Analyzing gully erosion dynamics in the Upper Blue Nile basin, Ethiopia

(エチオピア青ナイル川上流域における

ガリー侵食動態の解析**)**

Sebhat Mesenbet Yibeltal

The United Graduate School of Agricultural Sciences
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A dissertation submitted to
The United Graduate School of Agricultural Sciences, Tottori University
in partial fulfillment of the requirements for the Degree of Doctor of Philosophy
in Global Arid Land Science

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Acknowledgement

First and foremost, I would like to thank and praise the Almighty **God**, for giving me the patience and strength to successfully accomplish my study. I would also like to thank Japanese Government (Monbukagakusho) for providing me the opportunity to study in Japan with the financial support from MEXT Scholarship program. Funding for the thesis work was provided by the Science and Technology Research Partnership for Sustainable Development (SATREPS) in collaboration between Japan Science and Technology Agency (JST, JPMJSA1601) and Japan International Cooperation Agency (JICA) project aiming at improving land productivity by reducing soil erosion and introducing crop-livestock production systems as well as linking such efforts to improving the livelihoods of local residents in the northwestern highlands Ethiopia. I am also pleased to thank to the International Platform for Dryland Research and Education (IPDRE) of Tottori University for the financial support related to this work. Also, I would like to thank Bahir Dar Institute of Technology for giving me the opportunity to pursue my PhD research in Tottori University, Japan.

I am very much grateful to my supervisors Prof. Atsushi Tsunekawa, Dr. Nigussie Haregeweyn, Prof. Mitsuru Tsubo, Prof. Enyew Adgo, and Dr. Derege Tsegaye for the constructive critiques, enthusiastic supervision, guidance, inspiration and encouragement to pursue this thesis, and eventually contributed much to the improvement of my interest to research and related works. I would like also greatly thank to Prof. Paolo Billi, Prof. Sugiyuki Masunaga, and Prof. Matthias Vanmaercke for the valuable advice and contributions this thesis work.

The cooperation and assistance of colleagues and friends in Ethiopia and Japan have also contributed a lot to this work. A special thanks to Anteneh Wubet, Nigus Tadesse, Getachew Dagnaw, Agerselam Gualie, and Fentahun Ferede for facilitating our field and laboratory activities. I would like to acknowledge the support and guidance of my colleagues and close friends, Dr. Kindiye Ebabu, Dr. Zerihun Nigussie, Dr. Ayele Almaw, Dr. Dagnenet Sultan, Mulatu Liyew, and Getu Abebe for their valuable comments and cooperation during this PhD thesis work, and for the interesting discussions we had through.

My heartfelt appreciation to several friends that helped me in various ways during my stay in Tottori University (Shunsuke Imai, Misganaw Teshager, Birhanu Kebede, Shigdaf Mekuriew, Fekerimaram Asaregew, Muluken Bayabl, Gashaw Tena, Sisay Yemenu, Dr. Dr. Tana Qian, Du Wuchen, Gou Xiaowei, Tadesual Asamin, Benedict Nzioki, Abuelgasim Ibrahim, Buyantogtokh Batjargal, and others).

I would like to express my gratitude to Emako Tomemori, Yuki Miyata, Naoko Nagata, Masako Tamura, and Yumi Sakai for facilitating necessary administrative procedures, handling my oversea travel cases and other administrative issues.

I am very grateful to my wife, Alemzerf Garde, and my beloved sons (Eyob Mesenbet and Nahom Mesenbet) for all support, encouragement, and patience during my study. Their endurance and commitments during my absence for study and field activities had a lot to do for the successful completion of this thesis work. I would like to express my sincere appreciation to Yilkal Garde for giving my family care during my absence.

Last, but not least, I would like to thank my mother (Minalekute Alemu) for your caring and praying during my journey. I am very pleased to acknowledge the understandings and support from my parents, brothers, and sisters, and others.

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List of Abbreviations and Acronyms

ºC	Degree Celsius
º	Degree
BD	Bulk Density
CV	Coefficient of Variation
C:N	Carbon Nitrogen Ratio
D_g	Gully Density
DEM	Digital Elevation Model
ENVI	Environment for Visualizing Images
EC	Electrical Conductivity
FAO	Food and Agricultural Organization
GPS	Global Positioning System
GCPs	Ground Controlling Points
GeoTIFF	Georeferenced Tagged Image File Format
GIS	Geographical Information System
ha	hectare
LT	Local Time
m.a.s.l	Meter Above Sea Level
mm	millimeter
m	meter
OC	Organic Carbon
PVC	Polyvinyl Chloride
pH	power of Hydrogen
R^2	Coefficient of Correlation
RCA	Runoff Contributing Area
RDN	Rainy Day Normal
SD	Standard Deviation
SL	Soil Loss
SLM	Sustainable Land Management
SRTM	Shuttle Radar Topography Mission
SWC	Soil and Water Conservation
SY	Sediment Yield

TDS	Total Dissolved Solution
TN	Total Nitrogen
UBNB	Upper Blue Nile basin
UTM	Universal Transverse Mercator
VHR	Very High Resolution

Chapter 1: General Introduction

1.1 Background

1.1.1 Soil erosion and land degradation

Soils are a natural resource that plays a vital role in human life given that they provide several important supporting, regulating and cultural ecosystem services and a large variety of goods (Verheijen et al., 2009), particularly in relation to biodiversity, soil biota, plant composition, runoff control, water-holding capacity, carbon sequestration and ecosystem productivity (Van Oost et al., 2000).

Land degradation involves deterioration in soil properties related to crop production, infrastructure maintenance, and natural resource quality (Chalise et al., 2019; Lal, 2001). It also is associated with the decline in the productivity of ecosystems over time (Turner et al., 2016). Land degradation occurs in all types of landscapes over the world, though, the drivers of land degradation vary from region to region (Wieland et al., 2019). Approximately 60 % of the world's land area is regarded as degraded and land degradation (Fig. 1.1), including soil erosion, is one of the greatest challenges for land managers (Chalise et al., 2019). Similarly, land degradation due to soil erosion is a major challenge in Africa (Nyamekye et al., 2018). Soil degradation is threatened worldwide by human-induced degradation processes (Lal, 2001), including physical (e.g., soil erosion, compaction, and waterlogging), chemical (e.g., nutrient depletion and acidification), and biological (e.g., depletion of soil fauna and flora, and organic matter) processes (Lal and Stewart, 1990).

Soil erosion caused by water is one of the most important land degradation processes worldwide and losses of top soil and soil nutrients. It is a geomorphological hazard as it may cause property damage, loss of livelihoods and services, social and economic disruption or environmental damage (Lal, 2001). Ethiopia is one of the countries in sub-Saharan Africa which most severely threatened by land degradation.

