UNIVERSITY OF KWAZULU-NATAL

INYUVESI YAKWAZULU-NATALI

ANALYSIS OF GLOBAL GULLY CHARACTERISTICS AND THE IMPACTS OF GABIONS AND GRASS ON SEDIMENTS AND CARBON STORAGE

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Submitted in fulfilment of the academic requirements for the degree of Masters of Science in Soil Science

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Pietermaritzburg

2018

DECLARATION

I Hastings Bangani Dube, hereby declare that:

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Prof Vincent Chaplot

PREFACE

This thesis is made up of four chapters. Chapters 1 (General Introduction) introduces the reader to gully erosion problems on the Drakensberg Mountains in the Upper Thukela catchment in KwaZulu-Natal Province, South Africa. Chapter 2 (Overall Literature Review) looking at the available information on the prevalence of gullies and effectiveness of gully rehabilitation methods on trapping sediments. This is followed by Chapter 3 (data-analysis), the impact of environmental (climatic, soil, topographical and land use) factors on gully morphology variables (length, width, depth, width-depth ratio, top-view and cross-sectional areas, and volume). Chapter 4 (Results chapter based on fieldwork) deals with soil particle size distributions and contents of carbon and nitrogen of sediments from a rehabilitated gully and adjacent soils. Finally, conclusions and recommendations are reported in Chapter 5.

DEDICATION

This dissertation is dedicated to the memory of my father, Boniface Dube (1956 – 2017). Although he was my inspiration to pursue my *Master's* degree, he was unable to see my graduation. This is for him; until I see you again.

ACKNOWLEDGEMENT

This research study received financial support from the Water Research Commission of the Republic of South Africa (WRC K5/2402-4), which I greatly appreciate. I express my warm thanks to my supervisors Prof Muchaonyerwa and Prof Chaplot and to Dr Mutema for their support and guidance.

I would like to express my gratitude towards my parents Mr and Mrs Dube and family for their kind co-operation and encouragement, which helped me in completion of this project. Many thanks and appreciations go to my colleagues Mr Mehluli Moyo, Mr Bonginkosi Samuel Vilakazi, Mr Nhlakanipho Sicelo Zuma, Dr Khathab Mohamed, Lindo Myeni, Mr Isaac Mathew and Dr Mbulisi Sibanda, for their willingness to help during the various stages of the project.

ABSTRACT

Gully erosion has immediate and long-term negative impact on the environment. Rehabilitation effectiveness depends on gully characteristics and the trapped sediments, which can help to sequester carbon (C) and mitigate climate change. The C from the sediments, if not trapped, is either eroded into the ocean or mineralized to CO_2, which accumulates into the atmosphere and contribute to global warming. The objectives of the study were to evaluate (1) the main factors that affect gully characteristics at global scale, and (2) the potential impact of gabions and grass, as gully rehabilitation techniques, on sediment retention and C sequestration. In the global analysis of permanent gullies, available literature on factors affecting characteristics of gullies was explored. Data was collected from online search engines such as Google Scholar and electronic bibliographic databases (e.g. Science Direct, Springerlink). A database on published gully channel parameters such as volume (V), length (L), width (W), depth (D), W:D ratio (indicator of incision shape), top-view (A) and cross-sectional areas (Ac) for 435 permanent gullies across the world was compiled and used to analyse for the impacts of different climates (tropical, sub-tropical and temperate), land cover, terrain altitude and slope, soil texture and bulk density on the channel dimensions. Potential impact of gully rehabilitation on sediment and carbon storage was evaluated in Okhombe area near the Drankensburg mountain range in KwaZulu-Natal province, South Africa. The rehabilitation techniques used in the studied gully was a combination of stone-checks and vegetative methods. Soil samples (n= 206)) were collected from the 0-5, 5-15, 15-30, 30-60, 60-90 and 90-120 cm depth of lower, mid and upper gully positions, and adjacent positions outside the gully. These soil samples were analysed for particle size distribution, total organic carbon and nitrogen content (OCC, ONC) and soil bulk density. Information on soil bulk density allowed for OC and ON stocks (OCS, ONS) to be assessed. Finally, ^{14}C activity was

evaluated for informing on the origin of the stored OC. These quantitative results on the factors controlling gully morphology at global scale contribute to better understanding of gullying mechanisms, a prerequisite for modelling gully channel formation and for development of mitigation measures under different environmental conditions. The most important soil parameter was texture as sand content had the most significant influence (when it comes to gully initiation and development), while land use change was also essential (as change from natural to agriculture or residential increased the chances of gully initiation or development). The sediments from the gully under rehabilitation in Okhombe study site were sandier than soils adjacent to the gully. Sediments from the upper and mid slope positions of the gully also showed greater silt content within the 0-15 cm depth than adjacent soils outside the gully. There was a general increase of C stocks with depth of gully sediments. Selective deposition of fine and coarse sediments in the gully leads to a significant differentiation of sediments properties along pathways as affected by gabions. Fine material was deposited further down slope while heavy coarser material remained upslope. Carbon followed a similar trend with clay as more carbon was trapped down slope. The rehabilitation of the gullies helps to sequester carbon in the gullies as the trapped sediments become a sink for carbon. The findings of this study imply that rehabilitation of gullies with stone checks and grass results in sediment and carbon storage which helps in the sequestration of carbon, potentially mitigating global warming.

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CHAPTER 1 : INTRODUCTION

1.1 Background

Gully formation is the most dominant and problematic form of soil erosion after sheet and rill. Gully erosion is a critical concern worldwide because it restricts soil productivity and land uses, and causes severe water quality impairment and siltation of water bodies (Akande and Titilola, 1999). Studies by Wasson et al. (2002), Krause et al. (2003), de Vente et al. (2007) and Huon et al. (2005) indicated gully erosion as the main source of sediments in streams. As such, gully erosion contributes a critical part in biogeochemical cycle of carbon with significant implications on global warming. Although gully erosion is commonly trigged by land use change (Chaplot et al., 2005a, b) and extreme climatic events, antecedent history cannot be overlooked when attempting to understand its spatial patterns (Felix-Henningsen et al., 1997).

Many processes contribute to gully erosion, but the best known is surface run-off concentration and flow at a velocity sufficiently high to detach and transport soil particles (Wainwright et al., 2011). However, some gullies are initiated by piping, where the tunnels may eventually collapse. In both cases, complex linear processes further develop and sustain the gullies, which result in under-cutting and collapsing of gully heads and banks and transportation of the materials. The initiation and development of gullies are controlled by many interactive factors including climate, land use, soil properties, vegetation type and cover, and topography. Factors controlling gully morphology and gully erosion rates have been subjects of international studies for decades. There is need to establish a global view of the factors affecting gully characteristics.

Zhang et al. (2007) investigated the factors that control spatial distribution of ephemeral gullies, their morphology, development and soil losses in North-eastern China, where they found mean soil losses of 0.40-0.43 kg m-2 year-1 on croplands, which were beyond tolerable erosion rates, despite low slope gradients. The high loss of soil in these areas was due to frozen soil (more than 2m deep) which the top soil began to thaw after winter leading to reduce water infiltration as the sub soil is still frozen and lead to surface runoff (Øygarden, 2003). A study by Wischmeier and Smith (1978) also noted that thawed topsoil above frozen deeper layers were prone to erosion. While Zhang et al 2007 concluded that gulling took place during snowmelt, rainfall and thawed soil, it is important to understand the main driver of

gully erosion in an environment. The physical and biogeochemical disruptions caused by gully erosion have potential to significantly impact on the functioning of the soil system and its ability to sequester carbon. Soil erosion leads to low carbon sequestration and major land degradation, and plays an important role in the global carbon cycle (Berhe et al. 2007; Van Oost et al. 2008). Recent studies indicated that soil erosion and deposition acts as a C sink globally and can help to mitigate global warming (Harden et al. 2008; Van Oost et al. 2008).
Worldwide soils have long been recognised as one of the major carbon sinks (Lal, 2004). As such gully erosion has a negative effect on this important soil function. Erosion causes degradation of the land, leading to low soil carbon sequestration. The effects of gully erosion on soil carbon storage can be divided into direct carbon losses through the physical erosion of the peat mass, and indirect losses related to modifications of soil functions in response to gullying. However, soil erosion and subsequent sedimentation on land systems was reported to sequester 1 Pg C year−1 globally (Stallard 1998; Smith and Heath 2001). Berhe et al. (2007) also estimated a worldwide erosion-deposition induced terrestrial C sink of 0.72 Pg C year−1. Carbon sequestration has been emphasised as a way to mitigate increases in atmospheric CO_2 (Batjes, 1999; Lal, 2004). As such, gully control might be important.
Gully rehabilitation focus on the stabilization of soil erosion and the establishment of a dense and protective plant cover. Rehabilitation methods must focus on rehydration or ensuring that the maximum amount of rainwater infiltrates into the soil. Decreasing runoff through the "capture" and retention of water and establishing a soil protecting plant cover are thus primary objectives. Trapping sediments in the gully helps to mitigate soil loss. Physical structures like gabions can reduce the velocity of the water and trap sediments in the gully system. Sediments trapped in the gully are carbon source/sink at erosional and depositional sites. The impact of soil erosion on carbon cycling has not been well documented.
While man has controlled gully erosion for many years now, there is still little knowledge on the effectiveness of the gully control techniques on C sequestration and soil functioning under different environmental conditions

1.2 Problem statement

High carbon output into the environment has led to global temperature increase, which has significantly impacted on climate change. It is essential to come up with more stable carbon storage medium and mitigate carbon loss into the atmosphere. Some studies have concluded that soil is the best medium to store large quantities of carbon, and with soil erosion as a threat, new solutions are required in order to curb the catastrophe. Finding new solutions for reducing soil erosion will depend on understanding the factors that affect gully formation and gully characteristics, based on analysis of data produced by different studies, globally. In addition to erosion control, answers to the following questions could also be essential;

1 Can gully rehabilitation help store sediments that can be medium for carbon storage?

2 What are the factors that affect the initiation of and development of gullies?

3 What is the source of the stored carbon in the trapped sediments?

1.3 Justification

In modern times we are faced with growing global phenomena (climate change) that require our immediate response. Climate change is a threat to food security all over the world and it brings with it catastrophic events like floods and heat waves that need to be minimised. It is essential to understand the dynamics of gully erosion in order to use the soil as medium of carbon storage.

1.4 Objectives

This research aims at analysing the factors affecting gully morphology and the effectiveness of (passive and active) gully rehabilitation methods being used in the Okhombe area of KwaZulu-Natal province, South Africa. The specific objectives are to:

(i) Evaluate the main factors controlling gully morphology

(ii) Investigate the origins of the stored carbon in the trapped sediments

(iii) Determine the effects of gully rehabilitation techniques on carbon sequestration and other soil physic-chemical properties

1.5 Hypothesis

The study tested the hypothesis that:

(i) Climate and soil properties affect gully incision and development

(ii) Soil characteristics affect the trapping of sediment and the sequestration of carbon

(iii) The stored carbon in the sediments is contributed by growing vegetation on the sediment and eroded organic matter

CHAPTER 2 : LITERATURE REVIEW

2.1 Effectiveness of gully rehabilitation techniques on sediment yield

2.1.1 Introduction

Soil erosion is a major concern in many ecosystems as it reduces land productivity and leads to siltation of water bodies. Gully erosion is the worst form of erosion which, results in loss of soil. Gully erosion involves the removal of soil by runoff water and often persists in narrow channels (Schoonover and Crim, 2015). Over short periods, removal of soil from these narrow areas to considerable depths causes deep gullies that are difficult to control and manage. Gully formation is the worst stage and most visible form of all types of soil erosion, which affects several soil physical, chemical and biological functions. Soil is a good medium to store carbon, which reduces the amount of carbon in the atmosphere and global warming. During a rainfall event sediment are transported with pollutants that end up in water bodies if not trapped on land.

Many factors affect or control the initiation and development of gullies, and they may differ according to the regions they occur in. A study by Poesen et al (2002) concluded that factors affecting gully erosion were vegetation, climate and topography. Precipitation is one major climatic factors that affects gully incision and development as intensity, frequency and duration of a rainfall event affects the volume and rate of surface flow, which is the main driver of soil erosion. Soil physical properties like texture, depth, structure, infiltration capacity, permeability and organic matter content determine the runoff, which is the agent responsible for erosion (Toy et al 2002). Across the world gully erosion has been cited as a major problem affecting the environment, many studies on gully erosion have been done which includes Marden et al (2014) in New Zealand, Nyseen et al (2010) in Ethiopia and Chen and Cai (2006) in China, but understanding on the global control factors on gully morphology is still limited.

Rehabilitation of gullies through vegetative and use of physical structures traps sediments containing organic carbon, thus avoiding accumulation of carbon in rivers, ocean and the atmosphere (IPPC, 2000). Through gully rehabilitation sediments will be trapped, which will lead to carbon accumulation via trapped organic matter and vegetation growth. Soil erosion is a scale-dependent phenomenon and there is no fixed erosion rate for a specific region (Fang et

al, 2012). The actual sediment yield of a gully depends on a range of environmental factors and active erosion processes (Walling 1983; de Vente et al. 2007). Adopting localised gully-mitigating strategies is necessary in order to minimize the impacts of accelerated erosion in a particular region. Hence, selecting the best rehabilitation strategies is a complex and often controversial undertaking (Apitz et al. 2005; Yatsalo et al. 2007; Alvarez- Guerra et al. 2010).
Gully sediments cannot only trap particulate organic carbon but also constitute a favourable media for plant growth, which could allow atmospheric carbon sequestration, but this has yet to be quantified. Soil carbon sequestration refers to the ability of the soil to remove CO_2 from the atmosphere and storing it. Soil is the largest carbon sinks along with vegetation and oceanic as it stores large amount of carbon for a long time before it is re-emitted to the atmosphere. Soil carbon sequestration leads to soil organic matter replenishment, which in the long term helps in improving soil structure and stability (Bernoux et al, 2011). Soil organic carbon (SOC) is retained in the soil through physical protection as stable organo-mineral complexes. Through the protection of carbon by aggregates, decomposition is reduced (Christensen, 1992). The amount of C retained in the soils depends, on many parameters such as the nature of soil aggregation (Carter, 1996).
In gully rehabilitation vegetative methods are more cost effective than engineering techniques which require capital and expertise (Rodrigues and Bezerra 2010). Poor land management and removal of vegetation is usually the initiation of soil erosion, which eventually leads to gully erosion. Choosing a gully rehabilitation method is critical as it is determined by the climatic and soil characteristics of that particular area. The objective of this chapter was to (1) review literature on the impacts of gully rehabilitation techniques on sediment yield; (2) to assess the role of potential of trapped sediments in sequestration of C.

2.1.2 Factors that affect gully morphology

In a study by Bracken and Kirkby, (2005) cited by Mohamadi and Kavian 2015 their investigation confirmed that high intensity short duration storms have the ability to increase soil erosion and detach sediments. Poesen et al (2002) concluded that kinetic energy from raindrop with an intense splash will result in hydraulic erosion, which widens and deepens gully channels. Plunge pools on the gully head cut often reduce the stability of gully walls which results in undermining of the gully walls (Harvey., 1982). According to Rossi et al (2015), a larger drainage area will produce a large surface runoff volume which will result in the enlargement of the head cut. Soil characteristics and land cover (vegetation) have a great influence on runoff production and soil erosion (Torri and Poesen 2014). Other studies have confirmed the effect of rainfall depth on soil detachment and transportation during erosion (Dunne et al 1991).

The presences of vegetation on the surface help reduce the raindrop impact protecting the soil and reducing the effects of runoff. A study by Li et al (1992) shows that the presence of vegetation roots increases infiltration which in turn reduces the surface runoff and consequently soil erosion. Surface cover is essential as it helps to mitigate soil detachment and transportation, while densely vegetated areas will experience more infiltration and less runoff reducing erosion.

A study by Manyevere et al (2016) in South Africa established that soils in the humid regions were more stable than soils in the arid and semi-arid regions, which were more prone to erosion, irrespective of parent material. In the drier regions (arid and semi-arid) fine sand and very fine sand are the most controlling factors of erosion while in the humid or wet regions sesquioxides and kaolinite are the controlling factors. Nyamapfene (1991) and Manyevere (2016) found that fine sand content above 22% had severe implications on crusting and erosion of soil in semi-arid and arid areas. Increased bulk density usually leads to reduced infiltration and increased surface runoff and subsequently soil erosion. Gyssels (2005) suggested that high root density is required on the top soil to hold the soil together and prevent runoff. The presence of vegetation on the soil leads to organic matter input on the soil which helps the soil particles binds together and making them less prone to erosion. Soil physico-chemical properties like texture and organic matter are essential in soil stability (Morgan, 1996). The presence of organic matter on the soil improves the soil infiltration rate which leads to less surface runoff volume and erosion.

Slope gradient and length are among the factors that affect gully erosion as steeper and longer slopes lead to increased velocity of runoff water that results in more erosive power to detach and transport soil particles (Hudson 1987). Effects of slope gradient are also governed by other soil characteristics such as mineralogy and texture, as steep slopes with soils that are high in sesquioxides and kaolinite clay will not easily erode due to stable clay type and metal oxides that bind the soil particles together. Other soil characteristics such as sodium content have a direct effect on erosion as the known FAO limit of 15% exchangeable sodium percentage (ESP) can cause soil to disperse. In a study by D'Huyvettyer (1985) cited by Manyevere (2016) found that soils with as little as 2.5% ESP (Luvisols and Haplic Leptosols) were prone to erosion. Van der Merwe et al (2001) found that soil dispersion occurred at an

ESP of 0.12% on a melanic soil, while a study by Thompson (1986) reported that a highly weathered ‘red sesquioxides clay soil’ with an increased ESP of 42% could not dispense. Understanding the factors affecting gully morphology globally is essential to establish strategies for erosion control. While valuable land is lost through gully erosion, it is essential to rehabilitate gullied areas in order to reduce soil loss that usually ends up in the water system. Rehabilitation of the gullies will improve and stabilise the soil, which will favour plant growth and sequestrate carbon.

2.2 Rehabilitation methods

All over the world many rehabilitation techniques are used and the most used strategies in South Africa are physical and vegetative techniques. The physical techniques include check dams, logs, stone checks, gully reshaping, refilling and gabions, while afforestation and re-vegetation also contribute. Many of these techniques have been used in South Africa with some being used in combination, as practised in Okhombe on the Drakensberg foothills.

2.2.1 Check dams

Check dams are usually small structures that are dug and constructed across gully channels that intercept runoff reducing the flow velocity of water and impounding sediments. By reducing the flow velocity the runoff energy that detaches and transports sediments is reduced (Marsh., 2005). The ability of check dams to trap sediments has been confirmed by numerous studies (Xuemin et al 1998; Dachuan et al 2004). Check dams have relatively high sediment trapping efficiencies ranging from 51% to 92.8% from a study done Xu Mingquan, (2000) (Table 2.1).

In a study by Wand et al (2011) more than 100 000 check dams in the Loess Plateau of China have accumulate approximately 21 billion m^3 of sediments over 50 years. Ran et al (2011) documented sediment reduction of 57.8%, 37.2%, 62%, 72.2% and 64.7% in five catchments after check dams were implemented in China.

The existence of check dams interrupts and reduces the velocity of runoff increasing the infiltration rate (Addis et al., 2015). The effective use of check dams in gully rehabilitation in arid and semi-arid regions in prevention of soil erosion and runoff is still not documented, compared to soil water conservation (Guyassa et al., 2017). According to Sheng and Liao (1997), the use of check dams in mountainous areas proved to be the most effective way to control gullies and vegetative techniques are less effective due to low soil fertility and prevalent dry spells. In wet climates, use of check dams in conjunction with vegetative techniques is essential to have maximum results.

