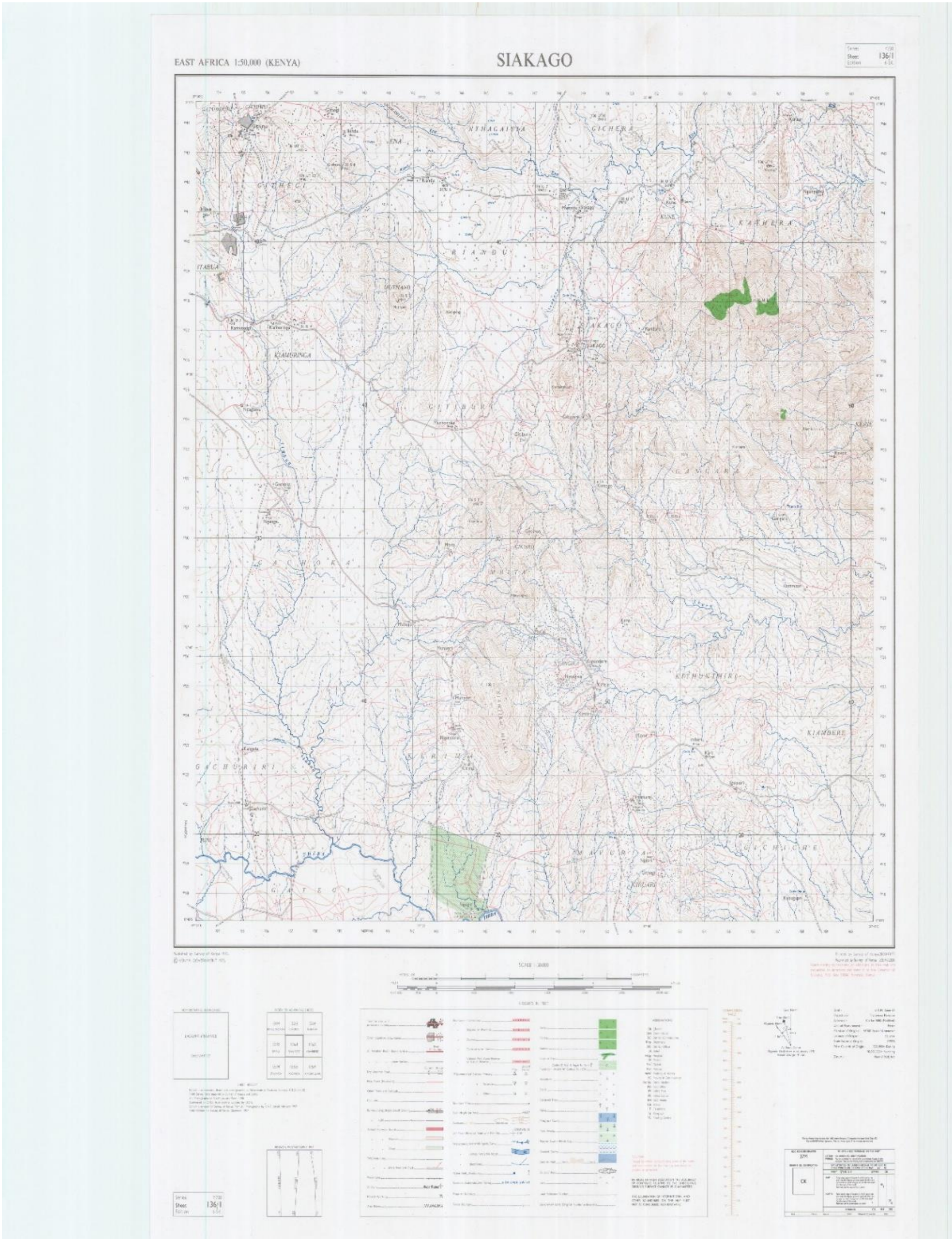
25		UPPER	650	0.75	0.32	0.54	1	0.21	0.375	130.4	19	850	3
26		UPPER	1300	2.3	0.74	1.52	0	0.12	0.285	563.2	9	850	4
27		UPPER	300	0.43	0.35	0.39	1	0.2	0.35	40.95	28	850	1
28		UPPER	1230	0.7	0.4	0.55	1	0.32	0.41	277.4	8	850	3
		upper	86	0.52	0.31	0.42	1	0.3	0.45	16.06	26	850	3
		upper	160	0.6	0.2	0.4	1	0.4	0.5	32	14	850	3
		upper	145	0.41	0.3	0.36	1	0.4	0.7	36.03	26	850	4
		upper	45	0.43	0.21	0.32	1	0.4	0.66	9.504	22	850	4
		upper	25	0.56	0.3	0.43	0	2.3	1.35	14.51	10	850	4
29		MID	1000	2.5	2.32	2.41	0	0.21	0.313	753.1	11	850	2
30		MID	2000	1.95	1.56	1.76	1	0.25	0.445	1562	7	850	2
31		MID	800	2.2	1.6	1.9	1	0.21	0.375	570	14	850	3
32		MID	921	0.84	0.64	0.74	3	0.64	1.605	1094	12	850	3
33		MID	1200	2.3	0.54	1.42	2	1.02	1.335	2275	18	725	3
34		MID	1000	4.36	1.4	2.88	2	0.8	1.6	4608	8	725	3
35		MID	785	2.41	0.6	1.51	1	0.62	0.98	1158	12	725	3
36		MID	1650	4.44	0.72	2.58	1	0.41	0.54	2300	6	725	3
37		MID	940	0.63	0.32	0.48	1	0.23	0.375	167.4	16	725	3
38		MID	600	0.65	0.25	0.45	0	0.31	0.34	91.8	21	725	3
39		MID	5500	7.51	2.62	5.07	6	3.3	4.46	1E+05	6	725	3
40		MID	1660	4.63	1.32	2.98	1	1,12	1.45	7162	12	725	3
41		MID	2300	4.74	1.62	3.18	1	0.32	0.82	5997	10	725	3
42		MID	2400	4.63	2.74	3.69	2	0.74	1.185	10480	6	725	3
43		MID	900	2.1	0.3	1.2	1	0.3	0.75	810	14	725	3
44		MID	650	5.46	2.72	4.09	4	0.77	2.615	6952	6	725	3
		mid	92	0.64	0.21	0.43	0	0.2	0.31	12.12	23	600	3
midmid		mid	80	1.2	0.4	0.8	0	0.2	0.25	16	18	600	3
		mid	150	0.45	0.23	0.34	0	0.12	0.26	13.26	16	600	3
		mid	450	0.85	0.32	0.59	1	0.34	0.48	126.4	7	600	3