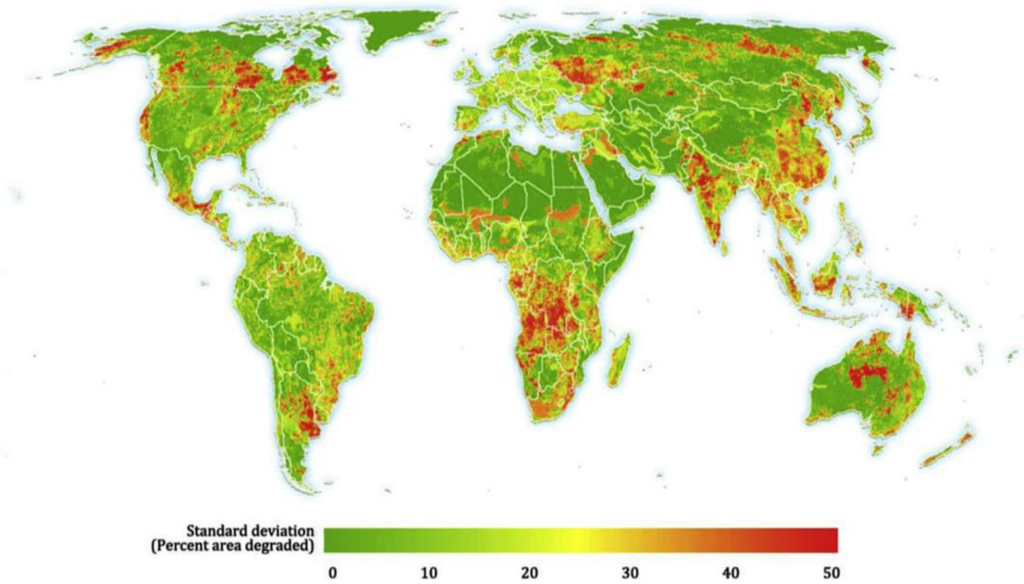

Figure 1. 1 Map of the global databases of degraded lands (Gibbs and Salmon, 2015).

The negative effects of soil erosion include water pollution and siltation, crop yield depression and organic matter loss (Hurni, 1988), which may lead to fundamental social challenges such as land abandonment and the decline of rural communities (Bakker et al., 2005). Similarly, land degradation due to water erosion is a major challenge in Africa (Fenta et al., 2019; Vanmaercke et al., 2014). Sediment yield values vary between 0.2 and 15,699 t km^{-2} y^{-1}. The highest sediment yield values occur in the Atlas region with sediment yield values frequently exceeding 1000 t km^{-2} y^{-1}. Also the Rift region is generally characterized by relatively high sediment yield values (Fig 1.2), while rivers in Western and Central Africa have generally low sediment yield values (Vanmaercke et al., 2014).

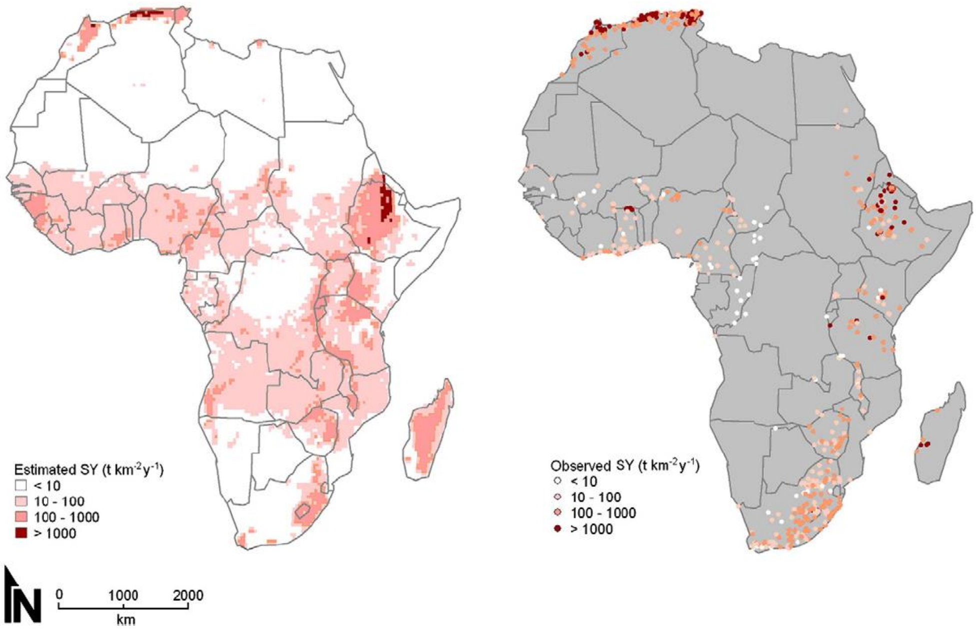

Figure 1. 2 Spatial patterns of sediment yield (SY) in Africa. Right: Observed catchment sediment yields at their outlet location (Vanmaercke et al., 2014).

Soil erosion is a major agent of land degradation in Ethiopia and more specifically in the Upper Blue Nile basin (UBNB), and it has significant impacts on ecosystem services, crop production downstream flooding and reservoir sedimentation, and economic costs (Haregeweyn et al., 2015). Ethiopia is the second largest country in East Africa area coverage and has a high mean soil loss rate (16.9 t ha^{-1} yr^{-1}) (Fenta et al., 2019). The country's contribution has the highest share (nearly 50%) of total soil loss by water erosion in East Africa (Fig. 1.3**)**. The estimated soil loss rates in this region are all exceeded both the suggested soil loss tolerance of 18 Mg ha^{-1} yr^{-1} and the estimated soil formation rates ranging from 2 to 22 Mg ha^{-1} yr^{-1} (Hurni, 1983). Such high soil erosion rates have had critical on-site consequences to the farmers—decline in potential crop and livestock yields—and external or off-site effects which indirectly affect the rest of the society: pollution and sedimentation of hydroelectric dams, Lakes, and reservoirs (Gebreselassie et al., 2016).

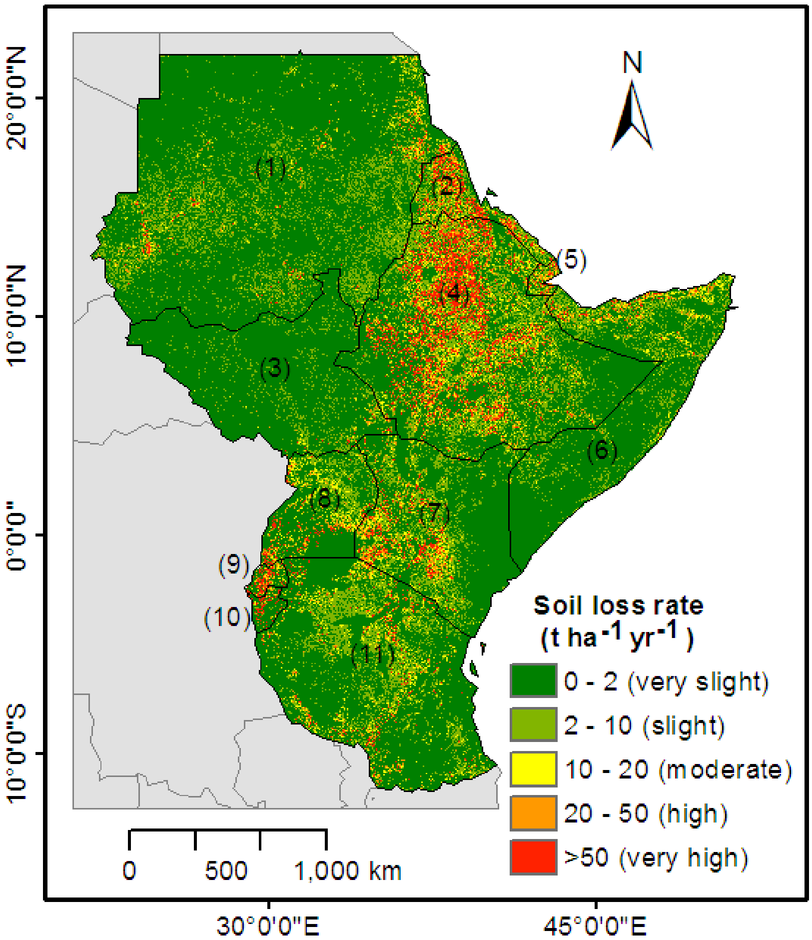

Figure 1. 3 Spatial distribution of soil loss rates by water erosion and corresponding erosion severity classes estimated for the East Africa region.