Table 2.1 Amount of retained sediment in check dams of the Yellow River watershed

Time	Retained sediment by check-dams (Mm^3)	Total retained sediment (Mm^3)	% of the retained sediment by check-dams
1952-1962	600.72	647.42	92.8
1963-1969	1,004.42	1,135.26	88.5
1970-1979	2,151.37	2,694.69	79.8
1980-1989	1,823.77	3,144.77	58.0
1990-1995	1,547.04	3,032.65	51.0
Total	7,127.32	10,654.79	66.9

(Source: Xi and Wangu Mingquan., 2000)

2.2.3 Afforestation and re-vegetation

The use of vegetation in gully rehabilitation such as grass, which can be grown in shallow and less fertile soil is common (Addis., 2015). The use of vetiver grass as contour in areas with a slope gradient of 1.7% reduced runoff 7.8% and soil loss by 10.5 t ha-1 which resulted in less soil loss due to erosion in the India (Truong., 1993). While planting of vetiver grass in Queensland Australia trapped more than 85% of the bed load and also reduced suspended sediments by between 25-65% (McKergow et al., 2004). In Nigeria the use of vetiver grass resulted in sediment being reduced to 6 kg ha^{-1} from 29 kg ha^{-1} in the control plot (Eden et al 2012). While in another observation by Robinson et al (1996) in Lowa USA brome grass trapped between 70-85% of sediments in silty loam soils. Shiono et al (2007) in Japan found that centipede grass trapped 24%-73% of sediments. In an experiment in Iowa USA, both under simulated and natural condition, switch grass had a sediment trap efficiency of 90-95% and 70-92% respectively (Lee et al 2000., 2003).

Planting of shrub as tree buffers in Shaanxi province in China resulted in 22-32% in reduction in runoff and by 45-61% reduction in sediment concentration and a further 64-79% in sediment yield compared to the control (Zhang et al., 2010). Leguedois et al. (2008) reported a 94% sediment trap efficiency from acacia in New South Wales, Australia. Vegetative rehabilitation of gullies is most successful and effective in humid area where extended period of plant growth is available. Use of vegetation as a rehabilitation technique is effectively utilised in combination with other techniques; for example physical techniques such as the check dams. Vegetation of gully beds and adjacent areas using a check dam traps sediment and reduces erosion power due to runoff (Addis et al., 2015).

Increases in basal cover after vegetative rehabilitation reduces the quantity of sediment generated (Table 2.2). Sediment reduction ranged from 5.1% to 44.73% which indicated the effectiveness of vegetation as a rehabilitation measure. According to Chen and Cai (2005) vegetative method is more effective with the rehabilitated site being protected from external disturbances.

Table 2.2 Effectiveness of vegetation as gully rehabilitation technique

Site	Area (km^2)	Pre-management vegetation coverage (%)	Post-management vegetation coverage (%)	Sediment reduction effect (%)
Damagou	10.2	12.78	72.09	44.73
Dahonghuagou	8.9	13.77	73.43	20.17
Chaotaigou	11.59	16.2	66.6	25.5
Wulasu	15.21	12.3	77.7	19.5
Dongwuselang	14.12	9.5	88.64	7.12
Teladonggou	48.64	14.28	79.8	15.29
Yingzigou	45.95	17.6	77.75	15.46
Telaxigou	31.26	14.09	79.8	14.47
Xiwuselang	23.94	13.6	70.1	5.1
Songbaigou	14.83	13.3	72.37	15.46
Nangou	6.83	15.73	75.4	9.3182
Mo Us gou	13.93	14.75	70.1	19.61
Mean	20.45	13.99	75.32	17.64

(Source: Hao and Qiangguo, 2005)

Establishment of vegetation as a rehabilitation techniques saw significant decrease in generated sediments during runoff but the construction of physical structures to retain sediments remains crucial to reducing sediment rates (Chen and Cai, 2005). Vegetative management in combination with a physical structure such as gabions to reduces the erosion rate (Addis et al., 2015). The main purpose of the check dam is to minimise runoff velocity and induce infiltration, which promotes vegetation growth and less scoring of the gully banks (Nyssen et al., 2009). Rehabilitation of gullies with vegetation requires enclosures which serve to restrict animals from disturbing vegetation during its development stages.

Zhuo (1993) reported that rehabilitation of the gullies with tree and check dams resulted in a effective sediment reduction of between 31% and 99.4% in the Yangjiagou basin of China (Table 2.3). In the early stages of development the reduction effect was lower and as the trees developed the reduction effect increased significantly. This trend is mainly due to the canopy cover that is provided by the trees reduce the kinetic energy of the raindrop making it less erosive. The litter from the trees provide the soil with organic matter which helps to bind the soil together and reduces soil loss.

In a study done by Sudhishri (2008) in India the use of vetiver, sambuta, stone bund and hill broom barriers reduced soil loss by 71%, 69%, 60% and 52% while carbon losses were reduced by 71%, 68%, 59% and 52%, this was most attributed to the fact that vegetative rehabilitation also contributes to insitu carbon. Combinations of these strategies could be essential. In the early stages of development the reduction effect was lower and as the trees developed the reduction effect increased significantly. This trend is mainly due to the canopy cover that is provided by the trees, which reduces the kinetic energy of the raindrop making it less erosive. Litter from the trees provide soil with organic matter, which helps to bind the soil together and reduces soil loss.

Table 2.3 Annual reduction of flood runoff and sediment yield in the Yangjiagou basin through afforestation.

Year	Annual reduction of floods volume (m^3 km^2)	Annual reduction of sediments (%)
1954	27.2	58.8
1955	64.3	80.2
1956	50.3	71.9
1957	29.6	31
1958	47.9	97.7
1959	85.7	99.4
1960	51.9	85.7
1961	25.9	84.1
1962	49.9	99.5
1963	47.4	97.4
1964	29.3	94.1
1965	-9.8	98.1
1976	73.7	91.1
1977	69.7	77.6

Source: Zhuo (1993)

Table2.4 Measured sediment yield responses of gully erosion remediation, globally**.**

Country	**Region**	**Management action**	**Treated area (km^2)**	**Sediment yield response**
USA	Colorado	Fencing / vegetation and check-dams	2.6 km^2	78% decline in net erosion rate for vegetation control only 90% reduction in sediment loads for sites with check dam
China	Loess Plateau	Fencing / increased vegetation cover	NA	50–60% reduction in runoff 60–80% reduction in soil loss
Philippines	Reservoir of the Binge Hydroelectric Plant	Trenches filled with brushwood	Small plot scale (<1 km^2)	Reduced soil erosion by 99%
Ethiopia	May Zeg Zeg catchment	Check dams and vegetation restoration	2 km^2	81% reduction in runoff volume (which resulted in sediment deposition)
China	Loess Plateau	Conversion of farmland to forest and grassland	9-49 km^2	Reduced erosion by 75%
New Zealand	Te Weroroa	Changing from grass to forests	29 km^2	Reduced sediment from gullies by 62%
New Zealand	Waipaoa River	Reforestation	140 km^2	51% reduction in denudation rates 12% reduction in sediment yield (due to remobilisation of stored sediments)
Ecuador	Andean Valley R	Re-forestation of barren land	0.1-20 km^2	10–45 fold decrease in sediment flux

Source: Thorburn and Wilkinson (2013)

Rehabilitation techniques have, to a certain extent, been successful in reducing sediment loss across the world. Where a combination of vegetation and check dams was used and keeping livestock away from the gull saw a 78% (Table 2.5) decline in net erosion rate for vegetation control, 90% reduction in sediment loads for sites with check dam in USA (Heede 1979). In

Ethiopia the installation of check dams in the gully resulted in 81% reduction in runoff volume, which resulted in sediment deposition (Nyssen et al 2010).

Due to the varying factors that affect gully erosion across the world, it is important that other factors be evaluated to determine factors that govern gully initiation and development across the world, which is addressed in the next chapter. There is a need to mitigate the effects that favour gully erosion in order to increase carbon storage in the soil.

2.3 Effectiveness of rehabilitation methods used in South Africa KwaZulu Natal Okhombe

Various methods are being used to rehabilitate the gullies in Okhombe area of KwaZulu-Natal and the surrounding areas. These techniques used are different combinations of swales, tree planting, vetiver grass, stone line, indigenous grass plagues and kikuyu grass. In Oqolweni, South Africa, 28% less runoff was observed after the re-vegetation of the affected land due to an increase in basal cover that increases infiltration and reduces surface flow (Everson et al 2007). A similar trend was observed in Enhlanokhombe in Okhombe, South Africa, where a period October 2003 to January 2004 re-vegetation saw an increase of surface cover from 55% to 71 %,which meant that the soils were more stable and less erodible (Everson et al, 2007). Re-vegetation and stone checks or gabions were used in combination and most of the transported sediments were trapped behind the stone checks or gabions (Everson et al., 2007). In eMpameni, South Africa, planting of grass resulted in a 4.29% decrease in sediment yield compared to un-rehabilitated areas while reducing splash erosion by almost 17%.

There are many challenges associated with gully rehabilitation in KwaZulu Natal, which range from human or and animal interference and lack of adequate resources. Poor construction of rehabilitation structure will subsequently result in low trapping efficiency of the structure (Mekonnen et al 2015). Regular maintenance of the gully rehabilitation structures makes them more efficient for a longer time (Zhang et al 2010b). Interference from livestock will also reduce the ability of the gully rehabilitation structure fencing off the remediated area until it is fully rehabilitated. Modelling the area of interest is also essential in order to allocate resources more efficiently (Verstraeten and Poesen 2001) and choosing the appropriate location for the rehabilitation is essential to maximise the sediment trap efficiency (Nyssen et al 2007). Another problem that can affect the effectiveness of gully rehabilitation is the general application of rehabilitation techniques without taking into consideration soil chemical and physical characteristics for instance sodic and dispersive soils will need extra attention compared to non sodic and non dispersive soil.

In South Africa, it was concluded that no single technique can be recommended for rehabilitation but the use of rehabilitation techniques in combination will increase the effectiveness of the gully stabilisation (Water Research Commission, 2007). The effectiveness and success of the rehabilitation method or methods depends on extent of the gully erosion and construction of the rehabilitation structure.

2.4 Final comments

A number of site factors affect gully morphology which includes catchment slope, soil texture, vegetation cover and soil density. It is essential to determine the factors affecting gully morphology at a global scale through data analysis from different studies conducted across the world. The combination of check dam and re-vegetation (planting grass) is the most effective way of rehabilitating gullies, while afforestation alone is the least effective.

CHAPTER 3 : A GLOBAL ANALYSIS OF PERMANENT GULLY CHARACTERISTICS

3.1 Introduction

Gullies are defined here as linear features (channels) where the soil has been removed from a minimum depth of 25-30 cm, e.g. in croplands these channels are deep enough not to be easily filled by ordinary tillage operations. Gully erosion is a natural phenomenon that has accelerated in recent decades. While climate change related events have contributed to this acceleration, anthropogenic activities have also played a major role (Chaplot et al., 2005a; b). Human activities that contributed to the acceleration of gullies appear to be driven by a combination of rising poverty and global population, which has seen fragile lands being put into agricultural production (Tato and Hurni 1992) without adequate measures to combat gully erosion. Gully erosion has escalated to global concern status contributing to challenges such as physical and biogeochemical disruptions, which significantly impact land productivity (Srebotnjak et al., 2010). Srebotnjak et al. (2010) explained the land productivity losses caused by soil fertility depletion, restrictions on land use due to inaccessibility and poor manoeuvrability of machinery, and impairment of water quality. In addition to polluting water bodies, carbon and nutrients that are lost from eroded lands can also contribute to atmospheric greenhouse gases and cause global warming (Batjes, 1999; Lal, 2004).

Gullying is a significant mechanism of soil erosion as it may represent 10 to 94% of total catchment sediment yield caused by water erosion (Poesen et al., 2003), a large fraction of which is delivered to water courses (e.g. Evans, 1993). Gullies are initiated through two main hydrological processes; (i) surface flow concentration at velocities sufficiently large to detach and transport soil particles, and (ii) subsurface flow resulting in piping. Concentration of surface flow is a function of rainstorm intensity and many soil properties that govern its water infiltration rate. Piping can be a result of abrupt retardation of infiltration rate by a subsoil layer, which facilitates high lateral flow. Soil fauna and decaying plant roots may also initiate tunnels which promote preferential subsurface water flow leading to a widening of the tunnels (e.g. Verachtert et al. 2013). The tunnels may eventually collapse leading to gully initiation. In both cases, the gullies further develop and are sustained by complex linear processes, which result in under-cutting and collapsing of gully heads and banks, and transportation of the materials from the collapsing heads and banks (Poesen et al. 2003, 2011). Gully initiation and development is controlled by many interacting driving factors including climate, topography, soil properties, vegetation type and cover, land use and land management (Poesen et al. 2011, Torri and Poesen 2014). Land use history needs to be considered as well when attempting to understand the spatial and temporal patterns of gullies (Felix-Henningsen et al., 1997).

Gullies are found all over the world and vary in their morphology within and across environments (e.g. Vanmaercke et al. 2016). For instance, Ghimire et al. (2006) and Ibitoye (2017) reported on vastly different gully channel lengths for similar mean annual precipitation (MAP: 1500 mm year-1) and temperature (MAT: 23-27°C year^{-1}) regimes. Ghimire (2006) evaluated gully dimensions in Nepal, while Ibitoye et al. (2017) reported gully features for study sites located in Nigeria. Top view areas of gullies also differed greatly for soils of similar topsoil bulk densities. Zegeye et al. (2016) reported gully top view area of about 440 m^2 for soil of 1.26 g cm^{-3} bulk density in Ethiopia, while Wu et al. (2008) reported up to 5738 m^2 on soils of 1.27 g cm^{-3} bulk density in China. Gully volumes also showed great variability under similar environmental conditions. For example, Grellier et al. (2012) reported volumes ranging from 423 to 79928 m^3 for gullies in one locality of KwaZulu-Natal, South Africa. Grellier et al. (2012) evaluated the impact of tree encroachment on gully extension on grassland and found positive correlations between gully retreat rate and tree canopy area. The sediment losses were high (200 Mg ha^{-1} of gully y^{-1}) and were mainly due to the collapse of gully banks after swelling and shrinking. Zhang et al. (2007) investigated the factors that control spatial distribution of ephemeral gullies, their morphology, development and soil losses in Northeastern China, where they found mean soil losses of 0.40-0.43 kg m^{-2} $year^{-1}$ on croplands, which were beyond tolerable erosion rates, despite low slope gradients. The erosion rates were greater in spring due to lack of vegetative barriers against surface flow. In contrast, summer soil erosion was primarily in response to intense rain events. Muñoz-Robles et al. (2010), in south-eastern Australia, concluded that gully erosion was most likely a result of interactions among topography, vegetation and human-made structures (roads) in space and time. While scientists have made significant progress in studying rates of gully erosion (e.g. Capra and Spada, 2015; Adediji et al., 2013), and gully head and bank retreats (Zegeye et al., 2016; Frankl et al., 2012; Vanmaercke et al., 2016), factors controlling gully morphology are still poorly understood.

Since gully size is key in determining the loss of fertile soil, various studies have measured gully characteristics (e.g. length, width, depth, surface area, volume). Although these studies yielded important scientific advances, the results remain mostly site or region-specific which makes generalization impossible. Therefore, reviewing and analyzing available site-specific studies may strongly improve our understanding of factors controlling gully morphology. No systematic compilation of the morphological characteristics of gullies and their controlling factors from different environments worldwide has been made (Poesen et al. 2003, 2011).

The present study aimed at (i) reviewing available works that reported gully dimensions and evaluating the regional variations; (ii) exploring the factors explaining the variability in gully dimensions at a global scale; and (iii) identifying and discussing scopes for further research to improve our understanding of gully size and its controls. This study sought to achieve these objectives by gathering quantitative gully channel data from various environments and land uses across the world, and subjecting these to appropriate statistical analyses to identify and understand the correlations that exist. Such quantitative analysis is important for land managers to foresee the types of gullies expected when planning land use changes (Poesen et al. 2003, 2011). The analysis also produce important quantitative information which allow gully erosion modelers to better identify the main controlling factors (Poesen et al. 2011), especially climate, which has largely been overlooked (Vanmaercke et al., 2016).

3.2 Methods and Materials

3.2.1 Gully database

Available literature on gullies from around the world was explored. Data was collected from online search engines such as Google Scholar and electronic bibliographic databases (e.g. Science Direct, Springerlink). The key words used to search the literature included gully volume, length, width, depth and area. The collected studies were conducted in different climates and landscapes having different land use types. These studies focused on issues such as the rate of erosion by gully bank retreat, retreat of gully head cut or spatial prediction of gullies using mostly terrain morphology. Various types of gullies were encountered, from ephemeral to permanent gullies of several hundreds of meters in depths and widths (Derose et al., 1998). Although 75 peer-reviewed ISI journal papers were obtained during the search, only 21 papers were eventually used in building the database for the analysis of gully properties (Table 3.1). Most of the papers (12) were from Africa where Ethiopia contributed 4 papers, Nigeria 3, Tanzania 2, while South Africa, DRC and Tunisia contributed 1 each. Europe contributed 4 papers, while Asia had 3 papers with 2 coming from China. The screened papers yielded data for 435 gullies from sites around the world (Figure 3.1). Each paper was treated as an independent study and source of data despite the suspicion that some papers, Adediji et al. (2013) and Ibitoye (2017) could have reported results from the same study or gully sites. The papers, accepted for inclusion in the current analysis, presented in their study results quantitative information on at least one main gully morphological variable and one controlling factor. Papers reporting on (i) ephemeral gullies and shallow linear erosion features less than 25-30 cm in depth, (ii) permanent gullies under rehabilitation, and (iii) gully head dimensions without dimensions for the main gully channel were not accepted for the current analysis.

Table 3.1 Sources of data and summary of gully locations (region, country, LONG: longitude, LAT: latitude and Z:altitude), properties of drainage areas (CA: drainage catchment area and CS%: drainage catchment slope gradient) and dimensions of the gullies(length, L; width, W; depth, D; width-to-depth ratio, W:D; top-view area, A; and cross-sectional area, AC). All the values are averages.