		mid	65	1.3	0.4	0.85	0	0.4	0.405	22.38	8	600	3
		mid	165	0.55	0.3	0.43	0	0.31	0.315	22.09	14	600	2
		mid	105	0.43	0.21	0.32	0	0.15	0.225	7.56	16	600	3
		mid	300	0.63	0.32	0.48	1	0.42	0.625	89.06	11	600	1
45		MID	940	0.84	0.35	0.6	1	0.4	0.815	455.8	11	600	2
46		LOWER	1341	5.37	2.4	3.89	1	0.34	0.52	2709	4	600	2
47		LOWER	2000	3.4	2.7	3.05	0	0.12	0.235	1434	7	600	2
48		LOWER	3700	4.5	2.14	3.32	1	0.14	0.32	3931	5	600	2
49		LOWER	5700	7.47	3.7	5.59	1	0.23	0.55	17509	3	600	2
		lower	530	0.5	0.2	0.35	1	0.3	0.45	83.48	18	600	2
		lower	750	0.52	0.23	0.38	0	0.2	0.3	84.38	5	600	2
		lower	400	0.53	0.4	0.47	1	0.53	0.915	78	9	600	2
50		LOWER	1420	1.01	0.65	0.83	1	0.54	0.54	636.4	6	600	2
51		###	4540	1.5	1.5	1.5	1	1	1	6810	U		
52		###	4945	2.6		2.6	2	1.5	1.5	19286	U		
53			5500	4.9			2		1.9	51205	U		
54		###	975	0.4		0.4	1		1.2	468	V		land cover
55		###	1012	0.7		0.7	1		1.4	991.8	V	year	forest
56		###	1300	0.9		0.9	2		1.7	1989	V	2000	1
57		###	2763	3.6		3.6	3		2.6	25862	T	2009	4
58		###	3430	4.2		4.2	3		3.3	47540	T	2018	5
59		###	5700	5.5		5.5	4		4.3	1E+05	T		
60			5500	4.9		4.9	2		1.9	51205			
61			4945	2.6		2.6	2		1.5	19286			