Numbers indicate countries: (1) Sudan, (2) Eritrea, (3) South Sudan, (4) Ethiopia, (5) Djibouti, (6) Somalia, (7) Kenya, (8) Uganda, (9) Rwanda, (10) Burundi, and (11) Tanzania (Fenta et al., 2019).

1.1.2 Gully erosion and its definition

Gully erosion is an important soil degradation process in a range of environments, causing considerable soil losses and producing large volumes of sediment (Vandekerckhove et al., 2000; Frankl et al., 2016). Gullies are effective links for transferring runoff and sediment from uplands to valley bottoms and permanent channels where they aggravate offsite effects of water erosion (Poesen et al., 2003). Field observations in different environments clearly indicate that the development of (ephemeral) gullies increases the connectivity in the landscape and hence also the sediment delivery to lowlands and watercourses. Gully erosion has been recognized throughout history as a major land degradation process (Dotterweich, 2012), and in many cases has been directly linked to unsustainable land management. It remains a global driver of landscape and soil degradation and most common degradation processes through the highlands of Ethiopia including the UBNB (Nyssen et al, 2004b).

Gullies have been studied in all climate zones, under different land uses and land covers, and within a variety of surface geologies (Castillo and Gómez, 2016) (Fig. 1.4). Many studies are located in the Mediterranean area, due to its semiarid conditions and rainfall variability. The abundance of studies on gully erosion in specific locations is related to a wide range of factors either natural (environmental susceptibility) or human (e.g. historical land management). The incidence of gully erosion in tropical areas is also frequent (Castillo and Gómez, 2016). Gully found everywhere in all climatic, soil, physiographic, lithologic and substratum settings in Ethiopia (Billi et al., 2003).

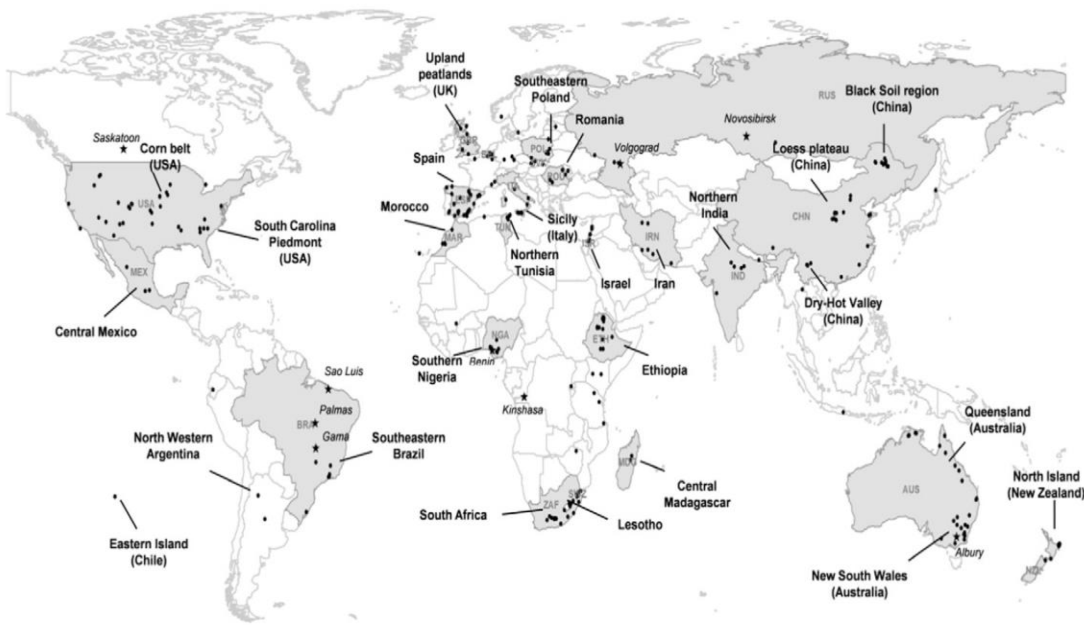

Figure 1. 4 Location of studies with gully erosion. Countries with >3 publications are shaded in grey. Severe or catastrophic gully erosion areas have been labelled in bold **(**Castillo and Gómez, 2016**)**.

A gully is known as a ‘cárcava’ in Spain, ‘ravine’ in France, ‘lavaka’ in Madagascar, ‘wadi’ in Arabic, ‘donga’ in South Africa, ‘voçoroca’ in Brazil and ‘barranco’ in Argentina (Castillo and Gómez, 2016). Gully erosion is defined as the erosion process whereby runoff water accumulates and often recurs in narrow channels and, over short periods, removes the soil from this narrow area to considerable depths. Ephemeral gullies are defined as small channels also eroded by concentrated flow that do not interfere with normal tilling operations, with the added recognition that these channels, once removed by tillage, will reform in the same location by subsequent runoff events. Permanent gullies, in contrast, are often defined for agricultural land in terms of channels too deep to easily ameliorate with ordinary farm tillage equipment (Soil Science Society of America, 2001). By definition, bank gullies develop wherever concentrated runoff crosses an earth bank (Poesen et al., 2002). Gully density implies the total gully length in a specified catchment area. It varies based on watershed size, slope gradient, land use types, and human activities. On the other hand, gully erosion dynamics shows the severity of gully development within different spatial and temporal period. It usually depends on the natural phenomena (rainfall intensity, soil type, earth quake, etc) and human activities (like land use change and farming practice).

Different criteria have been used to define gullies, such as: a) morphological and topographical criteria: relatively deep steep-walled, poorly vegetated incisions in the landscape with a catchment area of 10 km^2 or less (Eustace et al., 2011); b) hydrological criteria: water courses that are subject to ephemeral flash floods during rainstorms (Morgan-Jones, 2005); c) allowance of agricultural practices: stream channels whose width and depth do not allow normal tillage (Soil Science Society of America, 2001); and

d) instability: recently formed incisions within a valley where no well-defined channel previously existed, in Bettis and Thompson (1985).

1.1.3 Gully erosion controlling factors

The development of gully channels rapidly increases the runoff and sediment connectivity in landscapes and hence aggravates off-site effects of water erosion (Fig. 1.5). Many causes of gully erosion have been identified, and these include natural and human-induced soil erosion processes (Poesen et al., 2003; Valentin et al., 2005). Major factors of gully formation are climate (Valentin et al., 2005), lithology, soils (Vandekerckhove et al., 2001), relief and land use/cover characteristics (Mitiku et al., 2006), overgrazing (Valentin et al., 2005), road construction and building activities (Nyssen et al., 2002), disintegration of waterfall tufas (Virgo and Munro, 1978), land use changes (Moges and Holden, 2008; Nyssen et al., 2006), dry spells, and the presence of vertic soil characteristics (Nyssen et al., 2006). Capra et al. (2009) and (Campo-Bescós et al., 2013) reported that heavy rains result in a rapid mass movement in the gullies by undercutting the banks. Soil properties and soil types can also play a role in gully formation and expansion (Valentin et al., 2005). Similarly, in pasture bottom lands, piping has been mentioned as the reason for the development of permanent gullies (Valentin et al., 2005; Tebebu et al., 2010).