	Region	**Country**	**LONG**	**LAT**	**Z**	**CA**	**CS**	**V**	**L**	**W**	**D**	**W:D**	**A**	**A_C**
Source	--------Names--------		--------°---------		--masl--	--Ha--	--%--	--m^3--	-------------m-------------				---------**m^2**--------	
Adediji et al 2013	WA	Nigeria	1.74	7.57	348.33	15.14	6.26		131.44	5.12	1.66	3.37	761.37	11.34
Billi and Dramis 2003	EA	Ethiopia	38.37	8.12	1825.00				53.19	2.50	1.10	2.28		
Daba et al 2003	EA	Ethiopia	42.02	9.40	2000.00			22927	587.18	11.18	12.36	1.47		
Frankl et al 2011	EA	Ethiopia	39.50	13.50	2750.00					12.76	4.78	3.89		38.57
Galang et al 2010	NAm	USA	-82.31	34.13	150.00	0.38	8.63		57.25	6.21	1.85	3.34		
Ghimire et al 2006	SCAs	Nepal	86.62	26.78	267.50	0.61			21.33		3.67			
Grellier et al 2012	SA	S. Africa	29.36	-28.81	1334.50	3.54	22.30	15763	113.73					
Ibitoye 2017	WA	Nigeria	4.36	7.57	399.00				131.44	5.12	1.66	3.37	761.37	11.34
Makanzu Imwangana et al 2015	CA	DRC	15.25	-4.38	272.00			274973	525.45					
Maaoui et al 2012	NA	Tunisia	10.48	35.96	27.74	4.65	12.00	1483	320.93	10.99			3758.98	
Maerker et al 2015	EA	Tanzania	36.09	-3.59	954.00	5.57			283.54	8.20	121.45	0.08		
Malik 2008	EEu	Poland	18.00	50.50	285.00		61.98		25.56	0.94	0.89	1.19		
Mbaya et al 2012	WA	Nigeria	11.17	10.17	510.00				5466.67	29.32	9.34	2.88		311.93
Muñoz-Robles et al 2010	Au	Australia	145.80	-31.48	265.00	74.94		3275	1200.94	5.65	0.78	7.39		
Ndomba et al 2009	EA	Tanzania	37.47	-3.83	1243.00					16.17	1.97	9.66		
Panin et al 2009	EEu	Russia	36.37	55.20	206.00	26.78		32968	457.89		9.05			
Radoane et al 1995	EEu	Romania	28.12	45.44	250.00				496.07	23.55	5.17	4.38	11740.92	82.80
Smolska 2007	EEu	Poland	22.93	54.08	22.50		26.67		126.75		24.63			
Wu and Cheng 2005	EAs	China	110.28	37.45	885.00	0.15	46.35		8.29	1.33	1.83	0.79	10.63	
Wu et al 2008	EAs	China	125.16	48.92	400.00				351.40	5.93			2320.05	
Zegeye et al 2016	EA	Ethiopia	37.42	11.35	2242.00	15.38							2891.46	

Years are when paper was published; regions and countries are locations where the studies were performed; all values presented in the table are averages; Regions: Au=Australia; CA=Central Africa; EA=East Africa; EAs=Eastern Asia; EEu=Eastern Europe; NA=North Africa; Nam=North America; SA=Southern Africa; SCAs=South Central Asia; WA=West Africa.

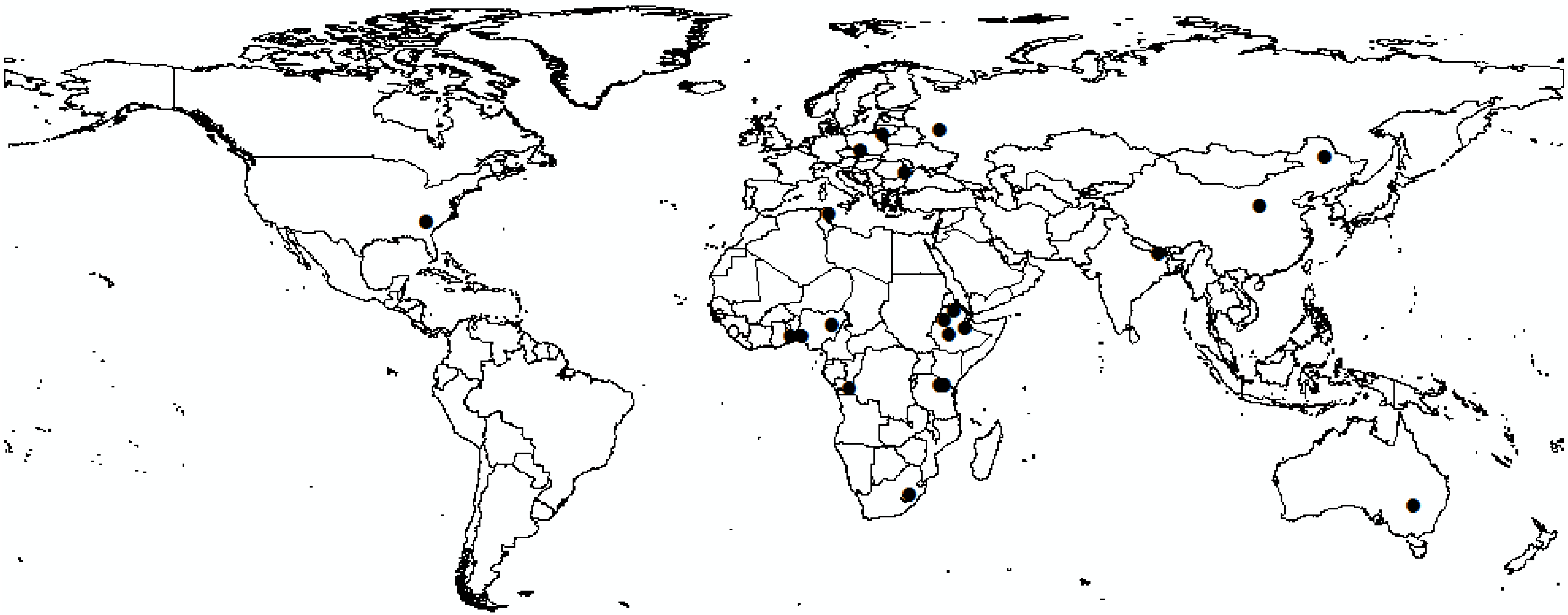

Figure 3:1 Global distribution of the study sites used in this meta-analysis

3.2.2 Definitions of environmental factors and gully variables

The environmental factors captured into the database mostly came from the papers accepted for the current analysis. The environmental factors that were sought (Table 3.2) related to site location (LONG: longitude, LAT: latitude and Z: altitude), climate (MAP: mean annual precipitation, and MAT: mean annual air temperature), gully drainage catchment area characteristics (CA: gully catchment size, CS: gully catchment slope gradient, top soil properties of the gully catchment i.e. clay, sand and silt content, and soil bulk density, and dominant land use class). When not stated in the papers, site location and climatic characteristics of a nearby prominent feature (e.g. town) were used as surrogates. The surrogate data were obtained from online sources Google-Earth, for site locations, and Wikipedia, for site locations and climate. The environmental factors used in the current analysis are defined in Table 3.5. Their magnitudes varied widely across sites and were stratified (Table 3.6) to facilitate the analyses performed in the current paper. The climate classes were defined in terms of MAP and MAT only (Mathew et al., 2017) and were not meant to necessarily comply with the Köppen (1936) system. Tropical climate was defined as hot (MAT>20°C year^{-1}) and wet (MAP>1240 mm year^{-1}), subtropical climate as warm (MAT: 13-26°C year^{-1}) and arid to humid (MAP: 400-1210 mm year^{-1}), and temperate climate as cool (MAT<9°C year^{-1}) and arid to moist (MAP: 400-680 mm year^{-1}) region. The change from temperate to tropical, through the subtropical class, was envisaged to represent increasing MAP and MAT conditions. Altitude was categorised into two classes, low (0-500 masl) and high (>500 masl), with low altitude class generally viewed to represent hotter and drier conditions than the high altitude class. Gully drainage catchment area (Microcatchment: 0-1 ha, Mesocatchment: 1-10 ha, Catchment> 10 ha) and slope gradient (Low: 0-10%, Moderate: 10-30%, Steep>30%) were stratified into 3 classes each. Soil textural components (clay, sand and silt content) were categorised into low and high class (Table 3.3), while 4 land use classes (Forests, Grasslands, Croplands and Settlements) were used in the analysis. These land use classes represented the dominant land use category in the gully drainage catchment or catchment area where the gully catchment was located in terms of soil surface coverage. The change of land use class from forests to settlements was envisaged to represent an increasing intensity of soil cover disturbance. The forests consisted of undisturbed ecosystems where trees dominated soil surface cover. Grasslands represented systems where grass cover was dominant and included systems exposed to various levels of livestock grazing intensities.

Croplands represented systems where crop production was the dominant economic activity without distinguishing the land management systems in place; however, there was no gully rehabilitation mentioned in the source papers. Settlements represented densely populated areas where vegetation cover is negligible because the spaces not occupied by buildings are generally bare and connecting roads not paved.

The gully dimensions are also defined for purposes of the analyses in Table 3.5. All the gully dimensions were obtained from journal papers. However, gully width-to-depth ratio (W:D) was calculated when data on the average gully width and depth were provided by a paper. Length (W, m) was defined as the approximate distance occupied by a gully channel from head to tail. Width (W, m) was the average distance from one bank of the gully to the other and measured perpendicular to the channel direction as provided in the papers. When both the top width and gully bed width were provided, an average of the two was calculated and captured as the representative W for the gully. Depth (D, m) was the average depth from the soil surface in the inter-gully area to the channel bed. Top-view area (A) was the aerial area of a gully, while cross-sectional area (AC) was the average area of gully cross-section as provided by a paper. Gully volume was also either as reported in the papers or it was calculated by multiplying the gully cross sectional area by the length of the gully.

Table 3.2 Definitions of the environmental factors and gully dimensions used in the data-analysis

Environmental factors and gully dimensions	**Symbols**	**Units**	**Definitions**
Mean annual precipitation	MAP	mm $year^{-1}$	Long-term (at least 30 year) mean annual precipitation for the study location from the papers
Mean annual air temperature	MAT	°C $year^{-1}$	Long-term (at least 30 year) mean annual temperature for the study location from the papers
Longitude	LONG	°	Longitude of the midpoint of study site or gully channel as given in paper
Latitude	LAT	°	Latitude of the midpoint of study site or gully channel as give in paper
Altitude	Z	m.a.s.l	Average elevation above sea level of the study site given in the papers
Catchment area	CA	Ha	Gully drainage catchment area as given in papers
Catchment slope	CS	%	Average slope gradient of gully drainage catchment area as given in papers
Soil bulk density	P	g cm^{-3}	Bulk density of the top soil as given in papers
Clay content	Clay	%	Average clay content (or fine textured soil particles) of the top soils in the area where the studied gully is located
Silt content	Silt	%	Average silt content (or medium textured soil particles) of the top soils in the area where the studied gully is located
Sand	Sand	%	Average sand content (or coarse textured soil particles)of the top soils in the area where the studied gully is located
Volume	V	m^3	Approximate volume of gully channel computed as the product of gully length (L) and cross sectional area (A_c)
Length	L	m	Distance covered by a gully channel from its head to outlet
Width	W	m	Average of top and base width of gully channel
Depth	D	m	Average depth of gully channel
Width-depth ratio	W:D		It is product of average gully width divided by the average gully depth
Top view area	A	m^2	Approximate top view surface area of a gully computed as product of gully length (L) and average width (W)
Cross sectional area	A_c	m^2	Average vertical side area of the gully which is calculated by half width multiplied by the average gully depth

Table 3.3 List of gully controlling factor classes describing the environmental conditions

Environmental factors	Remarks	Class range	Name
Climate	Hot and wet	MAT>20	Tropical
(MAP, mm year^{-1};		MAP>1240	
MAT, °C year^{-1})	Warm and arid-humid	MAT: 13-26	Subtropical
		MAP:<1210	
	Cool and arid-moist	MAT<9	Temperate
		MAP: 400-680	
Altitude	Height above sea level	0-500	Low
(Z, m asl)		>500	High
Catchment area	Gully drainage catchment area	0-1	Microcatchment
(CA, Ha)		1-10	Mesocatchment
		>10	Catchment
Catchment slope gradient	Average slope gradient of gully	0-10	Low
(CS, %)	drainage catchment area	10-30	Moderate
		>30	Steep
Clay (%)	Average clay content of the top soil	0-35	Low
	Average sand content of the top	>35	High
Sand (%)	soil	0-50	Low
	Average sand content of the top	>50	High
Silt (%)	soil	0-40	Low
	Dominant land use	>40	High
Land use		Forests	Forests
		Grasslands	Grasslands
		Croplands	Croplands
		Settlements	Settlements

Climate classes were adapted from Mathew et al. (2017), other factor classes were adapted from Mutema et al. (2015b)

3.2.3 Statistical analyses of the gully database

A preliminary step of the data analysis was the determination of overall sample sizes of gully variables for each controlling factor class (given as n in Tables 3.4-3.6 and bracketed figures in Figures 3.2-3.9). This step was followed by calculations of descriptive statistics for site factors (Table 3.6) and gully morphological variables (Table 3.8), to gain insights into their overall variability across the studied gully sites (Figure 3.1). The descriptive statistics are minimum, maximum, median, mean, standard error of mean (SEM), 25th and 75th percentiles (Q1 and Q3, respectively), skewness (Skew), kurtosis (Kurt), and coefficient of variation (CV %). The third step was a more in-depth analysis seeking to understand the impact of the factors controlling the gully variables using box-plots (Figures 3.2-3.9). Each box-plot shows the median, Q1 and Q3, lower and upper limit of the non-outlier range, and the outliers (shown as dots). Outliers are observations located abnormal distances from other values in random samples. Medians were preferred for describing general trends representing the gully variables (with controlling factors) because skewness and kurtosis statistics suggested the datasets were not normally distributed. Medians are the better measures of central location in highly skewed datasets because, unlike means, they are not pulled by extreme values nor highly influenced by the frequencies of single values (Wegner, 2000). In this step, gully data for the different factor classes were compared against each other using nonparametric t-test (Statistica 10.0) with significance of difference at $P<0.05$. The last step was a two-tier correlation analysis involving Spearman rank correlation analysis (Table 3.9) and principal component analysis (Figure 3.10). Spearman rank correlation analysis elucidated the one-on-one relationships between the gully site factors and gully variables, while the principal component analysis (PCA) evaluated the multiple relationships. Spearman rank correlations were adopted because the descriptive statistics showed that the datasets were skewed. The PCA is a multivariate exploratory analysis procedure geared at identifying the main factors controlling the variables. In general, PCAs are used when the correlations are not linear (Jambu, 1991) and they convert the factors and variables into linear combinations called principal components (PCs). Only the PCs with an Eigen value of 1 or more were considered. Parameters with a loading of at least 0.3 were considered to be significant for each PC.

3.3 Results

3.3.1 Global variations of the controlling factors

The mean annual precipitation (MAP) for all the 435 gully sites ranged from a minimum of 400 mm yr^{-1} of Qiaogou in China (Wu and Cheng, 2005) to a maximum of 1500 mm $year^{-1}$ for Udayapur district in Nepal (Ghimire et al., 2006) and Ondo-Ekiti in Nigeria (Ibitoye, 2017) and the computed overall average was 927±18 mm $year^{-1}$ (Table 3.5). Mean annual temperature (MAT) varied from minimum 0.5°C $year^{-1}$ in Nehe County, China (Wu et al., 2008) to maximum 27^{o}C $year^{-1}$ in Nigeria (Adediji et al., 2013; Ibitoye, 2017). The average MAT across the 435 gully sites was 18.7±0.3 ^{o}C $year^{-1}$. Altitude of the gully sites also varied greatly from 22.5 masl for upper Szeszupa in Poland (Smolska, 2007) to 2750 masl for Tekeze-Nile basin in Ethiopia (Frankl et al., 2011). The calculated average altitude was 1039±44 masl. Top soil properties also showed great variation with, for example, bulk density varying from 1.14 g cm^{-3} for Debre Mawi, Ethiopia (Zegeye et al., 2016) to 2.03 g cm^{-3} for Gombe town in Nigeria (Mbaya et al., 2012). The high soil bulk density for Gombe was probably calculated from very stony soils. Soil sand content was lowest (17.5%) in China (Wu et al., 2008) and highest (70.5%) in South Carolina, USA (Galang et al., 2010). Silt content ranged from 8% in Gombe town, Nigeria (Mbaya et al., 2012) to 47.5% in Nenjiang County, China (Wu et al., 2008) with a computed overall average of 16.02±1.13 soil clay content was also lowest (15.5%) in South Carolina, USA (Galang et al., 2010) and highest (67%) in Ethiopia (Zegeye et al., 2016). The smallest gully catchment area (0.02 ha) was reported for Qiaogou, China (Wu and Cheng, 2005) and the greatest (171 ha) for the Cobar pediplain in Australia (Muñoz-Robles et al., 2010).

Table 3.4 Summary statistics of the gully site factor characteristics included in the global gully database

	MAP	MAT	Z	BD	Sand	Silt	Clay	CA	CS	GHD	GHS
n	435	435	435	78	60	60	86	191	133	120	23
Mean	927	18.69	1039	1.48	47.53	16.02	43.32	15.75	21.48	3.41	11.26
Median	900	18.00	510	1.63	48.04	13.30	38.67	5.42	15.00	1.90	10.20
Min	400	0.50	22.50	1.14	17.50	8.00	15.50	0.02	2.38	0.13	5.00
Max	1500	27.00	2750	2.30	70.50	47.50	67.00	171	84.44	35.00	30.10
Q1	680	15.00	272	1.22	48.04	13.30	38.67	0.88	6.89	1.06	7.10
Q3	1325	25.50	1825	1.63	48.04	13.30	55.00	17.40	29.70	2.93	13.90
CV%	39	38	89	16	20	54	27	175	91	188	49
SEM	17.51	0.34	44.41	0.03	1.20	1.13	1.28	1.99	1.70	0.59	1.14
Skew	0.24	-0.48	0.73	0.29	-1.85	3.26	0.36	3.33	1.30	4.07	1.90
Kurt	-1.28	-0.73	-0.93	0.28	6.11	9.57	-0.35	13.13	0.88	16.06	5.50

MAP=mean annual precipitation (mm yr^{-1}); MAT=mean annual air temperature (°C yr^{-1}); Z=altitude above sea level (masl); BD=soil bulk density (g cm^{-3}); Sand=sand content (%); Silt=silt content (%) and Clay=clay content (%); CA=gully drainage catchment area (ha); CS=slope gradient (%); GHD=gully head depth (m) and GHS=slope gradient (%)

Table 3.5 Summary statistics of gully dimensions from the global dataset

	V	L	W	D	W:D	A	A_C	GS
n	116	310	317	331	274	180	129	142
Mean	59954.23	433.18	9.23	6.98	4.02	2135.24	42.76	7.27
Median	4652.50	139.93	7.22	1.94	2.97	576.71	9.76	5.97
Min	112.50	1.24	0.50	0.40	0.03	0.49	1.05	0.26
Max	1469805	6000	60.50	183.30	27.62	51266	816.75	50.22
Q1	1413.80	57.00	2.68	1.17	1.45	217.66	3.66	3.66
Q3	28475.00	399.00	12.63	5.97	5.54	2079.72	32.04	8.89
CV%	337	223	97	288	97	242	248	84
SEM	18786.32	54.88	0.50	1.11	0.24	384.44	9.33	0.51
Skew	5.78	4.52	2.51	6.65	2.53	6.64	5.20	3.25
Kurt	36.53	21.50	9.42	48.40	9.46	54.85	31.13	17.70

V=volume (m^3); L=length (m); W=width (m); D=depth (m); W:D=width to depth ratio; A=top view area (m^2); A_C=cross-sectional area (m^2) and GS=gully slope gradient (%)

3.3.2. Global variations of gully dimensions

The gully dimensions also showed great variability across the gathered studies (Table 3.6). The reported gully volumes varied from 112.5 m^{-3} (Muñoz-Robles et al., 2010) to 1469805 m^3 (Makanzu Imwangana et al., 2015), with an average of 59954±18786 m^3 from 116 sites. The shortest gully length was 1.24 m reported for a gully in Qiaogou, China (Wu and Cheng, 2005) while the longest was 6000 m for a gully in Gombe, Nigeria (Mbaya et al., 2012). Reported gully widths ranged from 0.5 m in China (Wu and Cheng, 2005) to 60.5 m in Nigeria (Mbaya et al., 2012). The computed average gully width was 9.23±0.50 m for 317 gullies. Depth varied from 0.40 m in Proboszczowicka, Poland (Malik, 2008) to 183 m in Manyara, Tanzania (Maerker et al., 2015), with an overall average of 6.98±1.11 m for 331 sites. The resultant width-depth ratios varied from 0.03 to about 28 with an average of 4.02±0.24 for 274 observations. Top-view area varied from as little as 0.49 m^2 reported for a gully in China (Wu and Cheng, 2005) to a greatest of 51266 m^2 at Moldavia, Romania (Radoane et al., 1995). The smallest cross-sectional area was 1.05 m^2 for Ode Irele in Nigeria (Adediji et al., 2013), while the maximum was 816.75 m^2 in Gombe, Nigeria (Mbaya et al., 2012). Gully slope gradient also showed high variation (CV=84%) with minimum and maximum of 0.26 and 50% reported for gullies at Butajira, Ethiopia (Billi and Dramis, 2003).