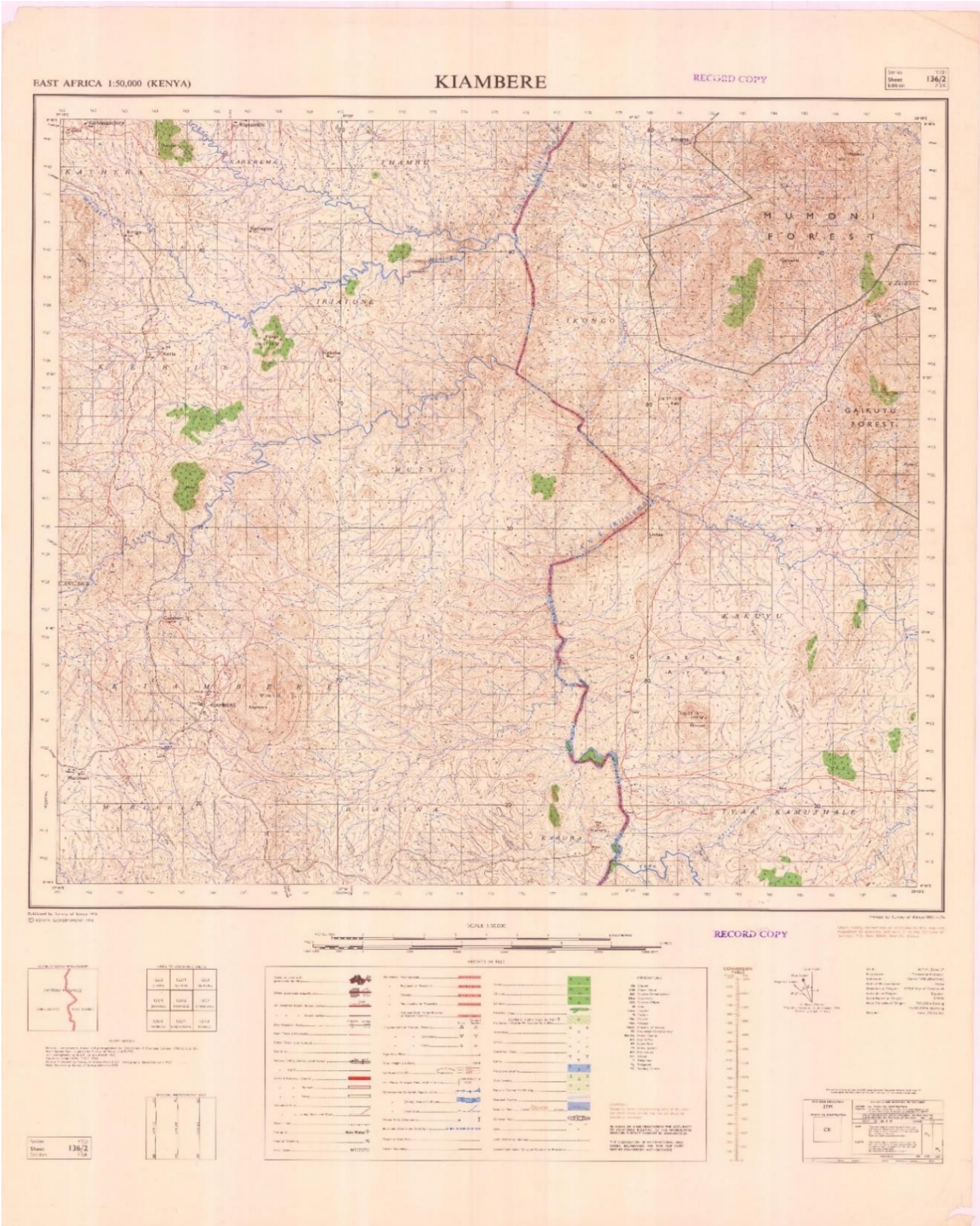
		date for treshold upper slope									slope °	m/m	area ha
62			700		1	1		0.75	0.75	525	27	0.47	0.002
63			1600		0.8	0.8		0.9	0.9	1152	31	0.54	0.18
64			1000		0.5	0.5		0.5	0.5	250	26	0.45	0.013
65			900		0.6	0.6		0.2	0.2	108	25	0.44	0.002
66			600		0.4	0.4		0.2	0.2	48	26	0.45	0.13
67			500		1.2	1.2		1	1	600	30	0.52	0.002
68			400		0.8	0.8		1	1	320	14	0.24	0.015
69			1500		1.2	1.2		0.2	0.2	360	14	0.24	0.13
70			600		1.8	1.8		0.45	0.45	486	18	0.31	0.016
71			1600		0.3	0.3		0.9	0.9	432	7	0.12	0.12
72			1300		0.7	0.7		0.3	0.3	273	9	0.16	0.09
		mid-slope											
73			1000		2.3	2.3		0.2	0.2	460	11	0.19	0.07
74			2000		1.6	1.6		0.3	0.3	960	7	0.12	0.13
75			800		1.6	1.6		0.2	0.2	256	7.2	0.131	1.7
76			921		0.6	0.6		1.6	1.6	884.2	10	0.17	0.8
77			1200		0.5	0.5		1.2	1.2	720	9	0.16	0.15
78			1000		1.4	1.4		0.8	0.8	1120	8	0.14	0.17
79			785		1.5	1.5		1	1	1178	10	0.17	0.98
80			1650		2.6	2.6		0.5	0.5	2145	6	0.105	1.75
81			5500		2.6	2.6		3.3	3.3	47190	6	0.105	1.82
82			1660		0.7	0.7		0.4	0.4	464.8	11	0.19	0.097
83			2300		1.6	1.6		2.3	2.3	8464	10	0.17	0.9
84			2400		2.7	2.7		0.8	0.8	5184	6	0.11	1.9
85			900		1.2	1.2		0.8	0.8	864	11	0.19	0.078
86			650		4.1	4.1		2.6	2.6	6929	6	0.11	1.2