Similarly, gully formation may be initiated with the occurrence of convergent shallow subsurface flow that leads to seepage-induced erosion of surface soils, gully heads and sidewalls (Tebebu et al., 2010; Vanmaercke et al., 2016). Gully erosion interacts with hydrological and other soil erosion processes. Moreover, many gullies are initiated by soil piping (Valentin et al., 2005; Poesen, 2011) but once formed gully channels will increase the hydraulic gradients in their banks and hence enhance soil piping and tunneling as well as various mass movement processes on their banks. Shallow landslides may affect piping and gully development (by redirecting subsurface and surface runoff) and in turn gully channel development may affect shallow landslide activity by either draining the landslide or by removing material displaced by the landslide (Castillo and Gómez, 2016).

Piping erosion may trigger gully erosion but also gully erosion may induce piping erosion. Once a gully channel is formed, several processes lead to channel expansion: i.e. tension crack development, piping, plunge pool and splash erosion, fluting and mass failure. Piping (subsurface concentrated flow erosion due to bypass flow) is mainly controlled by soil characteristics at depth, particularly the presence of differential porosity, solubility and strength (Harvey, 1982). Assessing rates of soil erosion processes by water, subsurface flow erosion (i.e. piping and tunnel erosion), in landscapes has often been neglected or considered of minimal importance compared to sheet, rill and gully erosion. This geomorphic process is difficult to monitor as it operates below the soil surface without any indication at the surface, unless the pipe roof collapses and a sinkhole is occurred (Poesen, 2011).

Despite the significant soil losses that piping causes, limited research is done to better understand the factors and processes controlling soil piping erosion and to predict spatial patterns of piping erosion rates in different environments (Poesen, 2011). These process interactions and conditions controlling the activity or stability of gully channels deserve more research attention so as to improve predictions of the hydrological and soil erosion response of gully-affected areas. In general, piping erosion has less understood and no research was done so far in the tropical highlands of Ethiopia.

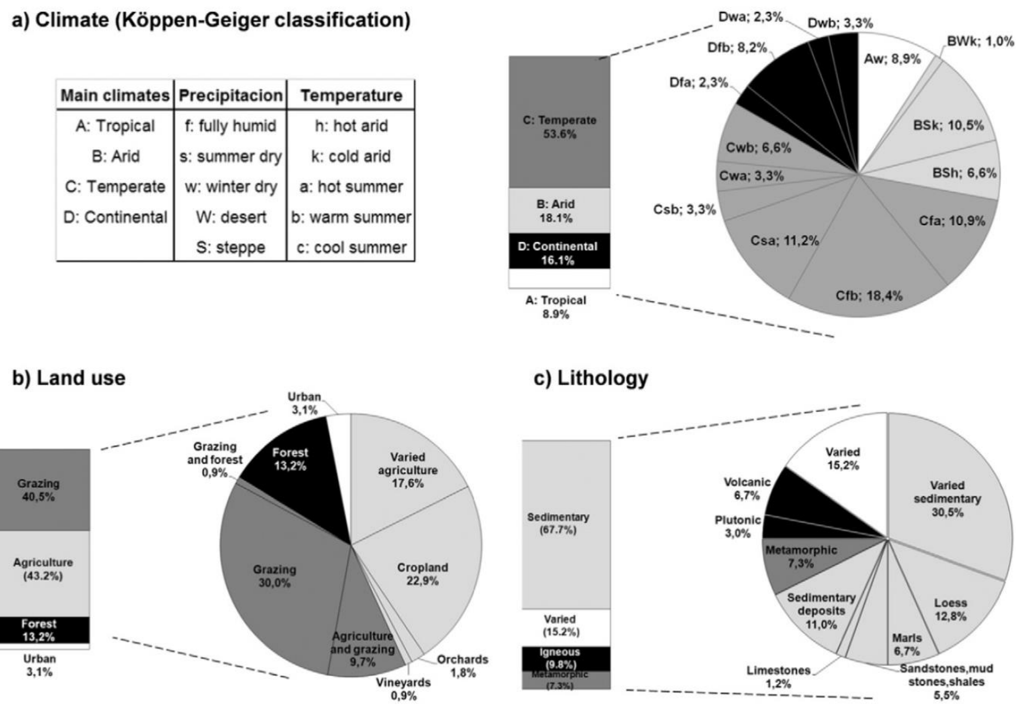

Figure 1. 5 Classification of gully erosion studies according to a) climate, b) land use and c) lithology (Castillo and Gómez, 2016).

Moreover, the extent of the drainage area at the gully head has been linked with the severity of gully erosion (Vanmaercke et al., 2016). However, some studies also indicate that antecedent soil moisture content (Karimov et al., 2014), soil thawing and snowmelt runoff (Ionita et al., 2015; Moeyersons et al., 2015) can play an important role. Land use type can play a dominant role in the initiation of gullies (Torri and Poesen, 2014). Topography can be considered as an erosive factor as slope gradient directly controls runoff erosivity (Knapen and Poesen, 2010; Torri and Poesen, 2014).

1.1.4 Gully erosion sediment yield and its consequence

Gully erosion is widespread in the Ethiopian highlands leading to high sediment loads in water bodies. It is a serious environmental concern due to its ubiquity and severity (Billi and Dramis, 2003), whatever the climate or lithology (Fig. 1.5). Quantifying total gully erosion rates for specific areas or estimating the contribution of gully erosion to catchment sediment yield will require an integration of these different aspects. Gullies are also effective links for transferring runoff and sediment from uplands to valley bottoms, where they aggravate offsite effects of water erosion. Furthermore, gully channel development increases runoff and sediment connectivity in the landscape, hence increasing the risk for flooding and reservoir sedimentation significantly.

For instance, it has been shown that gully channel formation enhances drainage of hillslopes leading to a lowering of water tables, a decrease in baseflow and an increase of stormflow (Costa and Bacelar, 2007) as well as a desiccation of the intergully zones (Poesen et al., 2003). In many countries, gully erosion has been reported to be reaching alarming dimensions, it is linked to unsustainable human activities (Smolska, 2007). Gully erosion has not been a homogeneous process in time or intensity everywhere (Fig. 1.6). Once formed, gullies modify local topography drastically and this induces significant interactions with hydrological and soil degradation processes.

Several studies reported that gully development leads to cause land degradation, damage to infrastructure, and sedimentation of water bodies (Valentin et al., 2005) and damage to agricultural land and agricultural infrastructure (Parkner et al., 2006). Gully erosion is one of the most damaging forms of soil erosion which can be expressed interms of onsite effects such as reduction of land productivity, destruction of property and natural habitats and offsite effects such as aggravation flooding of reservoirs and rivers which call for immediate solution (Haregeweyn et al., 2006; Nyssen et al., 2006; Tamene et al., 2006) and affect economic and social activities (Frankl et al., 2011).

Furthermore, gullies are often a major source of sediments at the catchment scale (Fig. 1.6), can strongly increase catchment sediment connectivity and can have strongly negative impacts on the hydrological functioning of catchments (Poesen et al., 2003; Vanmaercke et al., 2011). Once gully channels develop they interact with hydrological processes: e.g. drainage of the inter-gully area may lead to desiccation phenomena and crop yield losses in semi-arid environments or runoff transmission losses through the gully bed and banks may affect groundwater recharge and possible groundwater contamination. If gullies develop into hillslopes with temporary water tables, they may cause an enhanced drainage and a rapid water table lowering which results in a significant drying out of the soil profiles in the intergully (Moeyersons, 2000).