Table 3.6 Correlation coefficients between site characteristics and gully dimensions

	MAP	MAT	LONG	LAT	Z	CA	CS	BD	Clay	Sand	Silt
V	0.35*	0.37*	0.24*	-0.19*	0.33*	0.32*	-0.53*				
L	0.12	0.00	0.09	-0.08	0.19*	0.74*	-0.44*	0.04	0.11	-0.20	-0.24
W	0.12	0.00	0.04	-0.15*	0.16*	0.40*	-0.40*	0.22	-0.20	0.25	-0.04
D	-0.19*	-0.39*	0.14*	0.40*	0.12*	-0.12	0.17*	0.42*	-0.20	0.33*	-0.09
W:D	0.02	0.28*	-0.11	-0.54*	-0.12*	0.74*	-0.65*	-0.18	-0.04	-0.03	0.15
A	0.01	-0.11	-0.05	0.11	-0.40*	0.57*	-0.30*	-0.35*	0.25*	-0.17	0.17
A_C	-0.57*	-0.64*	0.52*	0.64*	-0.14	0.55*	0.16	0.42*	-0.15	0.42*	-0.42*
GS	0.07	-0.05	-0.15	0.58*	-0.12	-0.65*	0.51*	0.36*	-0.12	0.36*	-0.36*

*significant at $p<0.05$. MAP=mean annual precipitation (mm yr^{-1}); MAT=mean annual air temperature (°C yr^{-1}); LONG=longitude (°); LAT=latitude (°); Z=altitude above sea level (masl); CA=gully catchment area (ha); CS=gully catchment slope gradient (%); BD=soil bulk density (g cm^{-3}); Sand=sand content (%); Silt=silt content (%) and Clay=clay content (%); V=volume (m^3); L=length (m); W=width (m); D=depth (m); W:D=width-depth ratio; A=top view area (m^2), A_C=cross-sectional area (m^2); GS=channel bed slope gradient (%).

3.4 Impact of environmental and soil variables on gully dimensions

3.4.1 Climate and altitude

MAP and MAT showed significantly positive effect on gully volume (V) with respective Spearman rank correlation coefficients (r) of 0.35 and 0.37 (Table 3.6). However, both factors showed negative effect on gully depth (r=-0.19 and -0.39 for MAP and MAT, respectively) and strongly negative effect on gully cross-sectional area (r=-0.57 and -0.64 for MAP and MAT, respectively). It, therefore, appears that the correlations with V may largely be a result of the positive effect of MAP on gully length and width which, in our case, appeared to be very weak (r=0.12) for both L and W (Table 3.6). Latitude (LAT) and altitude (Z), factors which often have an impact on the climate of a site, had contrasting effects on V, with LAT (r=-0.19) showing a negative effect while Z (r=0.33) had a positive effect (Table 3.8). Latitude showed strongly significant effects on D (r=0.40), W:D (r=-0.54), AC (r=0.64) and GS (r=0.58). Box-plots show that V tended to decrease from temperate to subtropical climate, before increasing in the tropical zone (Figure 3.2a). Median V decreased by 92% from 29000 to 2375 m^3 in temperate and subtropical climate respectively, followed by a sharp 45 fold increase in the tropical zone. In contrast, L (Figure 3.2b), W (Figure 3.2c), W:D (Figure 3.2e) and A (Figure 3.2f) tended to increase from temperate to subtropical climate before decreasing in the tropical zone, with all changes being significant at $P<0.05$. Top view area appeared to be the most sensitive variable with change to climate as its median increased by a staggering 154 fold from 17 to 2659 m^2 in temperate and subtropical zone respectively before decreasing by 81% in the tropical zone. Gully depth (Figure 3.2d) and AC (Figure 3.2g) showed a tendency to decrease from temperate to subtropical climate followed by a further decrease in the tropical zone, but the change from temperate to subtropical climate was not significant in both cases. Despite tendencies to increase with altitude (Z), V (Figure 3.3a), W (Figure 3.3c) and AC (Figure 3.3g) did not change significantly from low to high Z. Width-to-depth ratios (Figure 3.3e) and A (Figure 3.3f) also showed no significant change with Z, but tended to decrease from low to high Z. However, L (Figure 3.3b) and D (Figure 3.3d) changed significantly from low to high Z with L showing a decrease while D increased. Length appeared to be more sensitive to change in Z than D because its median changed by 59% from 174 m in low Z as compared to a change of only 41% for D.

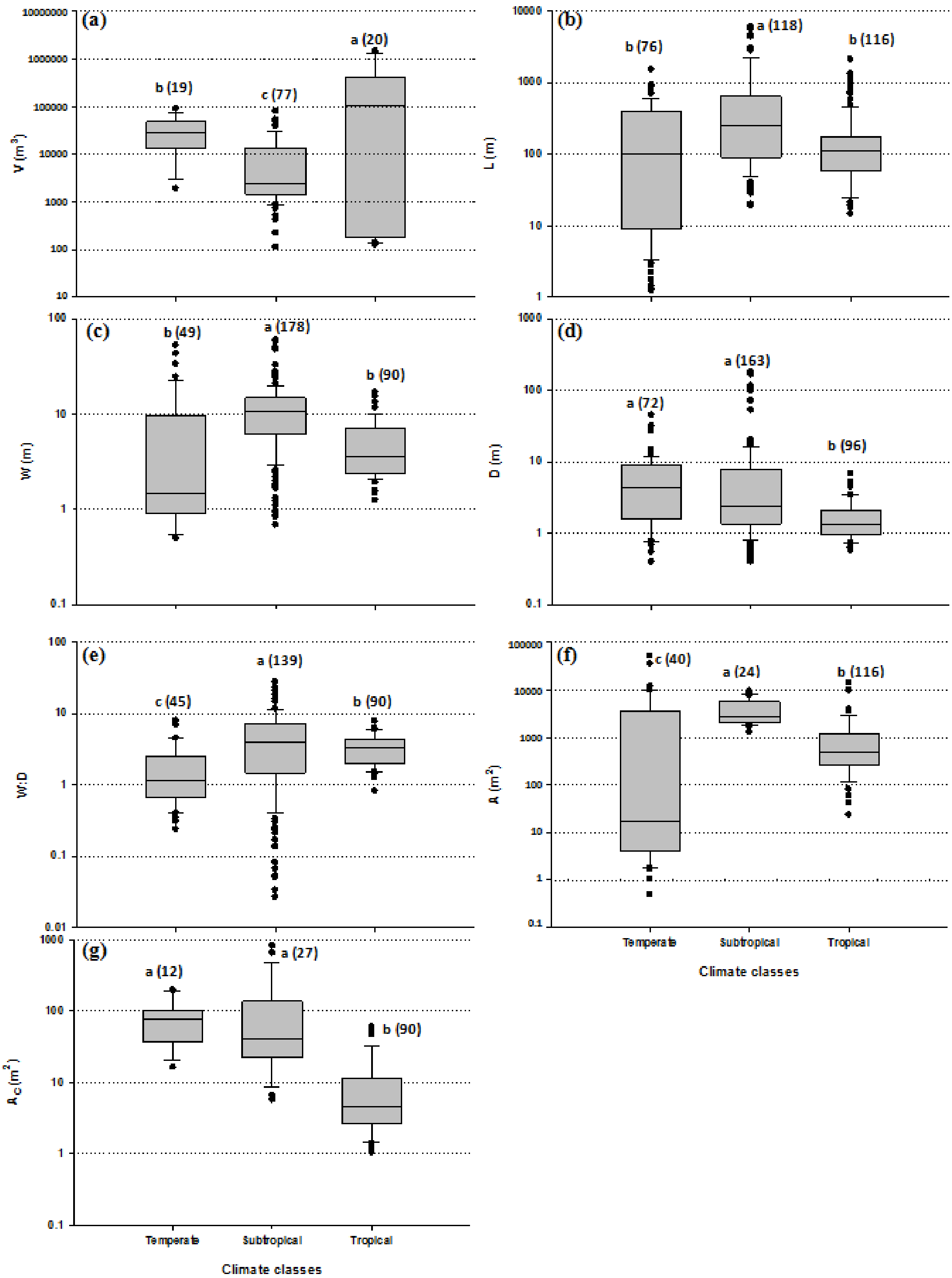

Figure 3:2 Box-plots showing variation of permanent gully dimensions (a) volume, V, m^3; (b) length, L, m; (c) width, W, m; (d) depth, D, m; (e) width-depth ratio, W:D; (f) top view area, A,m^2; and (g) cross-sectional area, Ac, m^2 corresponding to three climate classes (see table 3). Box-plots in the same figure which are accompanied by similar letters were not significantly different at $p<0.05$. Letters were not included when the differences were not significant. The numbers between brackets are the respective sample sizes. All y-axes are in logarithmic scale.

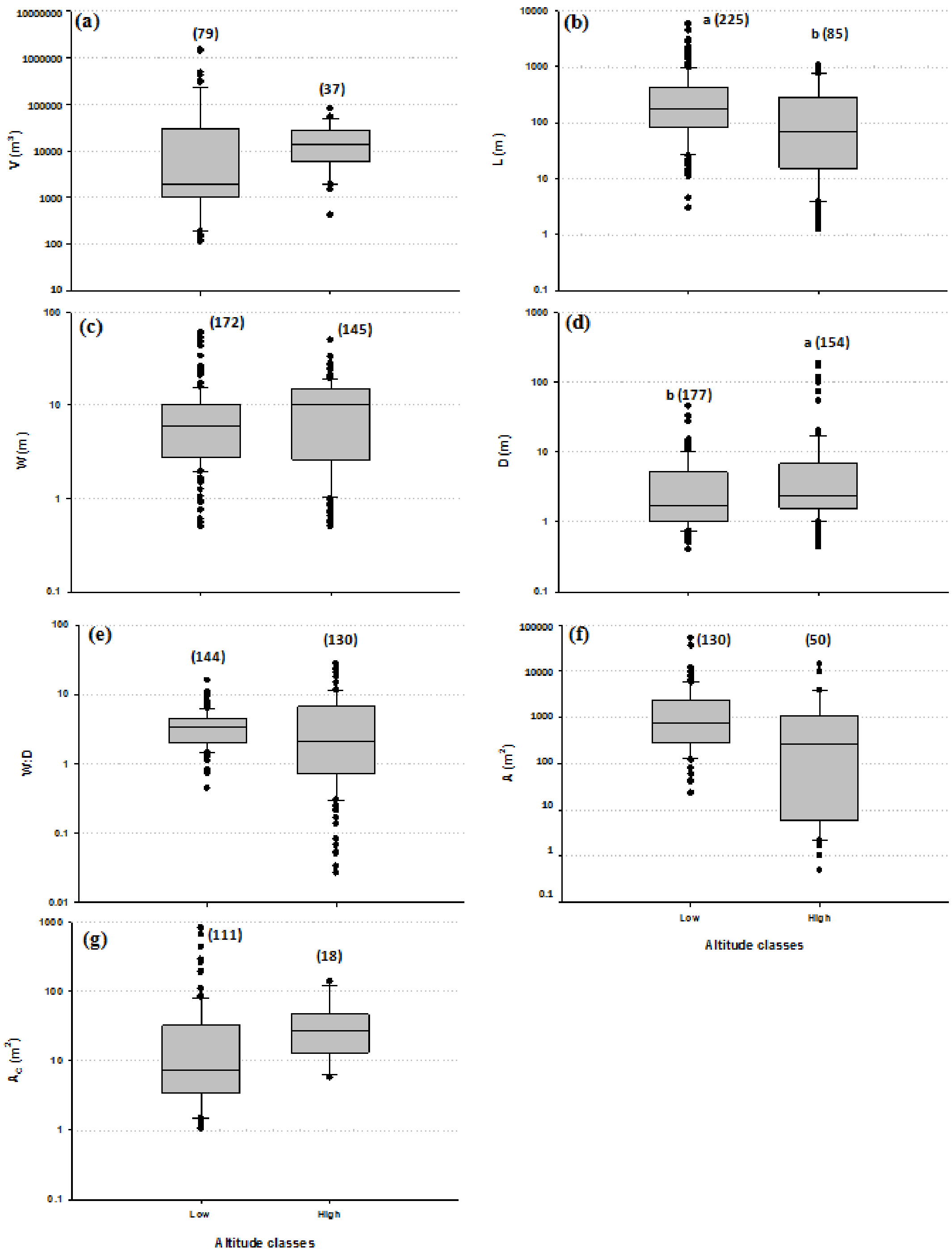

Figure 3:3 Box-plots showing variation of gully dimensions (a) volume, V, m^3; (b) length, L, m; (c) width, W, m; (d) depth, D, m; (e) width-depth ratio, W:D; (f) top view area, A, m^2; and (g) cross-sectional area, Ac, m^2 for two altitude classes.

3.4.2 Catchment area and slope gradient

The impact of drainage catchment area (CA) and slope gradient (CS) on the gully variables were contradictory (Table 3.6). CA correlated positively with all but GS; while CS correlated negatively except with GS. Their significant coefficients were quite strong (30<r<74), which signifies their importance as controlling factors of gully erosion. Box-plots showed no significant change of V from micro (median 2090 m^3) to meso-catchment scale (1791 m^3), but was significantly greater in the catchment scale (11232 m^3) (Figure 3.4a). In contrast, L (Figure 3.4b), W:D (Figure 3.4e) and A (Figure 3.4f) increased significantly from micro to meso-catchment scale followed by a further increase in the catchment scale. However, the increase of A from meso catchment scale was not significant. Depth showed no significant change with catchment scale (Figure 3.4d). There was no data for A_C at micro-catchment level, but median A_C increased by 3 fold from 3 to 9 m^2 in meso-catchment and catchment scale, respectively (Figure 3.4g). Gully volume tended to increase with catchment slope, but the changes with slope gradient class were not significant (Figure 3.5a). In contrast, L (Figure 3.5b), W (Figure 3.5c), D (Figure 3.5d) and A (Figure 3.5f) changed significantly with catchment slope class. All of them tended to increase from low to moderate catchment slope, followed by a sharp decrease in the steep class. Width-to-depth ratios tended to decrease with catchment slope, but the decrease from low to moderate catchment slope was not significant (Figure 3.5e). Lack of adequate data hindered proper assessment of the influence of catchment slope on A_C (Figure 3.5g).

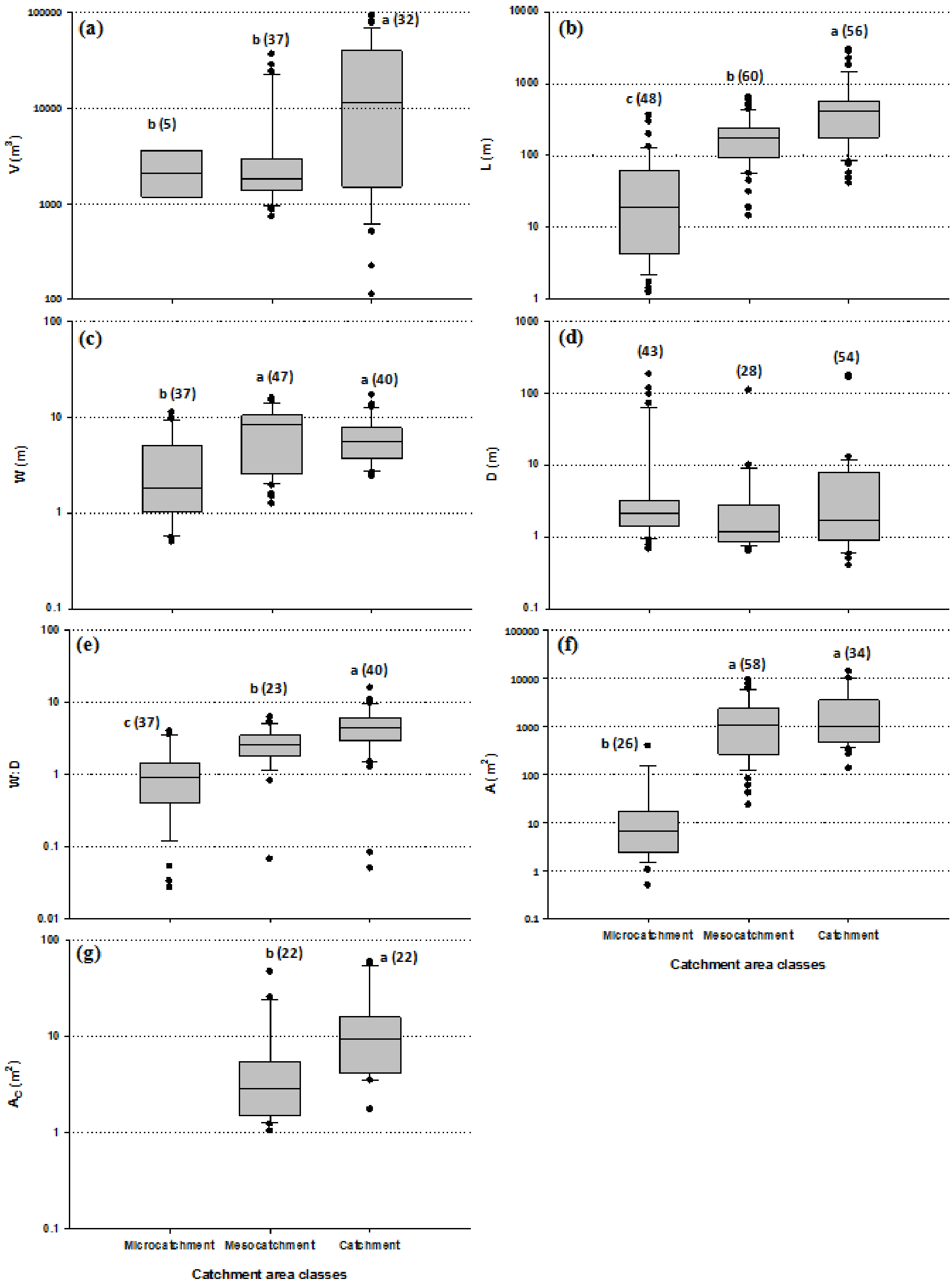

Figure 3:4 Box-plots showing variation of gully (a) volume, V, m^3; (b) length, L, m; (c) width, W, m; (d) depth, D, m; (e) width-depth ratio, W:D; (f) top view area, A, m^2; and (g) cross-sectional area, Ac, m^2 for three gully drainage catchment area classes