	lower slope segment											
87		940		0.4	0.4		0.7	0.7	263.2	4	0.069	0.19
88		1341		3.9	3.9		0.5	0.5	2615	4	0.069	1.12
89		2000		3.1	3.1		0.2	0.2	1240	6	0.11	1.5
90		3700		2.1	2.1		0.3	0.3	2331	5	0.089	10.01
91		5700		3.1	3.1		0.6	0.6	10602	3	0.052	1.550.13
92		1420		0.8	0.8		0.5	0.5	568	2	0.017	0.18

Appendix 10: SIAKAGO TOPOGRAPHIC MAP



Appendix 11: KIAMBERE TOPOGRAPHIC MAP



Appendix 12: Research license

THIS IS TO CERTIFY THAT:
MS. IRERI CECILIA WAWIRA
of UNIVERSITY OF NAIROBI, 2-20019
Karuri,has been permitted to conduct
research in *Embu County*

Permit No : NACOSTI/P/19/33229/31008
Date Of Issue : 24th June,2019
Fee Recieved :Ksh 2000

on the topic: *GULLY EROSION AND STABILIZATION IN SEMI ARID ENVIRONMENT OF WANJOGA RIVER CATCHMENT OF TANA BASIN,EMBU COUNTY*

for the period ending:
24th June,2020

....
Applicant's Signature

....
Director General
National Commission for Science, Technology & Innovation