In addition, gully erosion represents a major sediment-producing process, generating between 10 and 95% of total sediment mass at catchment scale whereas gully channels often occupy less than 5% of the total catchment area (Poesen et al. 2003; Capra, 2013). Tebebu et al. (2010) estimated an extremely high gully erosion rate of 530 t ha^{-1} yr^{-1} for the Debre-Mawi watershed in northwest Ethiopia (17.4 ha watershed scale). A similar gully erosion rate of 566 t ha^{-1} yr^{-1} was reported by Daba et al. (2003) for the Damota catchment in eastern Ethiopia (9 km^2 watershed scale) on the basis of an analysis of aerial photographs from two different dates (1966 and 1996). Studies in north Ethiopia show lower gully erosion rates, for example, Nyssen et al. (2006) reported an average gully erosion rate of 6.2 t ha^{-1} yr^{-1} over a 50-year time span. Rates of soil loss due to gullies significantly higher observed in agricultural areas, which can be the leading cause of landscape degradation worldwide (Fig. 1.6).

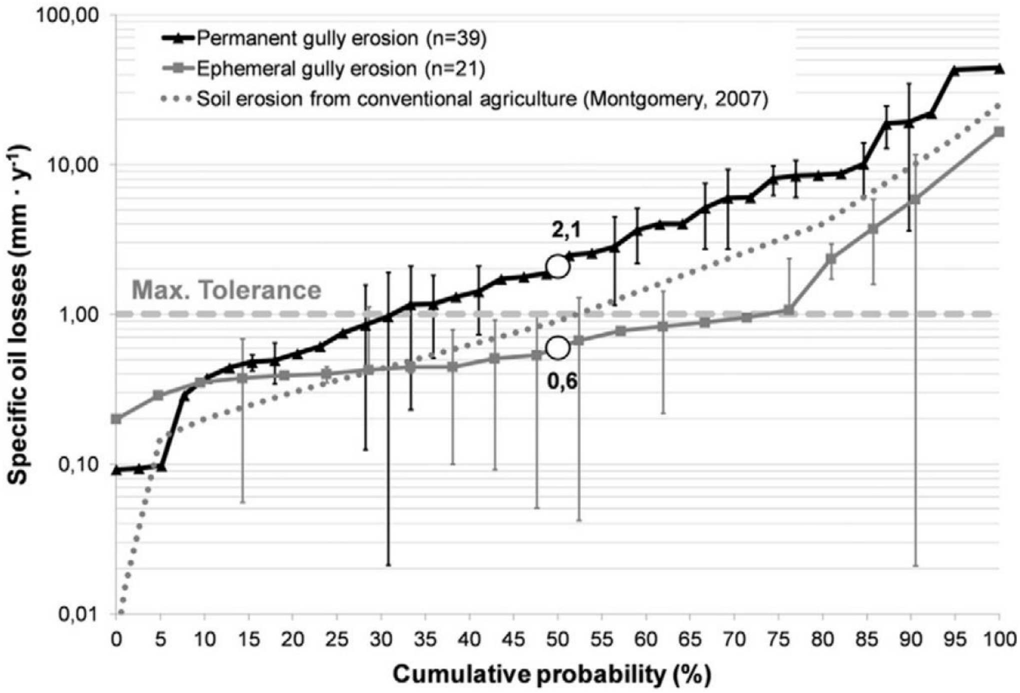

Figure 1. 6 Comparison of reported specific soil losses (mm yr^{-1}) from conventional agriculture and from permanent and ephemeral gully erosion in agricultural areas (Castillo and Gómez, 2016).

On the other, recent studies indicate that gully development in semi-arid areas may facilitate groundwater recharge (Leduc et al., 2001). Similarly, (Okagbue and Uma, 1987) reported that gullies located at the discharge areas of groundwater systems in southeastern Nigeria may become very active during the peak recharge times of the rainy season because high pore–water pressures reduce the effective strength of the unconsolidated materials along the seepage faces.

1.1.5 Gully erosion assessment methodology

Most of the gully studies have been made on measurement-based studies, but have been gradually leaving space to other approaches such as models or laboratory experiments or, more recently, predictive studies based on environmental variables (Castillo and Gómez, 2016). Several studies have focused to quantify and predict gully erosion in a range of environments, including linear measurements (Oostwoud Wijdenes and Bryan, 2001;

Vandekerckhove et al., 2003; Yibeltal et al., 2019a, b), area measures (e.g. Yibeltal et al., 2019b), volumetric measures (e.g. Yibeltal et al., 2019b; Vandekerckhove et al., 2003), and weight measures (e.g. Yibeltal et al., 2019b). Ground-based LiDAR, photogrammetry, and hand-held devices can now describe ephemeral gully erosion using millimeter-scale grids with millimeter-scale errors (Castillo et al., 2018).

Measuring directly the volumes of soil eroded by ephemeral gullying has been done in a range of cropland environments (Nachtergaele et al., 2001a, Yibeltal et al., 2019b). Short-term monitoring of gully head or gully wall retreat has been conducted by measuring regularly the change in distance between the edge of the gully head or wall and benchmark pins installed around the gully wall (Oostwoud Wijdenes and Bryan, 2001; Yibeltal et al., 2019b). At the medium-time scale (10–70 years) aerial photographs have been analyzed to measure temporal changes in length, area or volume of various gully types (Daba et al., 2003; Yibeltal et al., 2019 a, b). For the long-time scale, several studies have used historical data (documents and maps), artefacts and various dating techniques to reconstruct the conditions leading to significant gully erosion in the past (Yibeltal et al., 2019 a, b).

Development of gully erosion models, capable of predicting erosion rates at various temporal and spatial scales and the impact of gully development on sediment yield and landscape evolution. Though several attempts have been made to develop empirical and process-based models for predicting either permanent gully sub-processes or gully erosion rates in a range of environments (Poesen et al., 2011), there are still no reliable models available allowing one to predict effects of environmental change on gully erosion as well as the impact of gully erosion on sediment yield and landscape evolution.

In recent years, several studies have developed dynamic models that predict rapid changes of gully morphology during the early stages of gully development and static models to calculate final morphometric parameters of permanent gullies in different environments (Sidorchuk et al., 2003). Casali et al. (2003) and Torri and Borselli (2003) present process-based approaches to predict (ephemeral) gully cross-sections at various points along the gully. The agricultural community has been focus on developing a model for an ephemeral gully, and an initial attempt was the Ephemeral Gully Erosion Model (Woodward, 1999). At present, only a few models claim to be capable of predicting ephemeral gully erosion rates (Poesen et al., 1998), i.e. CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems; Knisel (1980)–GLEAMS (Groundwater Loading Effects of Agricultural Management Systems; Knisel (1993), EGEM (Ephemeral Gully Erosion Model; Woodward, 1999) and WEPP watershed model (Water Erosion Prediction Project; (Flanagan and Nearing, 1995). Topographic indices are typically expressed as a product of local slope and upstream drainage area, which are used as proxies for stream power and the susceptibility for gullying (Torri and Poesen, 2014).

Gullies became widespread in the Ethiopian highlands during the 20th century when the population pressure increased (Nyssen et al., 2006). Gullies are one of the few morphological evidences of past soil erosion periods reflecting impacts of environmental changes (land use, extreme rain events) in the landscape. Therefore, detailed studies of historical gullies are crucial, not only to reconstruct the past but also to learn from it. Consequently, there is a need for more monitoring, experimental and modeling studies of gully erosion as a basis to improve predictions of the effects of environmental change on gully erosion rates.

1.1.6 Gully erosion management activity

Rates of gully erosion vary with the stage and management condition in the catchment. Gully may stabilize through the development of vegetation in the gully channel through human interventions that actively aim to stop the gully headcut from retreating. Gully control approaches in concentrated flow zones are the establishment of grassed waterways and check dams with drop structures in gullies, dissipating flow energy so as to prevent gully development (Baade et al., 1993). The presence of vegetation at a gully headcut can strongly decrease gully head retreat rates in various ways (e.g. reducing flow velocity by increasing hydraulic roughness), but mainly by increasing the cohesion of the soil (De Baets et al., 2008; Vannoppen et al., 2015). Several studies have also demonstrated how a spatially integrated strategy for vegetation establishment at the hillslope and catchment scales can help in trapping large volumes of sediment (Mekonnen et al., 2015) and hence in reducing sediment connectivity (Marchamalo et al., 2016).