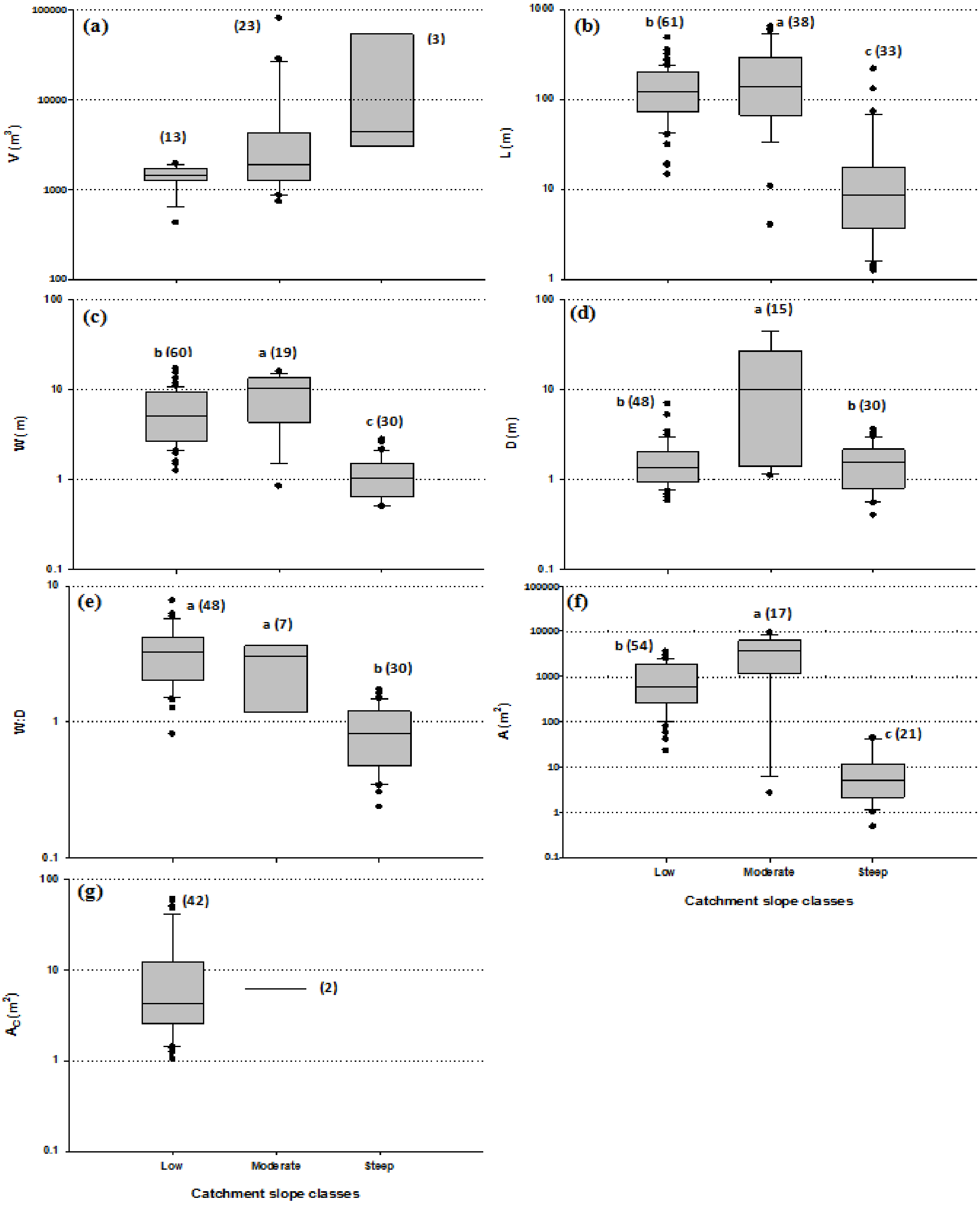

Figure 3:5 Box-plots showing variation of gully dimensions (a) volume, V, m^3; (b) length, L, m; (c) width, W, m; (d) depth, D, m; (e) width-depth ratio, W:D; (f) top view area, A, m^2; and (g) cross-sectional area, Ac, m^2 for three drainage catchment slope

3.4.3 Soil texture

There was also no adequate data to analyse relationships between top soil properties and V (Table 3.6, Figures 3.6-3.8). However, soil bulk density (BD) correlated positively with D (r=0.42), Ac (r=0.42) and GS (r=0.36) and negatively with A (r=-0.35) (Table 3.6). Clay content showed significant effect on with A (r=0.25) only, while sand content correlated significantly with D (r=0.33), A_C (r=0.42) and GS (r=0.36). Silt content showed negative correlations with Ac (r=-0.42) and GS (r=-0.36). Box-plots suggest no significant top soil clay content effect on any of the gully variables analysed (Figure 3.6). In contrast, L (Figure 3.7a), W (Figure 3.7b), D (Figure 3.7c) and Ac (Figure 3.7f) changed significantly from low to high sand content. However, L showed a decrease of median value while W, D and AC tended to increase. Ac was the most sensitive to change of sand content because it increased by 51 fold from low (5 m^2) to high sand content (258 m^2). Gully length (Figure 3.8a), W (Figure 3.8b) and A (Figure 3.8e) tended to increase with soil silt content; however, only A showed a significant change by increasing from 468 to 1662 m^2 for low and high silt soil, respectively. There was no adequate data to facilitate interclass comparisons of D (Figure 3.8c), W:D (Figure 3.8d) and Ac (Figure 3.8f).

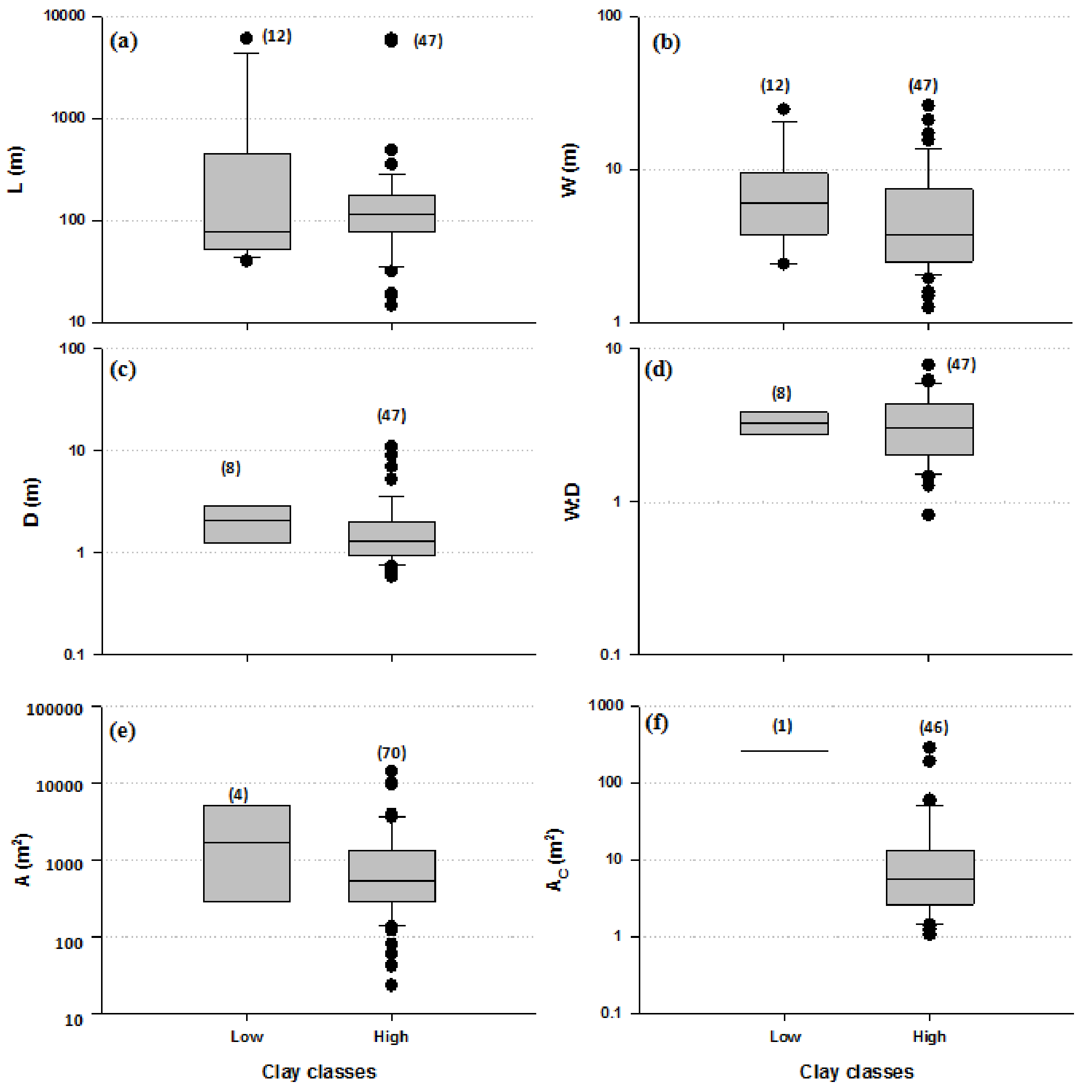

Figure 3:6 Box-plots showing variation of gully dimensions (a) volume, V, m^3; (b) length, L, m; (c) width, W, m; (d) depth, D, m; (e) width-depth ratio, W:D; (f) top view area, A, m^2; and (g) cross-sectional area, Ac, m^2 for two soil clay content classes.

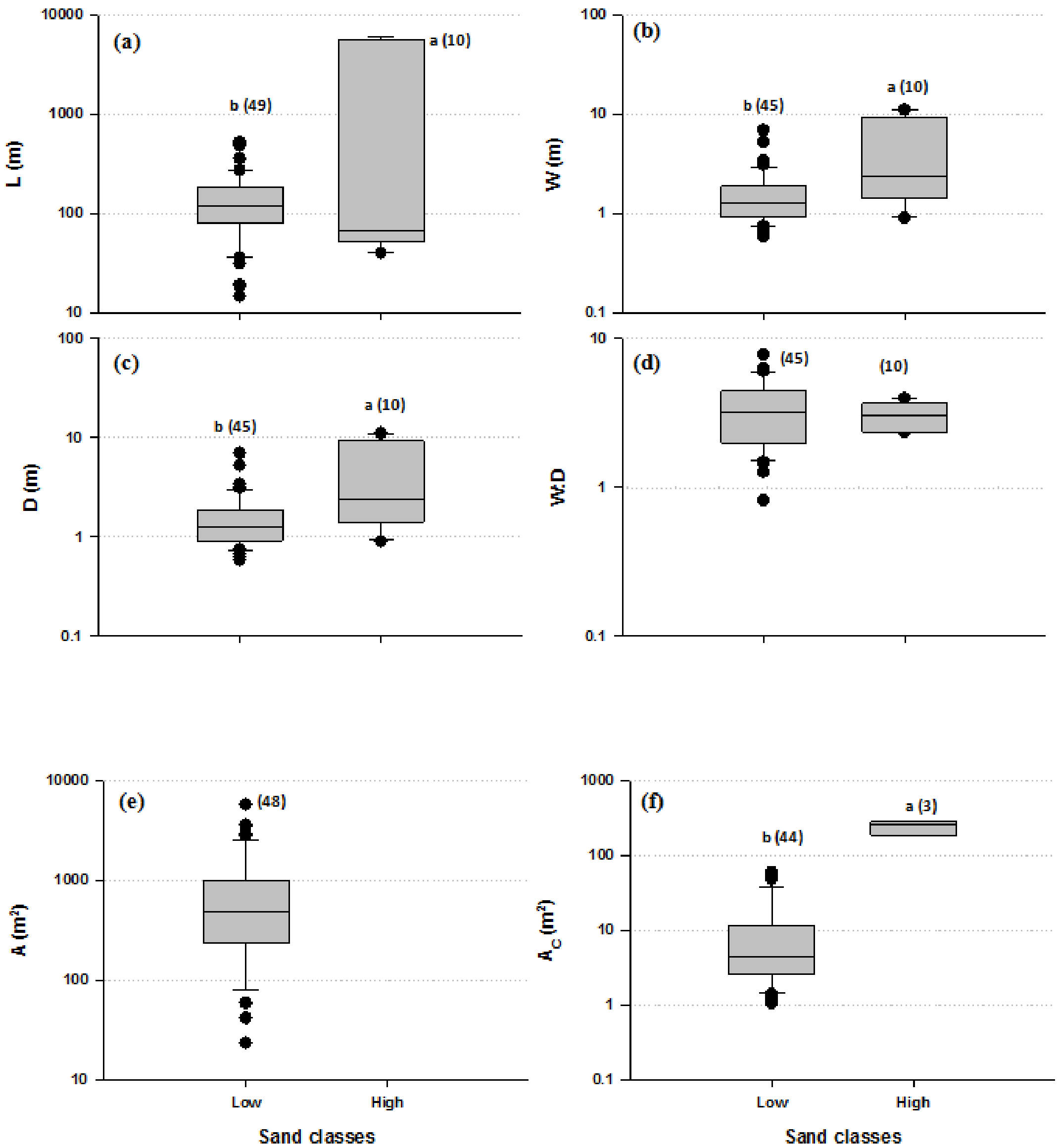

Figure 3:7 Box-plots showing variation of gully dimensions (a) volume, V, m^3; (b) length, L, m; (c) width, W, m; (d) depth, D, m; (e) width-depth ratio, W:D; (f) top view area, A, m^2; and (g) cross-sectional area, Ac, m^2 for two soil sand content classes.

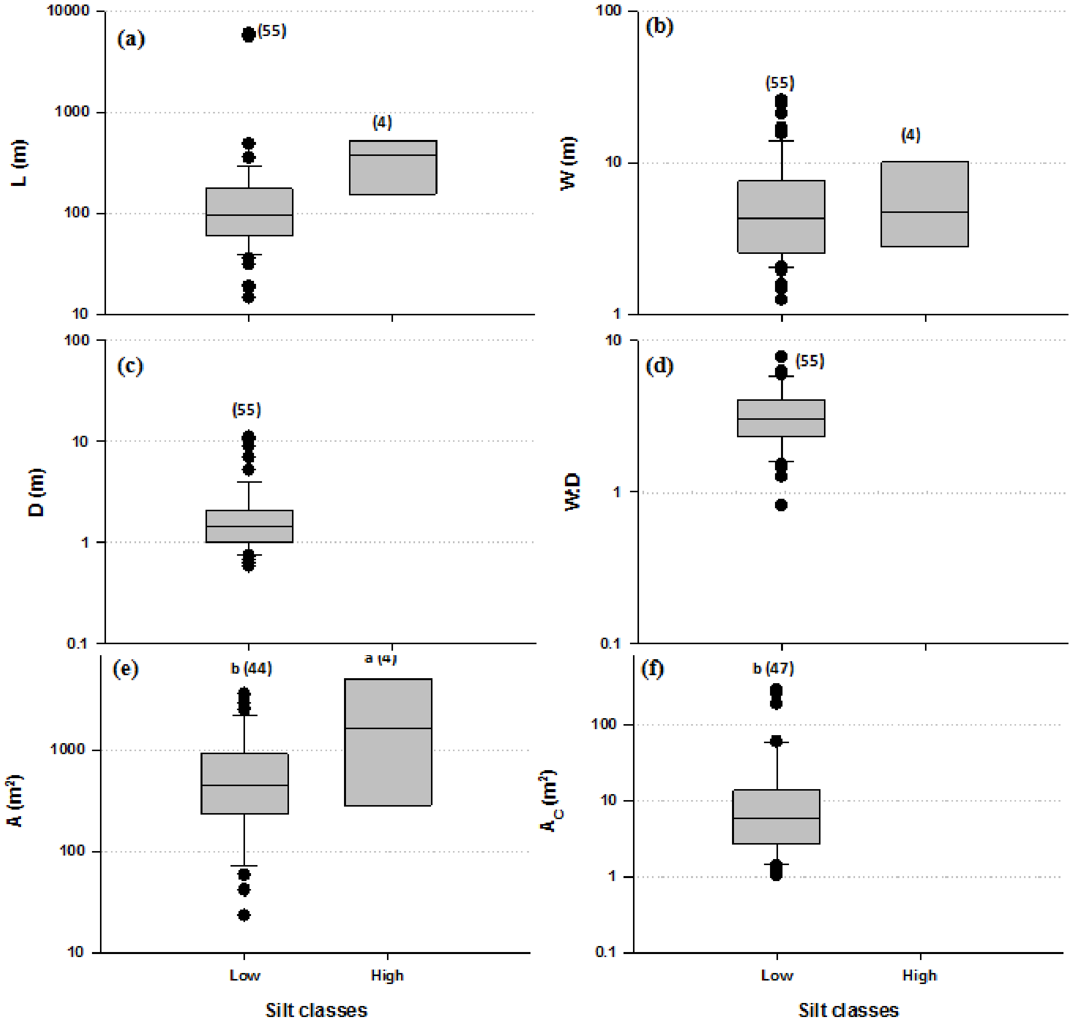

Figure 3:8 Box-plots showing variation of gully dimensions (a) volume, V, m^3; (b) length, L, m; (c) width, W, m; (d) depth, D, m; (e) width-depth ratio, W:D; (f) top view area, A, m^2; and (g) cross-sectional area, Ac, m^2 for two soil silt content

3.4.4 Land use

Comprehensive analysis of the impact of land use on V (Figure 3.9a), W (Figure 3.9c), D (Figure 3.9d), W:D (Figure 3.9e), A (Figure 3.9f) and AC (Figure 3.9g) was also hindered by inadequate data. However, V increased significantly from forests to grasslands with median value increasing 2.5 fold from 1704 to 4235 m^3. Length (Figure 3.9b) and W (Figure 3.9c) did not change significantly with land use class. However, L tended to decrease from forests to settlements. Gullies were deepest in croplands (113 m) followed by settlements (1.5 m) and shallowest in forests (0.95 m) (Figure 3.9d). All of them were significantly different from each other. Width-to-depth ratios were greatest in forests (4.7), followed by settlements (3.03) and least in croplands (0.06) (Figure 3.9e). Top view area did not differ significantly between grasslands (1045 m^2) and croplands (1662 m^2), but was significantly lower in settlements (468 m^2) (Figure 3.9f).