Control of soil loss and sediment production in erosion hot spots remains a big challenge: i.e. sites with intense gullying. Previous successes show that it is within our means to provide an effective solution to the problem, though it is still necessary to design cost-effective approaches which can be widely adopted by farmers or develop innovative solutions for specific conditions (Moges and Holden, 2008). Much less research emphasis has been put to gully control than to gully erosion dynamics, despite the fact that implementing a solution to the problem might be the reason behind most of the research activities. While gully expansion and rehabilitation have been researched in the semi-arid regions of northern Ethiopia, very few studies have been conducted in the tropical sub-humid regions of Ethiopia.

1.2 Problem statement

In Ethiopia, rates of land degradation by water erosion are alarmingly high and sedimentation in reservoirs, lakes, and rivers is a serious problem (Haregeweyn et al., 2006; Tamene et al., 2006). Global climate change, shifting land use, and increased population will potentially affect soil resources, aggravate gully erosion processes, and threaten agricultural productivity (Marzolff and Pani, 2018; Poesen, 2018; Yibeltal et al., 2019 a). Understanding gully erosion process is therefore highly relevant, both from a geomorphic and environmental degradation point of view (Poesen et al., 2018).

Most assessments of soil erosion by water have mainly focused on sheet and rill erosion rates, whereas gully erosion received less or no attention in the sub-humid tropical highlands. Study works on the extent, causes and controlling factors of gully erosion are poorly recognized especially in developing countries like Ethiopia (Nyssen et al., 2006, Poesen, 2011). Although gully erosion is a common feature throughout the Ethiopian Highlands, few gully erosion studies in Ethiopia have been carried out in the semi-arid region of northern Ethiopia (Nyssen et al., 2006; Frankl et al., 2013). In addition, the UBNB which is covering 173,000 km^2 areas is highly affected by soil erosion and soil losses from the basin is 473 Mt yr^{-1}, of which 10–15% due to gully erosion (Haregeweyn et al., 2017). Similarly, gully erosion causes loss of soil fertility, rapid degradation of natural systems, sediment depositions in the lakes and reservoirs and sedimentation of irrigation infrastructures in the UBNB (Awulachew et al., 2008).

Aiming at identifying and understanding the many interactions between the different processes and factors that control the total soil loss by gully erosion therefore offers a challenging but highly promising gap for our study. Despite the significant contributions of gully erosion to the overall sediment budget (Poesen et al., 2003; Haregeweyn et al., 2017), lack of data has limited the efforts to account for its effect at UBNB. Some major research gaps and therefore the need for more detailed investigations of the extent of gully erosion, mechanisms governing the role of topographic threshold, rainfall intensity, and land use type and change on gully development, factors and their interactions related to gully erosion, particularly for UBNB that received limited attention. In addition, little is known about the spatio-temporal gully erosion dynamics, morphological characteristics, and causes and controlling factors for gully erosion in high rainfall intensity. Therefore, better understanding of gully formation processes and factors is needed for better predicting gully erosion rates and develop mitigation strategies.

1.3 Objectives of the study

The objective of this dissertation is, therefore, to estimate the spatio-temporal gully erosion dynamics, to characterize gully morphology and to identify factors controlling gully erosion in the sub-humid tropical parts of UBNB, Ethiopia. The main objectives were to (1) analyze and quantify the spatio-temporal variation of gully lengths and densities; (2) quantify gully morphological characteristics and gully headcut retreat rates; and (3) investigate the role of subsurface water on gully headcut retreat. The results of these objectives used to assess and quantify the spatio-temporal dynamics of gully length and density and identify the controlling factors for gully initiation. The results of this study indicate that careful site-specific identification of factors controlling gully initiation and development is crucial so that appropriate management strategies can be developed for these three sites and for other areas with similar agro-ecologies in the UBNB. Based on the key findings from field observations and appropriate recommendations are also given to be taken in to consideration by future research and related works.

1.4 Description of the study area

1.4.1 Location and climate

The study was conducted in three sites in the UBNB, Ethiopia (within 10° 46′ 12″N–11° 40′ 24″N and 36° 15′ 51″E–37° 29′ 49″E) with different agro-ecologies: Guder has a highland agro-ecology; Aba Gerima is in a midland area; and Dibatie is a lowland agro-ecology (Bekele-Tesemma and Tengnas, 2007; Sultan et al., 2018). Each agro-ecology is characterized by specific climate conditions, soil and water conservation (SWC) practices, land use or cover types, and topographical features (Table 1). The average annual precipitation is 2454, 1343, and 1022mmyr^{-1} in Guder, Aba Gerima, and Dibatie, respectively, based on daily rainfall data obtained at the nearest rainfall measurement stations during 1984–2016 (Guder), 1962–2016 (Aba Gerima), and 1981–2016 (Dibatie). The rainfall distribution varies greatly during each year (Fig. 1.7) : >86% of the total rainfall amount falls during the rainy season (May to September), and high-intensity rainstorms are likely in summer (June to August) in all three agro-ecologies. The dry season is from November to April.

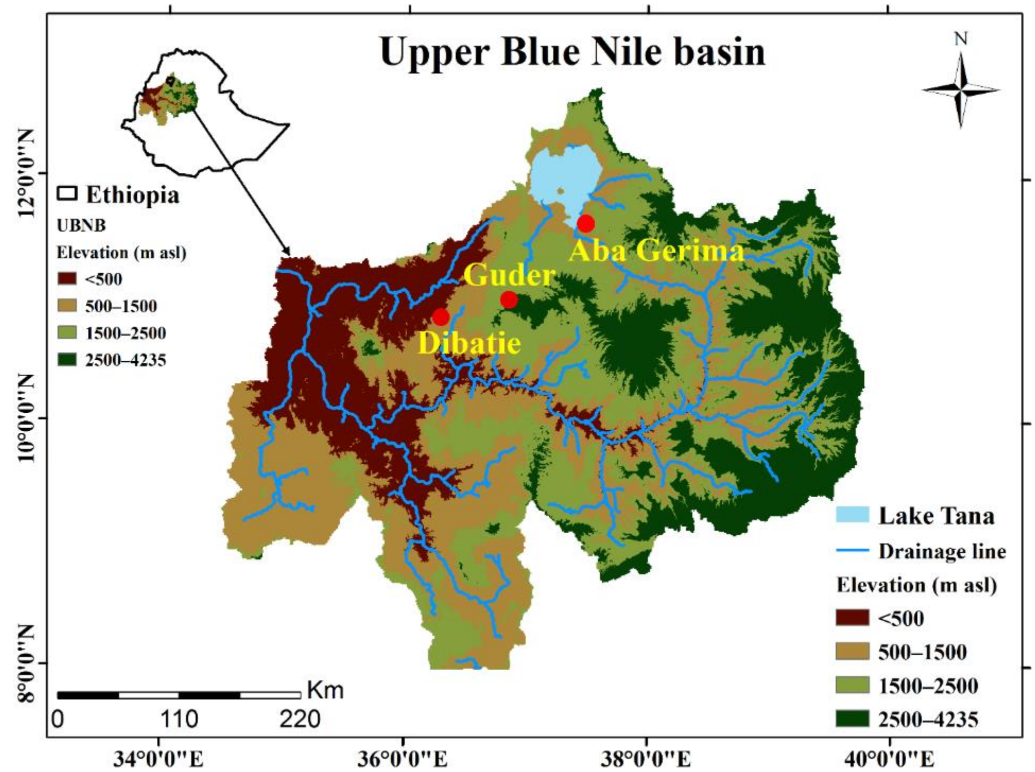

Figure 1. 7 Location maps of the study area: (A) Ethiopia in Africa; (B) the UBNB in Ethiopia; (C) the study sites in the Upper Blue Nile basin.

According to the local climate zone classification, based on elevation and mean annual precipitation (Hurni et al., 2016), the Dibatie, Aba Gerima, and Guder sites, respectively, are belong to Moist Kolla (500–1500 m a.s.l., mean annual precipitation of 900–1400 mm), Moist Weyna Dega (1500–2300 m a.s.l., mean annual precipitation of 900–1400 mm), and Wet Dega (2300–3200 m a.s.l., mean annual precipitation of ≥1400 mm) agro-ecological zones (Table 1.1).

Table 1. 1 Main characteristics of the three study sites.

Characteristics (units)	Guder	Aba Gerima	Dibatie
Altitude (m.a.s.l)	2492–2882	1911–2222	1482–1706
Total area (ha)	741	760	644
Annual rainfall (mm)	1951–3424	895–2037	850–1200
Drainage density (km km^{-2})	5.72	2.41	3.01
Major soil types[a]	Acrisols and Leptosols	Leptosols and Luvisols	Vertisols and Luvisols
Slope (°)	0–39	0–36	0–28
Major land use types[b]	Cropland, grazing land	Cropland, grazing land	Cropland, grazing land
Soil bulk density (g cm^{-3})[a]	0.83–1.34	1.21–1.40	1.11–1.44
Primary soil texture[a]	Clay loam	Clay	Clay
Mean daily temp. (°C)	15–24	17–31	18–29
Agro-ecology zone[b]	Moist subtropical	Humid subtropical	Tropical hot humid
Major crops[c]	Barley, tef, wheat, potatoes	Tef, finger millet, wheat	Finger millet, tef, maize
Major livestock[c]	Cattle, sheep, donkeys, horses	Cattle, sheep, goats, donkeys	Cattle, sheep, goats, donkeys

[a] Mekonnen (2016); [b] Sultan et al. (2018); [c] Nigussie et al. (2017).
Tef (*Eragrostis tef*); finger millet (*Eleusine coracana*); wheat (*Triticum aestivum*); maize (*Zea mays*); barley (*Hordeum vulgare*); potato (*Solanum tuberosum*).

1.4.2 Major soil types

Mekonnen (2016) summarized the four dominant FAO soil types of the study sites as follows: (1) Acrisols are soils with subsurface accumulations of low-activity (i.e., highly weathered) clays, low cation exchange capacity, and low base saturation; (2) Luvisols are very deep and well-drained soils that form on gentle slopes; (3) Leptosols are thin, degraded soils that developed from variable parent materials on steep slopes; (4) Vertisols are soils with high concentrations of clay minerals that shrink and swell during dry and wet seasons, respectively. All four soil types occur in Guder; Luvisols, Vertisols, and Leptosols are present in Dibatie (though Vertisols dominate); Luvisols and Leptosols occur in Aba Gerima.

1.4.3 Land use and farming systems

The landscape at the three sites is fragmented as a result of different traditional land use practices over many decades. The major land use types in the study area are cultivated lands, grazing lands, and degraded bushlands (Table 1). In all sites, cultivated lands proportion is larger than grazing lands and degraded bushlands. The farming system is mixed crop-livestock, characterized by rain-fed and continuous cropping. Livestock types are more or less similar across the three sites, though the stocking rate and grazing intensity on non-cultivated lands is higher in Aba Gerima than in the other sites (Nigussie et al., 2017; Ebabu et al., 2018).

Major crops include tef (*Eragrostis tef*), barley (*Hordeum vulgare*), wheat (*Triticum aestivum*), and potato (*Solanum tuberosum*) at the Guder site, whereas finger millet (*Eleusine coracana*), maize (*Zea mays*), and tef are the major crops at Aba Gerima and Dibatie sites.

Sheet, rill, and gully erosion continue to be major problems in the Upper Blue Nile basin (Haregeweyn et al., 2017; Ebabu et al., 2019; Yibeltal et al., 2019) and have significant environmental impacts. The landscape of all study sites is fragmented as a result of different land use practices over many decades. The most active period of gully initiation and expansion in all sites is the main rainy season (May to September). Gullies are typically observed during field surveys regardless of topographical setting, land use types, and soil characteristics.

1.5 Organization of the thesis

This thesis is organized into chapters (Fig. 1.8). The first chapter (Chapter 1) presents the introductory sections (background, problem statement, objectives, and the study area). It explains the impacts of gully erosion and its causes and consequences on environment based on the existing literatures, field observation, and indicates the rationale of this study. Chapter 2 analyzes the spatio-temporal dynamics of gully lengths and densities in three different agro-ecologies (lowland, midland, and highland) that are typical representative of the different biophysical and socioeconomic conditions of the basin. Chapter 3 quantifies gully morphological characteristics and gully headcut retreat rates in three different agro-ecologies (lowland, midland, and highland) that are typical representative of the different biophysical and socioeconomic conditions of the basin. Chapter 4 investigates key factors contributing to the development of gullies in the tropical humid highland of the Upper Blue Nile basin, Ethiopia. We continued our study in Chapter 3 and Chapter 4 to understand the causes of gully dynamics in spatio-temporal scale in Chapter 2. The last chapter (Chapter 5) presents the general conclusions and recommendations based on the key findings from the three main chapters (chapters 2, 3, and 4).