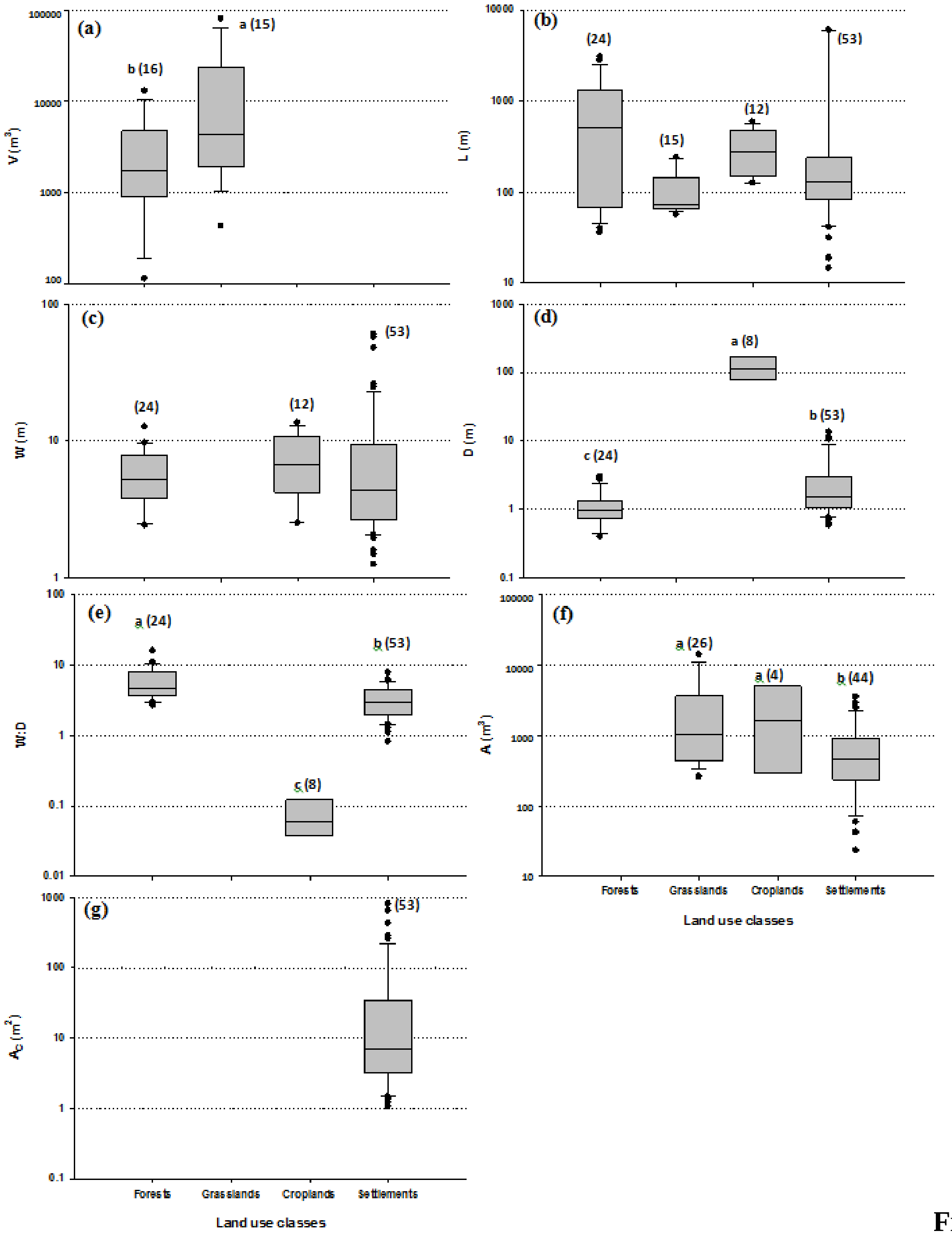

Figure 3:9 Box-plots showing variation of gully dimensions (a) volume, V, m3; (b) length, L, m; (c) width, W, m; (d) depth, D, m; (e) width-depth ratio, W:D; (f) top view area, A, m2; and (g) cross-sectional area, Ac, m2 for four land use/land cover class

3.4.5 Multiple correlations between controlling factors and gully dimensions

Over 90% (93%) of the dataset variability was accounted for by 8 PCs, with 29, 18, 11, 9, 8, 7, 6 and 6% for PC 1, 2, 3, 4, 5, 6, 7 and 8, respectively (Table 3.7). Principal component 1 explained 29% of the total variance with the volume, MAP, MAT, sand and bulk density having a positive loading and a significant but negative loading from altitude and silt. PC 2 accounted for 18% of the data set with area, width, volume, altitude and slope having a significant and positive loading and a significant but negative loading came from MAP. PC 3 explained 11% of the total variance and the following parameters had a positive score; width depth ratio, silt and latitude while sand, altitude and slope had a significant but negative loading on the PC. Width, Area, volume and longitude had a significant and positive loading for PC4 which accounted for 9% of the total variation of the dataset while length and bulk density had a negative and significant loading. PC 5 accounted for 8% of the total variation and had significant and positive loading from volume and longitudes while the width depth ratio had a negative and significant loading. PC6 had a positive and significant loading from the cross sectional area and clay. PC7 had a positive loading from the depth and a negative loading from width depth ratio. Finally PC8 had a positive loading from the longitudes and negative loading from the depth.

Table 3.7: PCA summary statistics showing percentage variance of principal component with a Eigen value greater than 1.

Principal component	1	2	3	4	5	6	7	8
Eigen value	3.03	2.47	2.10	1.79	1.46	1.24	1.14	1.06

Variance %	29	18	11	9	8	7	6	6
Variables								
Ac	0.16	0.21	0.03	0.07	-0.39	**0.66**	0.09	0.1
Length	0.15	0.18	0.16	**-0.33**	-0.72	0.22	-0.26	0.08
Width	0.07	**0.69**	0.26	**0.58**	-0.003	-0.24	-0.1	-0.10
Depth	0.15	0.07	0.02	-0.10	0.18	-0.10	**0.64**	**-0.51**
Area	0.12	**0.75**	0.24	**0.52**	0.02	-0.26	-0.08	-0.04
Volume	**0.37**	**0.42**	0.23	**0.43**	**0.54**	0.12	-0.12	0.06
W:D	-0.14	0.07	**0.35**	-0.05	**-0.33**	0.28	**-0.53**	-0.12
Factors								
MAP	**0.70**	-0.3**6**	0.01	0.29	0.17	-0.02	0.06	0.09
MAT	**0.74**	-0.28	0.23	0.22	0.03	0.12	0.18	-0.02
Sand	**0.74**	-0.05	**-0.45**	0.12	-0.11	0.07	-0.22	-0.07
Silt	**-0.75**	0.032	**0.48**	-0.16	0.07	-0.11	0.17	0.09
Clay	0.014	0.29	-0.20	0.24	0.08	**0.35**	0.18	-0.13
BD	**0.47**	0.08	-0.06	**-0.51**	-0.19	-0.49	-0.1	-0.06
Longitude	-0.022	-0.26	0.007	**0.43**	**0.33**	0.08	0.06	**0.61**
Latitude	-0.09	-0.23	**0.64**	0.11	-0.03	0.22	0.18	0.003
Altitude	**-0.35**	**0.36**	**-0.71**	0.02	0.11	0.07	-0.04	0.09
Slope	-0.27	**0.35**	**-0.53**	-0.01	0.1	0.16	0.22	0.09

Ac = cross sectional area, W:D = width depth ratio BD = bulk density, MAT = mean annual temperature and MAP = mean annual precipitation.

3.5 Discussion

3.5.1 The impact of climate and soil properties on gully dimensions

The fact that MAP, in our study, correlated positively with gully parameters, such as length, width and volume (Table 3.6, Figure 3.10), resonates with the notion that gully activities increase with amount of rainfall (e.g. Vanmaercke et al., 2016; Zegeye et al., 2016; Karimov et al., 2014; Ehiz and Omougbo, 2013; Essien and Okon, 2011) due to slaking of soil aggregates upon wetting (Barzegar et al., 1996) and the resultantly higher surface flow volumes which offer greater traction for the loosen soil materials. The significant positive loading of gully volume, MAP and MAT on PC1 (29% of variation) support the view that gully volume is higher in tropical environments, with high MAP and MAT, especially on sandy soils with high bulk densities, which also loaded positively on this PC. However, most studies observing such positive correlations used short-term data from selected localities. For example, Ehiz and Omougbo (2013) concluded, from their evaluation of factors responsible for gully development at the University of Benin, Nigeria, that high precipitation was one of the main drivers of gully development. Karimov et al. (2014) detected greater gully headcut propagation under saturated soil conditions of a three-day storm.

However, results of this study contradict with results from some studies (e.g. Manyevere et al., 2016; Lado and Ben-Hur, 2004; Six et al., 2000) who reported on negative correlations between precipitation and soil erosion. Manyevere et al. (2016), who elucidated soil and slope factors as erosion controlling variables under varying climatic conditions in the Eastern Cape, South Africa, reported that gullying decreased with precipitation and they argued that greater pedo-genesis in the higher precipitation zone gave the soils greater stability due to prevalence of metal oxides and kaolinite clays. The metal oxides and kaolinite clays result from the breakdown of primary smectites and micas. Six et al. (2000) also explained that soils richer in kaolinite clays were more stable because the clay particles attract each other through electrostatic edge-to-face interactions. The positive correlations between altitude (Z) and gully parameters, except width-to-depth ratios and top view area, (Table 3.6, Figure 3.10) are supportive of this notion because annual soil moisture state tends to increase with Z. Low Z areas, generally characterised by low and erratic rainfalls, are dominated by young soils of low stability (Schoonover and Crim, 2015). In contrast, high Z soils tend to be more stable due to greater degree of weathering which give rise to higher levels metal oxides and kaolinite clays in the soils.

The negative correlations between climatic factors (MAP and MAT) and gully variables, such as depth and cross-sectional area (Table 3.6, Figure 3.10), was rather surprising because the same factors correlated positively with gully volume (Table 3.6). This was in agreement with results of PCA where gully width and area, altitude and slope loaded positively on PC2 (18% of variation) while MAP loaded negatively on the same PC. In support of this relationship were that the positive correlations between latitude and the same gully parameters (i.e. depth and cross-sectional area) as well as gully slope gradient which suggested that tropical (high MAP and MAT) areas, located close to the equator, are underlain by relatively stronger material, which are bound together by metal oxides and organic matter while the temperate zone is underlain by weak and easily eroded (once the top material is removed) saprolite material. In this regard, tropical gullies would be wider and shallower, while temperate gullies tend to be narrower and deeper. Climate and its impact on soil properties also have very important effect on soil cover by vegetation resulting in high soil moisture areas incurring lower soil erosion rates because the soils are protected by dense vegetation, which overrides the impact of rainfall erosivity (Laker, 1990). Vegetation growth also plays an important role in organic matter input into soils, which is a key cementing agent of soil particles and aggregates (Arias et al., 1999).

While these study results can be generalised, caution it still called for there are some exceptions to some of these explanations due to control by local conditions. For example, while low Z areas are generally associated with low annual rainfalls, coastal areas experience uncharacteristically high MAP for low Z areas; as a result they exhibit lower soil erosion rates (due to better soil cover by vegetation) in comparisons to areas inland areas of similar Z. Another caution is that MAT at very high Z may be detrimental to plant growth, and ultimately soil cover, thereby exposing soils to erosive forces. The other exception is that once gullies are initiated, by any means, high rainfall amounts in high MAP zones may act to elongate, deepen and/or widen the gullies, through combinations of linear erosion processes such as gully head and bank undercutting, as well as scouring of the gully bed, to uncharacteristic magnitudes. Also, while soil compaction (presumably by rain drop impact) was reported to improve soil cohesion and shear strength (El Maaoui et al., 2012; Valentin et al., 2005), many other studies have reported severe gullying on compacted soils across the world e.g. Spain (Martinez-Casasnovas et al., 2003; Poesen and Vendekerckhove, 2004), South Africa (Kakembo and Rowntree, 2003), the Sahel (Descloitres et al., 2003) and New South Wales (Erskine et al., 2002). Prasad and Römkens (2004) also observed that gully heads tend to start in cracks on compacted soil surfaces.

3.5.2 The impact of catchment area and slope gradient on gully variables

The increase of gully dimensions, except gully channel slope gradient, with gully drainage catchment area (CA) (Table 3.6, Figure 3.10) can be linked to increasing total amount of surface runoff generated with increasing catchment size. It is important to note that, unlike unit-area runoff which decreases with catchment scale (Mutema et al., 2015a), the total flow in a channel tends to increase with CA provided connectivity of the flow is not hindered. Greater surface flows tend to be more erosive and have greater traction. On the other hand, greater CAs tends to be flatter with longer slopes, which promote longer and wider gullies. The spread of surface flow over wider areas results in shallower depths. Catchment slope gradient (CS) is also an important factor influencing surface flow generation and soil erosion. Under the same rainfall, soil cover by vegetation and other environmental conditions, soil erosion tends to increase with CS in areas were the soil is not cemented together by sesquioxides or organic matter (Zhang et al., 2015; Janeau et al., 2003) because steeper CS generates higher surface flow volumes with greater capacity to transport sediments. Our results show that gullies tends to get deeper and steep with increasing CS; however, Qing-quan et al. (2001) pointed that gully parameters only increase with CS up to a critical CS. For instance, steeper CS tends to associate with shorter slopes and this might explain the observed negative correlations between CS and gully length (Table 3.6, Figure 3.10) because gully length depends on the available slope length (Valentin et al., 2005). Therefore, the positive CS-gully depth correlation may be indicative of pressures on soil resources at global scale where human activities are encroaching marginal lands on mountain sides (Odada et al, 2006). However, very steep slopes may not yet be as intensely invaded by humans and this might explain the general decrease of gully dimensions from moderate to steep CS shown by box-plots (Figure 3.5).

3.5.3 The impact of top soil bulk density and texture on gully variables

Although soil texture and compaction are widely regarded the main controlling factors of soil bulk density (BD), it was not possible to decipher the main drivers of inter-site BD differences due to data scarcity. The change of BD, in our study, was still attributed to compaction and change in soil texture which means greater BD was associated with compaction, which promote greater surface runoff generation (Adedji et al., 2013) and/or higher proportion of coarse soil particles (Chaudhari et al., 2013) which weaken soil stability. This view was supported by the results of PCA where W:D, silt and latitude loaded positively on PC3 (11% of variation) while sand, altitude and slope loaded negatively on this PC. Greater surface flows were envisaged to result in greater soil erosion rates (Morgan, 1996). The positive correlation between BD and gully depth, A_C and GS (Table 3.6) suggests an overall increase of BD with soil depths across the study sites with the result that gullies tended to be deeper and narrower giving rise to the negative BD-A correlation (Table 3.6). The foregoing assumptions appear to be true sand content also correlated positively with the same gully variables as BD (Table 3.6, Figure 3.10). Clay and silt content appeared to influence gully variables in the same way, but clay had greater effect on A while silt was more influential on A_C and GS. It was not clear why clay content did not show much effect on the gully parameters because it is generally regarded an important aggregating factor in the soils (Amézketa, 1999). Its effect is dependent on its mineralogy and smectite is generally expected to be more efficient in soil aggregation because of its large specific surface area and high CEC, and consequently high physiochemical interaction capacity.

3.5.4 The impact of land use on gully dimensions

Vegetation dynamics are a key factor influencing catchment hydrology (Nunes et al., 2011); however, it was difficult to assess the impact of land use/land cover change on the gully dimensions because of limited data availability (Figure 3.9). Never-the-less, the general increase of gully volume from forests to grasslands (Figure 3.9a) was anticipated because this change represented while forests are generally left undisturbed for years, grasslands are often exposed to overgrazing which exposes them to severe erosion processes. The forests also exhibited the shallowest gully depths (Figure 3.9d) suggesting that trees are quite effective in holding soils together, especially using their roots (Archibold et al, 2003; Billi and Dramis, 2003; Morgan and Rickson, 1995; Habib et al., 1990; Pojasok and Kay, 1990; Graf, 1979). Gullies are initiated through many different means which natural systems may not withstand (Stokes et al., 2009), but high root density in forests often keep proliferation of the gullies under better control as compared to ecosystems devoid of trees. Croplands and settlements represent land uses where natural vegetation is normally removed and the soils are disturbed (by humans through), for example, during cultivation (Valetin, 2004; Kakembo and

Rowntree, 2003), installation of hydraulic structures and vehicle tracks (Bruijnzeel, 2004). In addition to generally poorer soil cover as compared to forests and grasslands, soil disturbance in croplands promotes greater erosion rates evidenced by greater gully depth (Figure 3.9d) and top view area (Figure 3.9f). However, gully top view area in croplands was not significantly greater than in grasslands. Cultivation breaks down soil aggregates and exposes soil organic matter (a binding agent of soil particles and aggregates) to rapid oxidation (Valentin et al., 2004), which ultimately reduces soil stability. Cultivation on susceptible soils without adequate soil erosion control measures has also been reported to be a key cause of gully development on croplands (Kakembo and Rowntree, 2003). Hydraulic structures and vehicle tracks in croplands and settlements trigger and accelerate gully erosion because they tend to direct surface flow to places not originally under concentrated flows (Adedji et al., 2013). Development of irrigation channels has also been reported to promote gully erosion in some environments (Vanacker et al., 2003; Nyssen et al., 2004b; Poesen and Vandekerckhove, 2004). Further increase of gully dimensions from croplands to settlements can largely be attributed to increased soil compaction and paved areas, as well as buildings, which uncharacteristically high surface flow volumes (Adedji et al, 2013).

3.5.5 Knowledge gaps and recommendations

The current study showed that numerous studies have, over the past decades, quantified gully dimensions in different environments, soil conditions, climates and land uses as means for quantifying erosion rates, topographic thresholds for gully initiation and gully head-cut retreats. Such information provided an opportunity for elucidating main controls of gully dimensions and morphology as a first step towards better understanding of gullying processes at global and continental scales. While the results indicate that climate, as influenced by site location and altitude, tended to have dominant effects due to its impact on weathering and plant growth, some important research gaps in the understanding of gully erosion, which can become potential topics for further research, were revealed.

Firstly, the analysis compiled measurements on gully dimensions from 435 individual gully channels worldwide which, arguably, represent an important data set, but additional data and analysis is certainly needed to further improve the understanding of, for instance, the impact of climate, land use and/or land use change, and soil mineralogy. Also, the analysis showed larger gullies in the inter-tropical zone, but information on the different sub-climates and especially the number of dry seasons, their duration, the maximum rainfall amounts and/or intensity, to further the identification of gully morphology and the associated mechanisms of gully formation and evolution was lacking. Moreover, land use and land use change have a tremendous influence on gullying and gully dimensions, but the available measurements were not informative on the impact of rehabilitation measures such as installation of gabions and stone checks perpendicular to gullies, or of measures that improve soil infiltration or soil resistance to sheering upslope gully head cuts. Currently, little is known about their long-term effectiveness in different environments to improve selection of best gully rehabilitation measures.

Secondly, while some trends on gully morphology were observed such as the presence of shorter but narrow gullies under dense and clayey soil conditions and steep slopes, and the presence of short, deep and wide structures under sandy soil conditions, there was a large unexplained variability in the factors controlling gully dimensions, which was probably due to unexplored factors such as presence of land rehabilitation measures and gully erosion control measures (Frankl et al. 2013), resistance or permeability due to lateral and vertical change of soil textural classes, soil crusting (Munoz-Robles et al, 2010; Hessel and van Asch, 2003; Hessel et al., 2003; Li et al., 2003; 2004; Vanwalleghem, 2004; Vanwalleghem et al.,2005), natural weather events (Lillesand et al., 2014), which are key in governing gully dimensions and were mostly missing in the data source papers. The other aspect missing from the papers was the link to age of gullies since their formation which is critical and should, thus, be systematically investigated and reported. Mechanisms of gully formation (piping *vs* overland flow *vs* mass flow) that can be inferred from in depth analysis of the surface area and mean slope gradient above gully head cuts (Chaplot, 2013) was also missing. Greater quantity of observations integrating a greater number of controlling factors and greatest possible ranges of the ancillary dimensions could enhance our confidence in these trends. An understanding of all these is vital to devise strategies for gully stabilization over long durations.

Therefore, it is recommended that future research focus on further reporting of the controls of gully dimensions and morphology. Without necessarily needing to enhance the publication rate on gully erosion worldwide, scientists should, when publishing their results, report more consistently on not only gully morphology but also on the main controls. This could be relatively easily performed by providing maps of the study sites, showing the location and the size of gullies and by publishing analytical data from limited soil profiles.

3.6 Conclusions

Climate exhibited highly significant effects on gully morphology through its impact on weathering and plant growth, which subsequently affects soil stability. Average gully volume was greatest under tropical conditions, and was 8 and 26 fold greater than under temperate and sub tropical climate respectively. Grasslands tended to have dramatically higher gully size than natural forests ecosystems. This better knowledge on variability of gully dimensions and the main controlling factors, generated by this study, is expected to help land managers with better understanding of how to improve protection of land resources, especially where land use changes from natural systems to croplands and/or from forests to grasslands are planned. Indeed, the understanding of gully controlling factors is a prerequisite to gully erosion control. While the study elucidated the quantitative effects of selected controlling factors, more research integrating a wider range of controlling factors for example texture is important as sandy soils are prone to gully initiation and development like land use change which can trigger gully initiation and development. Investigation is still recommended for more in-depth understanding of the drivers of gully morphology at a global scale and for improving gully erosion models.

CHAPTER 4 : THE IMPACT OF GULLY REHABILITATION USING GABIONS ON SEDIMENT AND CARBON RETENTION: A STUDY FROM A SMALL-HOLDER AREA IN THE DRAKENSBERG

4.1 Introduction

Gullying is a critical soil erosion concern worldwide because it degrades land productivity through, for example, restricting accessibility. It also contributes to siltation of water bodies and severe impairment of terrestrially stored water quality. It is often associated with steep sloping lands (Wald and Allen 2007). However, gully erosion also occurs on soils subjected to crusting, such as sandy soils (Valentine et al., 2005), and soils prone to piping and tunnelling, such as dispersive soils (Valentine et al., 2005). Both natural and anthropogenic phenomena such as extreme climatic events and land use change are common triggers and/or accelerate gully erosion. Most gullies are formed by surface runoff concentration and flow at velocities sufficiently high to detach and transport soil particles (Morgan, 2009). However, piping is also important for gully initiation is some environments (Moges and Holden, 2008).
In general, soil erosion plays an important role in the global carbon (C) cycle (Berhe et al., 2007; Van Oost et al., 2008). Soil erosion has been associated with low C sequestration and excessive land degradation (Lal, 2005). Several studies have shown that soil deposition can act as a C sink (Harden et al., 2008; Van Oost et al., 2008; Campbell, 2009) $^{-1}$ globally (Stallard, 1998; Smith et al., 2001; Berhe et al., 2007), which is important in mitigating global warming. Several investigations on OC cycling in the Yellow River basin, China, showed that most of the OC is transported in particulate forms (e.g. Zhang et al., 1992; Cauwet and Mackenzie, 1993; Gan et al., 1983), thus making it prone to re-deposition together with sediments if entrapment mechanisms are put in place.
Sediments entrapment can act as a C sink, which helps in reducing CO_2 emissions to the atmosphere. The trapped sediments could contain organic C, which is prevented from travelling further to rivers and other water bodies which will result in dam and river siltation and organic matter can lead to aquatic hypoxia. In this regard, deeply buried sediments can be effective C sinks due to lack of aeration at great soil depths. In addition, trapped sediments also constitute a favourable media for plant growth. Therefore, full rehabilitation focusing on both gully stabilization and dense protective plant cover establishment enhances the C sequestration by sediments (Zhang et al., 2015). The gully rehabilitation methods often focus

on rehydration to ensure maximum amount of rainwater infiltration into the soils and reducing runoff. The "capture and retention" of water is, thus, a primary objective of most gully rehabilitation methods, while the establishment of a soil protecting plant cover is another important one. Physical structures such as check-dams, stone-lines and grass strips, and gabions are used in gully rehabilitation to reduce surface flow velocity and to trap sediments in the gully systems (Nyssen et al., 2009). Even without any artificial gully rehabilitation effort, some sediments naturally collect on the gully floor due to gravity and overland flow during low rainfall events and may initiate the "recovery" process of the gully (Valentine et al 2005) in the absence of subsequent disruptive events.

The dynamics of soil C during sediment detachment, transportation and re-deposition is a complex process requiring a good understanding of the controlling processes (Chaplot, 2005). In particular the carbon found in the trapped sediments may either have an in-situ or ex-situ origin. Part of the carbon can come from the vegetation growing in the sediments after sedimentation occurs, while some of the carbon may come from the surrounding eroded soils. Is the carbon found in the trapped sediments entirely from the original soil or from the vegetation growing in the sediments? There is a need to discriminate the age of carbon in the sediment to determine the sources of carbon. The carbon in the sediments might be of different sources (eg eroded carbon and from the vegetation growing in the sediments). It is vital to determine the age of carbon, assuming that carbon from vegetation in the sediments is younger than the carbon from the surrounding areas. Despite a general understanding that sediments trapped in gullies can be C sources and/or sinks, the impact of gully rehabilitation on C cycling has not been well documented (Ran et al., 2014). Radioactive carbon dating of soil organic matter is very difficult as the soil is a very complex system that has external influences (Pessenda et al 2001). Studies by Campbell et al 1967, Schapenseel et al 1968 and Trumbone 1996 confirmed that carbon in the soil was formed from different sources and was made up of different components and age. There are many problems associated with C14 dating in the soil as contaminates like infiltration of dissolved carbon and micro-organisms tend to affect the Chrono-sequence of carbon deposition in the soil horizons. Thus, the objective of the study was to investigate the effect of slope position and sediment depth in particle size distribution, carbon and nitrogen sequestration after gully rehabilitation with gabions.

4.2 Materials and Methods

4.2.1 Study site description

The study was performed at Okhombe, also known as eMahlabathini (28°42′39″ S, 29°05′39″E) on the foothills of the Drakensberg Mountains (Figure 4.1). The elevation of Okhombe varies between 1000 and 1800 m.a.s.l (Everson et al., 2007) in the Upper Thukela catchment in KwaZulu-Natal province, South Africa. The area receives annual precipitation of 1032.5 mm yr^{-1}, mostly in summer. Air temperature changes considerably with season, with a monthly mean between 11.5°C and 16°C (Mansour et al., 2013). The summer temperatures are moderate, while winters are cold, with frost being common through the coldest winter months of June and July (Everson et al., 2007). Although snow commonly falls on the higher slopes of the Drakensberg Mountains, it is not common at Okhombe.

The main geology of the Drakensberg Mountains area is Sandstone with Basalt on the higher altitudes. Therefore, the soil materials are shale, sandstone, and mudstone in the low lying areas, while basalt-derived silty clays soils prevail on the slopes and plateaus (Everson et al., 2007). Sandstone produces soils that are high in quartz, which also makes them less coherent and prone to erosion. In addition, soils derived from sandstones tend to be of low fertility, which results in poor vegetation growth, hence little to no ground cover to protect the soils from water erosion.

Vegetation of the area is predominantly grassland with some patches of forests and shrubs (Mucina and Rutherford, 2006). The commonest land use is substance farming of summer crops and livestock rearing. Overgrazing by livestock is rampant and the soils are generally left bare during winters. Although the area often receives winter rains, these rainfalls are generally insufficient for grass growth.

Figure 4:1 Map showing the study site where the gully under rehabilitation is located

Large parts of the study area were severely degraded with evidence of vegetation cover losses, high surface run-off, poor water infiltration and severe soil erosion (Everson et al., 2007). Gullies are prevalent at Okhombe and are being rehabilitated by the local community, with technical assistance from some researchers. Physical (gabions) and vegetative (e.g. planting of Kikuyu and vertiver grass) methods were in use at the time in the current study (Figure 4.2). Rehabilitation of the gullies started in 2000 and soil sampling for the current analysis was performed on 24 and 25 March 2016.

Figure 4:2 Picture-combo showing different views of the gully at Okhombe in South Africa

4.2.2 Soil sampling procedures

Soil samples were collected from the sediments trapped in the gully (sediments) and adjacent bulk soils from outside the gully (soil). Three positions were selected for sampling on the channel bed, i.e. the upper, mid and lower slope positions. Samples for analysis of carbon and nitrogen content (Cc and Nc, respectively), as well as particle size distribution, were collected using augers at 6 depth intervals of; 0-5, 5-15, 15-30, 30-60, 60-90 and 90-120 cm. Further drilling was performed on the channel bed to estimate the depth of sediments. However, drilling could not go beyond the 90-120 cm level at some points in the mid and upslope positions due to solid bedrock material while the lower slope was 2.2m deep. Three sampling were used points at each slope position. The samples were air dried and sieved through a 2 mm sieve. Analysis was done as soon as was possible after sieving.

Undisturbed soil samples were also collected close to the auger sampling points for bulk density determination. A hand operated core sampler (223.64 cm^3) was used to collect the undisturbed soil samples from 6 depth levels, i.e. 0-5, 5-15, 15-30, 30-60, 60-90, and 90-120 cm from an edge of an open pit. The soil surface was first cleared off any loose material to create a level surface. The core sampler was placed on the level surface and driven into the soil gently to minimise disturbances. The sampler was carefully removed and trimmed on both ends, and the samples placed in clearly marked self- sealing plastic pockets. Three replicates were taken from each depth. Once at the laboratory, each sample was oven dried at 105°C until constant weights were attained and then weighed. The soil bulk density of each sample was computed by dividing the oven dry sample weight by the sampling core volume (Blake, 1965).

4.2.3 Determination of total C and N content

A portion of each air dried soil sample was ground into a fine powder and then 0.2 g of the ground soil were analysed for total C and N using a LECO TruMac CNS analyser (LECO Corporation, 2012). The machine works by combustion at 1250 °C for about 6 minutes and then estimating total C and N content automatically as % of the soil sample mass. The total carbon in the soil was assumed to be equivalent to organic carbon as there were no carbonates in the soil. The SOC and N stocks for each sample were subsequently calculated using equation 1, an adapted version of the Batjes (1996) equation, because coarse fragments >2 mm were absent following grinding and sieving procedures.

$$S = X_1 * X_2 * X_3 * b \qquad (1)$$

Where S is the C or N stock (kg m^{-2}); X_1 is the C or N concentration in the soil sample (g kg^{-1}); X_2 is the soil bulk density (kg m^{-3}); X_3 is the thickness of the soil layer (m); and b is a constant equal to 0.001 which is used to convert g/m^2 to kg/m^2.

4.2.4 Soil particle size distribution

Particle-size analysis of the air dried samples was done using a combination of the hydrometer (Walter et al., 1978) and dry sieving methods. The hydrometer method was performed after dispersing weighed 50 g portions of the soil samples using Calgon solution prepared by mixing 35.7g sodium hexametaphosphate ($(NaPO_3)_6$) and 7.9g sodium carbonate (Na_2CO_3) in de-ionized water to make 1 litre. Each 50 g soil sample was placed in a 100 ml metal dispersion cup and 50 ml of the calgon solution added to the (metal milkshake) dispersion cup. The dispersion cup was put on the milkshake mixer, and stirred for 5 minutes (at 300 revolutions per minute).

The soil suspension was transferred to a sedimentation cylinder and distilled water was added to make 1 Litre. Temperature reading of the suspension was taken. A plunger was used to stir the suspension for 2 minutes by moving it up and down through the cylinder (40 plunges). Immediately after removing the plunger, a timer was started and a hydrometer gently inserted into the suspension. Hydrometer readings were taken 40 seconds after insertion and again after 7 hours. These hydrometer readings were used to calculate particle size distribution and compared against blank hydrometer readings. The blank hydrometer readings were determined by running hydrometer tests of water-Calgon solutions without soil.

Soil fractions coarser than 0.053 mm were transferred from each cylinder into a 250 ml beaker and oven dried overnight at 105°C. A weighed amount of each oven dried sand sample was transferred onto a nest of sieves, whose individual weights were predetermined, in the apertures 0.500, 0.250, 0.106 mm and a pan. Each nest of sieves (with soil) was shaken for 3 minutes (at 40 shakes per minute). The weight of each sieve and pan plus soil fractions was then determined and recorded. Soil sample moisture correction was performed by oven drying 10g of each air dried soil sample at 105°C for 24 hours in order to remove any remaining moisture from the soil. The samples were left to cool in a desiccator before being reweighed to determine the new weight of solids (without moisture).

4.2.5 Quantification of sediments and C trapped in the gully

Figure 4.2 shows different views of the gully and typical gabions used to trap sediments at the time of the current evaluation. Top width of the gully was measured on 44 locations along both banks at 2 m intervals. Channel bed width was also measured on the sediments, at the same intervals as the top width. Remaining depth of the gully was measured on both banks of the gully at intervals similar to top and channel bed width measurements. Gully length was measured along both banks, from the topmost to the lower-most position. Sediment depths had already been estimated by drilling holes using soil augers along the channel bed until hard material was reached. Average values were computed for the gully width, depth and length. Remaining gully volume was calculated assuming the geometry of the unfilled space was trapezoidal in cross-sectional shape. Sediment storage volume and mass were estimated using Equations 2 and 3, assuming the gully cross-sectional area to be triangular shaped.

$$V_{Sed} = ½b * h \quad (2)$$

$$M_{Sed} = V_{Sed} \times BD_{Sed} \quad (3)$$

Where V_{Sed}=volume of sediments (m3); b=average channel bed width (m); h=average depth of the sediments (m); M_{Sed}=mass of sediments (kg); BD_{Sed}=average bulk density of the sediments (kg m^{-3}). It is appreciated that gullies rarely take regular geometric shapes and the above equations certainly under or over-estimate the actual values. Amounts of C and N stored in the soil were calculated by multiplying the sediment mass by the respective average content (i.e. overall mean Cc and Nc), Cc is the carbon content while Nc is the nitrogen content

Amount of sediments trapped by gabions in the gully under rehabilitation was estimated in volumetric terms as a product of cross sectional area (half average width of the gully multiplied by the average depth) and length of the gully (Table 4.5). This volume was multiplied by the bulk density of the sediments to estimate the mass of the sediments stored in the gully. The total carbon stocks in the sediments were quantified by calculating the average carbon concentration of the sediments by the estimated mass.

4.2.6 Radiocarbon dating

The ^{14}C activity was determined at the Institute of Research for Development | IRD · 182 - Laboratory of Oceanography and Climate: Experiments and numerical Approaches (LOCEAN) in Paris, France. The radiocarbon dating analyses used the < 20 µm fraction obtained after physico-chemical. CO_2 was obtained from combustion of the solid soil samples at 900 °C and was reduced to graphite using H_2 over a iron catalyst. The CO_2 was subsequently analysed by accelerator mass spectrometry (AMS) following Nadeau et al. (1997). A sequential acid-alkaline-acid extraction was used to obtain the humin fraction which was used for the $^{14}C/^{12}C$ isotopic determination to calculate the age. The measured ^{14}C activity was corrected for $\delta^{13}C$ isotope fractionation and was expressed in percent modern carbon (pMC). Radiocarbon ages in years before present (yr BP), were calculated from the $F^{14}C$ and Libby mean life of radiocarbon (8033 yr) using the following equation:

Radio carbon age (yrBP) $= -8033 \ln (F\ 14C)$ (4)

4.2.7 Potential sediment and carbon accumulation in the gully

The total sediments in the gully were calculated by measuring the average sediments depth, width and length to get the volume, while the mass of the sediments was calculated by multiplying the sediments bulk density with the sediments volume. The average rate of sedimentation in the gully was calculated by dividing the total sediment mass by the number of rehabilitation years. The gully potential to store sediments was calculated by measuring the empty space above the trapped sediments to the surface of the gully.

4.2.8 Data analyses

Analysis of variance (ANOVA) was performed to evaluate the impact of slope position and soil depth on the physical-chemical properties (Table 4.4) using GenStat (version 12.1) statistical software. The least significance difference was tested using the Tukey-Kramer test at $p<0.05$.

4.3 Results

4.3.1 Summary of ANOVA results for soil and sediment physico-chemical properties

Table 4.1 shows the ANOVA results on the evaluation of the effects of slope position (Slope) and depth level (Depth), and their interaction (Slope*Depth), on the physical and chemical properties of the sediments trapped in the gully under rehabilitation and bulk soils from outside the gully. The slope *depth interaction effects were only significant ($p < 0.05$) for the bulk density and C/N of the sediments, while for the adjacent soil bulk density and fine and medium sand were also significantly affected. Besides Cs and Ns, FS, C:N ratio and CS, all other parameters of the sediments were significantly affected by slope position but not depth. The sampling depth significantly affected BD, C:N ratio Cs and Ns of the sediments trapped in the gully under rehabilitation. For the adjacent soil (bulk soil), all other parameters were not affected by either depth or slope, except Cs and Ns, which were only affected by depth.

Table 2.1 General summary of measure analysis of variance for soil properties bulk density, carbon and nitrogen content, and C/N ratio of sediments collected in the gully (Sediments) and soils from outside the gully (Soil)

Factor	**Cc**	**Nc**	**Cs**	**Ns**	**C/N**	**BD**	**Clay**	**Silt**	**Sand**	**FS**	**MS**	**CS**
Sediments												
Slope	**	*	ns	ns	ns	**	***	*	**	ns	*	ns
Depth	ns	ns	***	***	*	***	ns	ns	ns	ns	ns	ns
Slope*Depth	ns	ns	ns	ns	*	*	ns	ns	ns	ns	ns	ns
Soil												
Slope	ns	ns	ns	ns	ns	**	ns	ns	ns	**	***	ns
Depth	ns	ns	***	***	ns	***	ns	ns	ns	*	**	ns
Slope*Depth	ns	ns	ns	ns	ns	***	ns	ns	ns	*	**	ns

Level at which factor had significant effect * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$;
ns: not significant ; Cc and Nc: carbon and nitrogen concentration (%); C/N: carbon: nitrogen ratio; BD: bulk density; FS: fine sand; MS: medium sand; CS: coarse sand; Cs: carbon stocks; Ns: nitrogen stocks

4.3.2 Selected physico-chemical properties of sediment

Sediment particle size distribution

The clay, silt, total sand and medium sand were significantly affected by slope position but not depth. The lower position had higher clay and lower sand than the upslope and midslope (Table 4.2). When compared to the midslope, the lower slope had higher silt content while the sand content decreased from the upper slope to the lower slope.

Sediment carbon and nitrogen concentrations and stocks

The gully sediment carbon content was significantly higher in the lower slope position (0.84%) compared to the mid (0.62%) and upper (0.67%) slopes, which were not differently different from each other. The depth did not affect C content of the sediments, which ranged from 0.61 to 0.80% (Table 4.2). The carbon stock was not affected by slope position (1.94 to

2.37 kg m^{-2}) but increased with depth, with the 0-5, 5-15 and 15-30 cm depths having lower stocks than the deeper layers (30-60, 60-90 and 90-120 cm) (Table 4.2). Similarly to C content, sediment N content was higher in the lower slope than in the mid slope (Table 4.2), while there was no significant effect of the depth. Also similar to C stock, sediment N stock was not affected by slope position but increased with depth, where the 0-5, 5-15 and 15-30 cm depths having lower stocks than deeper layers.

Table 4.2 Selected physico-chemical properties of the sediments as affected by depth and slope position.

Factor	Cc(%)	Nc(%)	Cs	Ns	Clay	Silt	Sand	FS	MS	CS
Sediments										
Upslope	0.67a	0.06ab	2.24	0.19	15.31a	19.84ab	58.32b	63.4	31.5a	5.06
Midslope	0.62a	0.06a	1.94	0.18	17.57a	18.71a	57.75b	56.4	39.6b	3.92
Lower slope	0.84b	0.07b	2.37	0.21	21.20b	22.90b	50.82a	63.4	63.4ab	3.88
Depth (cm)										
0-5	0.79	0.07	0.55a	0.05a	17.23	21.54	57.58	59.2	35.9	5.10
5-15	0.69	0.07	1.05a	0.10a	18.14	22.00	56.06	58.6	37.7	3.85
15-30	0.64	0.06	1.42a	0.13a	19.50	17.46	56.13	61.6	34.2	3.90
30-60	0.74	0.06	3.42b	0.27b	18.37	21.32	54.33	61.0	35.5	3.47
60-90	0.80	0.07	3.76b	0.32b	17.46	20.41	54.23	63.4	31.7	4.84
90-120	0.61	0.06	2.92b	0.29b	17.46	20.18	55.24	62.3	32.9	4.54

Levels of statistical significance *= $p < 0.05$; **=$p < 0.01$; *** $p < 0.001$; ns: not significant
Cc and Nc: carbon and nitrogen concentration (%); C/N: carbon: nitrogen ratio; BD: bulk density; FS: fine sand; MS: medium sand; CS: coarse sand

Bulk density and C/N

The interaction effects of slope position and depth was significant on soil bulk density and C/N (p <0.05) (Table 4.3). The bulk density in the 90-120 cm depth on the upslope position was higher than that of the 5-15 cm depth on the same slope position, 0-5 cm depth of the midslope and 0-5 and 15-30 cm depth of the lower slope position. The bulk density of the 60-90 cm depth on the upslope was also higher than that of the 0-5 cm depth on the midslope and lower slope positions. The C/N ratio of the sediments in the 30-60cm depth on the lower slope was higher than the 5-15 and 15-30 cm depth on the midslope and 0-5, 5-15 and 90-120 cm depth on the lower slope position (Table 4.3).

Selected physico-chemical properties of bulk soil outside the gully

Soil particle size distribution

There were no significant effects of slope position and depth on clay, silt, total sand and coarse sand contents of the soil (Table 4.4). However, interaction effects of slope position and depth were significant for silt and fine sand (Table 4.5).

Soil carbon and nitrogen concentrations and stocks

The C and N contents, and the C/N of the soil, were not significantly affected by slope position or by depth (i.e., they were the same levels across all depths and slope positions) (Table 4.4). The C and N stocks were not affected by slope position but increased with depth, with the 0-5, 5-15 and 15-30 cm depths having higher stocks than the deeper layers (30-60, 60-90 and 90-120 cm) (Table 4.4).

Table 4.3 Bulk density (g cm^{-1}) and C/N ratio of gully sediments as affected by slope and depth.

Depth (cm)	**Upslope**	**Mid slope**	**Lower slope**
Bulk density			
0-5	1.55abcd	1.38ab	1.31a
5-15	1.47abc	1.51abcd	1.57abcd
15-30	1.51abcd	1.57abcd	1.45abc
30-60	1.59bcd	1.47abcd	1.57abcd
60-90	1.66cd	1.50abcd	1.53abcd
90-120	1.74d	1.59bcd	1.56abcd
C/N			
0-5	12.36ab	10.10ab	9.95a
5-15	11.01ab	9.69a	9.26a
15-30	10.33ab	9.97a	10.08ab
30-60	12.14ab	10.10ab	14.34b
60-90	10.46ab	11.07ab	12.27ab
90-120	10.45ab	10.98ab	8.83a

Table 4.4 Selected physico-chemical properties of the bulk soil as affected by depth and slope position.

Factor	**Cc(%)**	**Nc(%)**	**Cs**	**Ns**	**C/N**	**Clay**	**Silt**	**Sand**	**CS**

Slope									
Upslope	0.68	0.06	2.01	0.17	11.07	22.22	18.74	52.35	3.95
Midslope	0.74	0.07	2.07	0.19	11.01	25.26	17.55	51.96	4.57
Lower slope	0.84	0.07	2.21	0.21	11.11	26.76	18.82	48.96	4.48
Depth (cm)									
0-5	0.93	0.08	0.66a	0.06a	10.85	24.94	17.01	51.30	4.17
5-15	0.88	0.08	1.28a	0.12a	11.24	24.04	17.44	54.08	5.12
15-30	0.69	0.06	1.43a	0.13a	11.40	23.81	18.82	52.23	6.35
30-60	0.64	0.06	2.94b	0.27b	10.45	25.62	16.53	52.67	3.42
60-90	0.76	0.07	3.39b	0.30b	11.75	24.72	19.27	49.92	2.83
90-120	0.63	0.06	2.88b	0.26b	10.68	26.76	21.15	46.36	4.30

Soil bulk density

The interaction effects of slope position and depth was significant on soil bulk density, medium and fine sand ($P < 0.05$). Bulk density of the soil significantly changed with soil depth only for the midslope, where the 0-5 and 15-30 cm depth had lower density than the 30-60, 60-90 and 90-120 cm depths. For the 30-60 cm depth and deeper layers bulk density was not significantly different across the slopes (Table 4.5). The 15-30 cm depth on the midslope had lower density than all depths of the upslope (except the 5-15 cm) and lower slope. The 90-120 cm depth on the upslope had higher bulk density than the 0-5 and 15-30 cm depth on the midslope.

Medium and fine sand of soil

There were no depth effects on fine and medium sand fractions of the midslope and the upslope positions (Table 4.5). The 30-60 cm depth of the upslope had higher medium sand and lower fine sand than that of the 5-15 and 90-120 cm on the upslope, all depths of the midslope, and the 60-90cm depth on the lower slope (Table 4.5).

Table 4.5 Bulk density (g cm-1) fine sand and medium sand from adjacent soil as affected by slope and depth

Factor Soil	Upslope	Mid slope	Lower slope
Bulk density			
0-5	1.51bc	1.34ab	1.46bc
5-15	1.41abc	1.40abc	1.53bc
15-30	1.44bc	1.23a	1.48bc

30-60	1.50bc	1.56c	1.50bc
60-90	1.46bc	1.45bc	1.50bc
90-120	1.58c	1.54bc	1.43bc
Fine sand			
0-5	59.28ab	67.83ab	67.97ab
5-15	72.99b	71.04ab	63.24ab
15-30	63.21ab	64.75ab	62.06ab
30-60	51.38a	74.86b	57.54ab
60-90	61.67ab	76.73b	70.1ab
90-120	76.5b	73.94b	65.29ab
Medium sand			
0-5	35.93ab	27.37a	29.1ab
5-15	21.68a	24.4a	31.29ab
15-30	31.07ab	27.29a	32.55ab
30-60	46.63b	21a	38.33ab
60-90	35.93ab	20.52a	26.56a
90-120	20.01a	22.85a	28.5ab

4.3.4 Age of carbon in the soil and sediments

A complementary investigation showed that C in the sediments was much younger (645±30 years) than soil C (1665±30 years) for the 0-5 cm depth. The C in the 0-5 cm depth of the soil was also younger than at 60-90 cm depth (16400±100 years) (Table 4.6).

Table 4.6 Comparison of 14C in soil organic matter age sampled in the soil outside the gully and sediments inside a rehabilitated gully

Sample	Depth (m)	Age (years BP)
Topsoil	0 - 0.05	1665±30
Subsoil	0.6 - 0.9	16400±100
Sediments	0 - 0.05	645±30

4.3.5 Sediment and Carbon accumulation in the rehabilitated gully

Although the rate at which the gully is developing was not ascertained, the calculated total volume of the gully at the time of this study was almost 1248 m^3 (Table 4.7). Out of this volume, 453 m^3 was already filled up with sediments to leave 795 m^3 available if the rehabilitation process continues. The estimated mass of the sediments already trapped was 689 tons, while the C and N stocks stored were 5107 and 551 kg, respectively.

Table 4.7 Mass and volume of trapped sediments and potential gully storage volume

	--------------------------Current------------------------				-------------------------Potential------------------------				---------------------------Total---------------------------			
	V_{Sed}	M_{Sed}	M_C	M_N	V_{rem}	M_{Sed}	M_C	M_N	V_{tot}	M_{Sed}	M_C	M_N
Upper	102	161875	1085	113	105	166641	1117	117	207	328516	2201	230
Mid	122	182687	1133	129	275	412133	2555	288	397	594821	3688	416
Lower	229	343980	2889	310	415	622440	5229	560	644	966420	8118	870
Total	***453***	***688542***	***5107***	***551***	***795***	***1201215***	***8900***	***965***	***1248***	***1889756***	***14007***	***1516***

V_{Sed} =volume of sediments already trapped (m^3); V_{rem} =volume of empty space above the sediments (m^3); V_{tot} =total gully volume (V_{Sed}+V_{rem}, m^3); M_{Sed} =mass of sediments (kg); M_C= mass of carbon (kg); M_N=mass of nitrogen (kg)

4.4 Discussion

The results of this work show that the use of gabions and grass could make a significant contribution in trapping eroded sediments and organic matter and this is confirmed by Rey (2009) in a study in France. Assuming that all processes and factors remain constant, the 1247 m^3 gully space is expected to hold 1890 tons in sediments when the gully is eventually filled up. This translates to total C and N storage of 14 and 1.5 tons, respectively, assuming no losses occur (gaseous losses). Given that the rehabilitation process had been going on for about 15 years, it suggests that the sediment entrapment rate was 46 t yr^{-1}. The rates of C and N accumulation in the gully were, therefore, estimated to be 340 and 37 kg yr^{-1}, respectively. On the basis of these estimations and all processes and efforts remaining the same, the remaining gully space was anticipated to fill up in the next 261years and by that time would be storing about 8.9 and 1.0 t more C and N, respectively.

The higher content of sand and lower silt and clay in the sediments upslope than down slope could be in response to gabions and grass, resulting in rapid settling of heavier materials (sand) than lighter material (clay and organic) (Moss et al 1979). The gabions upslope reduced the velocity of the water resulting in settling of the heavier sand particles, leaving silt and clay in the suspension. As the suspension passed through increasing number of gabions the velocity decreased further, resulting in settling of lighter materials. This view was further supported by the results of C in the sediments, which was lower upslope than down slope.

While there were differences in particle size distribution of the sediments between slope positions, these differences were not significant for the soils adjacent to the gully, indicating that the soils were formed from insitu weathering of the same parent material (Daniel et al, 1987), while the sediments were a result of sorting of the eroded particles in response to the gabions (Allan and Castillo, 2007). The higher medium sand and lower fine sand fraction in the 30-60 cm than the 5-15 and 90-120 cm of the soil on the upslope, suggests that this layer (30-60 cm) could have been at the initial stages of the formation of an E-horizon (Dumanski and Arnaud 1966).

The similarity on the trends of C and N suggests that the N in the sediments was in organic form (Ruttenburg and Goni, 1997). The lack of depth effect on particle size distribution and concentrations of C and N of the sediments shows that the sediments were relatively young and still developing, and as such the particles did not undergo enough vertical sorting to result in sufficient differentiation of the layers (Soil classification working group of South Africa 1991). The higher sediment C/N in the 30-60 cm depth of the lower slope position than shallower depths of the midslope and lower slope and the 90-120 cm depth of the lower slope suggests deposition of organic matter of different stabilities to microbial degradation. However, all the C/N ratios were lower than the critical 25:1 (Barbhuiya et al 2004) and as such, are not likely to limit decomposition.

A complementary investigation showed that sediment C was much younger (645±30) than soil carbon (1665±30 and16400±100) years for the 0-5 and 60-90 cm horizons respectively (Table 4.9). Assuming that sheet erosion only affects the top soil and that linear erosion affects the entire soil profile, these two mechanisms will contribute equally to gully sediments (following Chaplot., 2013 and Dlamini., 2011 at an neighbouring site), the average age of the sediment C entering the gullies would be 9032±75 years (9032±75 = (1665±30+16400±100)/2). Since the age of carbon in sediments is lower (645±300 years) than the two likely sources, a third carbon source for the carbon is stored in sediments by plants colonizing them. The average proportions of sediment C coming from eroded soils will be 7.1% vs 92.8% for the in situ carbon plant allocation. However, it is necessary to state that determining the actual age of the carbon in the soil is difficult as new C and other C from different sources tend to mix to create a composite sample (Wang et al 1996). The assumption is that the carbon in the sediments is from more than one source.

The generally higher C stocks in the sediments can be attributed to better vegetation in the gully because the trapped sediments provided a better plant growth medium with regard to deeper sediment depth and higher moisture. There was good vegetation growth behind the gabions. The vegetation was planted to complement the gabions in the rehabilitation of the gully (Garzon-Garcia et al., 2014). Carbon in the gully was of much younger age suggests that sediment C was not derived from outside the gully. The age of the soil organic matter from the 0-5cm is 1665 years which is younger than the 60-90 cm which is 16 400 years. This is because of the newly established organic matter that is on the surface and in deeper horizons organic matter is protected by aggregates from decay which makes them remain longer on the soil (Buurman and Jongmans., 2005). The young carbon on the sediments is from newly established vegetation on the sediments that is why it younger than the surrounding soils. If it was eroded from the adjacent areas it would have a similar carbon age as the adjacent areas. There is a possibility most of the carbon from the adjacent areas is transported out of the trapped sediments and the greater contribution of carbon is from new vegetation that grows on the sediments (Li et al., 2014). In a study by Pessenda et al (2001) the results showed that the shallow horizons were highly affected by the input of carbon from the plant matter compared to the deeper horizons. The old stable organic carbon was mostly due to the stable n-alkaline formed organic matter which was not prone to further decomposition, this might have contributed to an older age of carbon (Zhang 2017).

A study by Mutema et al (2017) concluded that in a micro plot the particulate carbon is preferable transported while the dissolved carbon tends to travel a longer distance. Mutema et al (2017) showed that 80% carbon exiting the soil is in particulate form vs 20% in dissolved form. Preferential transportation of C forms by water erosion has been reported extensively (e.g. Lal, 2003; Boegling et al., 2005; Mchunu and Chaplot, 2012; Wang et al., 2013; Zhou et al., 2013). The process of aggregate break down preferential transportation and deposition in gullies, leads to carbon enrichment in the sediments exiting in the gullies as shown in the hill slope (Muller-Nededock et al 2016).

While the assumption that the sediments in the gully were not coming from outside the gully need verification, the pictures in Figure 4.2 show evidence of complex erosion processes that ultimately result in the gully walls collapsing into the gully. Many reasons were proffered for the losses including mineralisation and subsequent C losses in gaseous forms and deposition outside (Nadeu et al., 2012; Hoffman et al., 2013).

The lower bulk density of the sediments in the 0-5 cm depth on the midslope and lowerslope than the 60-90 and 90-120 cm depths of the upslope position could be a result of the sandy texture and compaction due to the over burden on the upslope. Aggregated and porous soil which are usually rich in organic matter have a low bulk density compared to sandy soil that have high bulk density due to less pore spaces in sandy soils compared to clay, organic rich soils (Hillel, 2013). According to Koolen and Kuipers (1983) the bulk density of the soil increased with an increase in sand content. Since there were no slope and/or depth effects on particle size distribution of the soil adjacent to the gully, the higher bulk density on the 90-120 cm depth of the upslope than the 0-5 and the 15-30 cm depth of the midslope could be due to compaction in response to the overburden.

There are inherent factors that tend to affect bulk density which includes clay silt sand and soil organic matter content. Soil high in organic matter tend to be loose and have a relatively low bulk density, while sandy soils have a higher bulk density due to low total pore space in the sand compared to clay and silt. Bulk density tend to increase with depth as there is less organic matter content in the sediments and relative accumulation of sand which is confirmed by the current study. Clay has a direct effect on the bulk density as clayey soils have lower bulk density due to high porosity (Lampurlanes and Cantero-Martinez., 2003). The association of higher C stocks and bulk density, and sand, silt and medium sand fraction content in the sediments in comparison with bulk soils from outside the gully was rather surprising because the ability of soils to store C is mainly controlled by clay content (Doetterl et al., 2015; Schoonover and Crim, 2015). Clay materials help to bind soil C and protect it from decomposition and mineralisation (Six et al., 2000; von Lutzow et al., 2006). The high surface area of clay particles is known to help in chemically stabilising soil organic C by forming stable interactions between the C carbon and the reactive surfaces of clay (Feller and Beare, 1997). It is also generally accepted that soils with relatively higher clay content tends to higher infiltration rate, hence higher water holding capacity that has direct influence on vegetation growth which consequently increases C input in the soil (Dlamini et al 2014). On average the sediments upper slope had higher sand content and low clay content compared to the lower slope which explains the high bulk density in the upper slope and an opposite on the lower slope. Fujisaki et al (2015) confirmed the relationship between bulk density and soil organic matter to be inversely proportional. However, the study site was characterised by steep slope, which promotes high soil runoff generation and, subsequently, erosion rates (Descroix et al., 2001; Arnáeza et al., 2004), hence the shallow soils observed. As such, plant growth was generally poorer outside the gully than in the sediments held behind the gabions, to due water entrapment. Plant materials are the main contributor of organic C in most soil systems (Gleixner, 2013; Pei et al., 2015), while soil erosion, decomposition and mineralization are the main agents of soil C losses (Lal, 2003; Guillaume et al., 2015).

The general increase of topsoil C in the downslope direction in both the sediments and bulk soils from outside the gully gives credence to the notion that deposition tends to increase in that direction (Cammeraat, 2004; Chaplot et al., 2005; Hemelryck, 2010; Nadeu et al., 2012; Mutema et al., 2017). Deposition occurs in depressions and behind vegetation tufts, and is also facilitated by loss of slope gradient. The lower C concentrations in the upper regions of the study site might also be explained by higher mineralization rates of shallowly buried C (Jackman, 1964; Lawrence et al., 2015). The prevalence of bare surfaces at the upper slope position was enough visual evidence that soil erosion was generally higher in that area and any soil accumulated C was bound to be shallowly buried. Soil erodible organic carbon oxidises during erosion, which leads to carbon mineralisation and carbon loss from the soil surface (Schlesinger 1995). Higher carbon content was on the lower slope which is directly proportional to the clay content and the sand content showed an opposing trend. Higher carbon on the lower depths might be due to old plant roots or due to leaching of dissolved carbon to lower horizons (Dosskey and Bertsch 1997).

Soil carbon and nitrogen are generally thought to be positively associated (Crecchio et al., 2001; Deng et al., 2013). However, this result might be explained by the fact that nitrogen is more labile and reactive than carbon (Neff et al., 2002; Jiang et al., 2014). Nitrogen is also highly mobile and subject to high leaching losses to deeper soil horizons under wet conditions (Lamb et al., 2014). Though not reported here, the sediments were evidently wetter than the bulk soils which might have promoted greater vertical migration of nitrogen to deeper horizons in the sediments than bulk soils.

4.5 Conclusions

Selective deposition of fine and coarse sediment in the gully leads to a significant differentiation of sediment properties along pathways as affected by gabions. Heavy coarse material was deposited on the upper slope position, while fine lighter material (clay and organic matter) where dominate on the lower slope and the mid slope was dominated by medium sized material (silt). There was no variation with depth for both the sediments and soil. The carbon and nitrogen followed a similar trend as higher C and N storage occurred on lower slope position than upslope. The gabions managed to trap 5107 kg of sediment carbon and 551 kg of nitrogen. The rehabilitation of the gullies helps to sequester carbon in the gullies as the trapped sediments become a sink for carbon. Further studies should focus on effects of gabions as rehabilitation strategy for gullies formed on different soil types and under different climatic conditions. Other rehabilitation strategies also need to be tested in terms of their effectiveness in storing sediments and C.

CHAPTER 5 CONCLUSIONS

The database on morphological characteristics of 435 permanent gullies across the world showed that gullies tended to be deepest (r=0.33) and steepest (r=0.36) on sandy soils. Grasslands had higher gully volume than forest ecosystems, while change from croplands to settlements resulted in the decrease of gully length, depth, width and area. These quantitative results on factors controlling gully morphology contribute to better understanding of gulling mechanisms, a prerequisite for modelling gully channel formation and for development of mitigation measures under different environmental conditions.

Gully rehabilitation did not only result in sediment yield but also significant carbon storage. Trapped sediments have the ability to store carbon while restoring the gully and reducing land degradation. The ability of the trapped sediment to store carbon helps to reduce atmospheric carbon and sequentially having less impact on global warming. This work has also contributed to improved understanding of carbon sequestration in rehabilitated gullies. It is important to extend this research to investigate other parameters including the most stable form of carbon, other soil physical and chemical properties that promote carbon storage. Identifying both climatic and geomorphological characteristics to prevent and control gully erosion at a broader scale in order to mitigate the effects of erosion at affected areas. In future it is important to implementing the study in areas of different climatic conditions with different parent material in order to increase the available knowledge on gully activities and appropriate rehabilitation strategies for particular conditions.

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