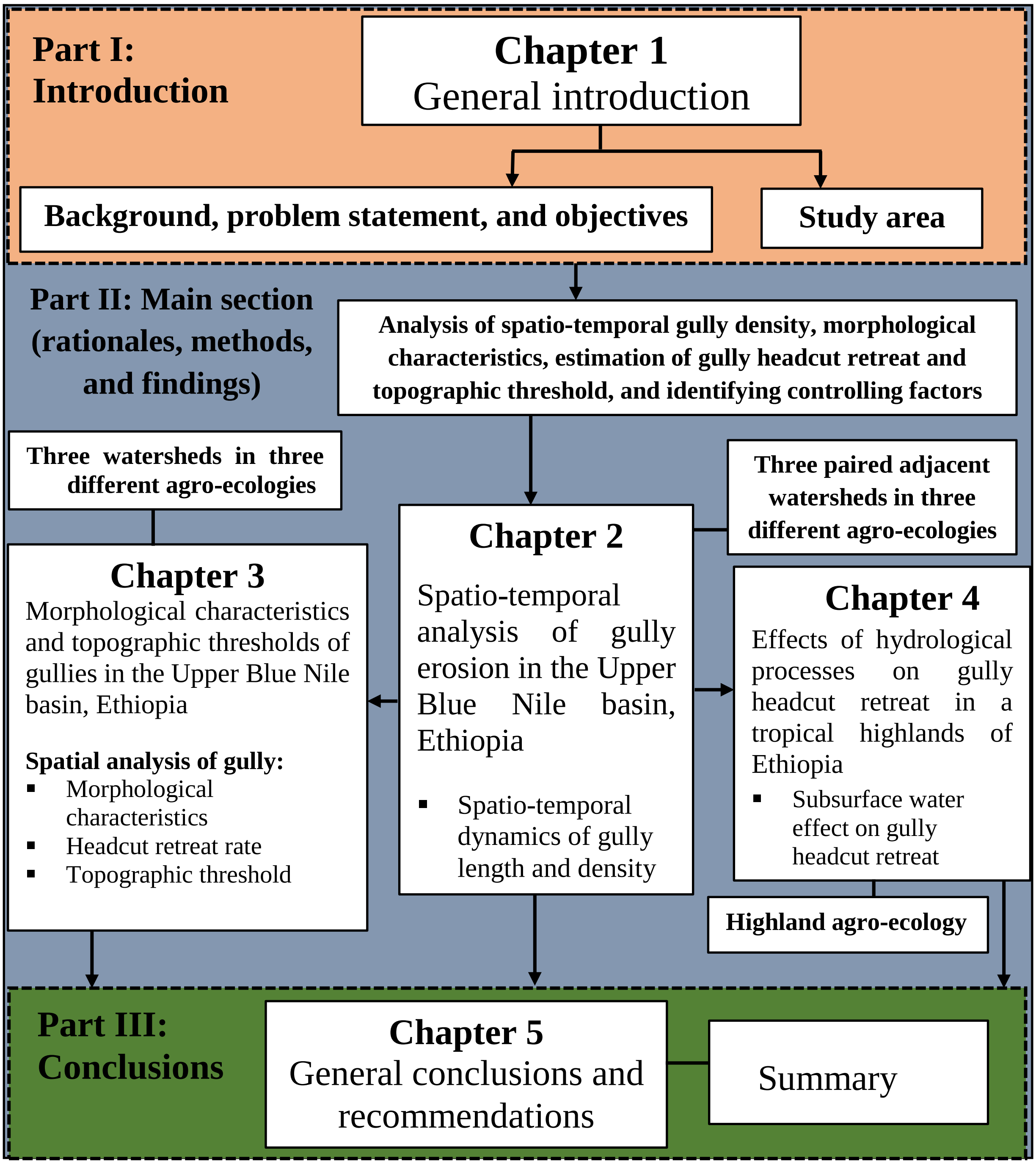

Figure 1.8 Structure of the thesis

Chapter 2: Spatio-temporal analysis of gully erosion in the Upper Blue Nile basin, Ethiopia

This chapter is published as:

Yibeltal, M., Tsunekawa, A., Haregeweyn, N., Adgo, E., Meshesha, D.T., Aklog, D., Masunaga, T., Tsubo, M., Billi, P., Vanmaercke, M. and Ebabu, K., 2019. Analysis of long-term gully dynamics in different agro-ecology settings. Catena, 179, pp.160–174.

2.1 Introduction

Gully erosion is a central soil degradation process, affecting both land and water resources (Frankl et al., 2016; Kakembo et al., 2009; Le Roux and Sumner, 2012; Poesen, 2011; Vanmaercke et al., 2016). Gully erosion not only damages agricultural land (Harden, 2016; Parkner et al., 2006), but can reduce crop yields (Frankl et al., 2016; Poesen, 2018), contributes to the siltation of lakes, reservoirs and other water ways (Haregeweyn et al., 2005; Haregeweyn et al., 2006; Haregeweyn et al., 2012; Martínez-Casasnovas et al., 2003), damages infrastructures such as roads and buildings (Harden, 2016), lowers groundwater tables (Daba et al., 2003; Tebebu et al., 2010), and can lead to increased flooding risks (Costa and Bacellar, 2007).

Many factors can contribute to the formation of gullies, often in interaction. These include soil physical properties (Nyssen et al., 2006; Valentin et al., 2005; Vandekerckhove et al., 2001), the size of the upslope contributing area (Le Roux and Sumner, 2012; Poesen et al., 2003), topographic and land use and land cover characteristics of the catchment (Billi and Dramis, 2003; Kakembo et al., 2009; Mitiku et al., 2006; Poesen et al., 2003; Sonneveld et al., 2005; Torri and Poesen, 2014), diversion of concentrated runoff due to construction activities (Nyssen et al., 2002) and rainfall intensity (Vanmaercke et al., 2016). In many cases, gully erosion is accelerated by overgrazing, land use change, extreme climatic events (Moges and Holden, 2008; Valentin et al., 2005) and inappropriate agricultural activities (Kakembo and Rowntree, 2003).

Gully erosion rates are typically high in Ethiopia and other similar environments, but are also characterized by large spatial and temporal variability. Haregeweyn et al. (2017) estimated that gully erosion rates vary between 1.1 t ha^{-1} yr^{-1} and 17.6 t ha^{-1} yr^{-1} in the Upper Blue Nile basin. Likewise, Bewket and Sterk (2003) and Zegeye et al. (2018) found that gully erosion contributed 70% and 90% of sediment production from catchments in northern Ethiopia, respectively. Nonetheless, relatively little is known about the rates and controlling factors of gully erosion in the northwest Ethiopia, especially at longer time scales.

Soil erosion studies in different parts of the world including Ethiopia have generally focused on sheet and rill erosion, while gully erosion has received less attention (Nyssen et al., 2006; Poesen and Valentin, 2003; Valentin et al., 2005; Vanmaercke et al., 2016; Poesen, 2018). In Ethiopia in particular, gully erosion has been widely observed in different climatic regions (Billi and Dramis, 2003). Despite its wider occurrence, there are very limited studies available on the spatial and temporal evolution of gullies that focused in the semi-arid regions (e.g. Frankl et al. 2011a, 2011b, 2013a). Understanding the dynamics, extent, and severity of gully erosion and its controlling factors is therefore an important step in the development of gully models and controlling strategies.

Several studies (Betts and DeRose, 1999; Daba et al., 2003; Frankl et al., 2013a; Frankl et al., 2013b; Wang et al., 2014) indicated that remote sensing is an effective tool to understand the spatial and temporal trends of gully features, to identify gully erosion risk areas and to propose appropriate mitigation measures. Therefore, the main aim of this study was to assess the spatial and temporal extent of gully evolution in three different agro-ecologies of the Upper Blue Nile basin over the last six decades (1957–2017) by using aerial photographs and very high resolution satellite images. The specific objectives are (1) to assess and quantify the spatial and temporal variation of gully lengths and densities (2) to identify key factors contributing to the formation and development of these gullies.

2.2 Material and methods

2.2.1 Study areas

The study was conducted in three sites in the Upper Blue Nile basin, Ethiopia (within 10° 46′ 12″N–11° 40′ 24″N and 36° 15′ 51″E–37° 29′ 49″E) with different agro-ecologies: Guder has a highland agro-ecology (>2000 m above sea level [a.s.l.]); Aba Gerima is in a midland area (1500–2000 m a.s.l.); and Dibatie is a lowland agro-ecology (<1500 m a.s.l.) (Bekele-Tesemma and Tengnäs, 2007; Sultan et al., 2018). Each agro-ecology is characterized by specific climate conditions, soil and water conservation (SWC) practices, land use or cover types, and topographical features (Table 2.1). The average annual precipitation is 2454, 1343, and 1022 mm yr^{-1} in Guder, Aba Gerima, and Dibatie, respectively, based on daily rainfall data obtained at the nearest rainfall measurement stations during 1984–2016 (Guder), 1962–2016 (Aba Gerima), and 1981–2016 (Dibatie). The rainfall distribution varies greatly during each year (Fig. 2.1): more than 86% of the total rainfall amount falls during the rainy season (May to September), and high-intensity rainstorms are likely in summer (June to August) in all three agro-ecologies. The dry season is from November to April. Unfortunately, hourly rainfall data for these areas are not available. Major land uses include cultivated land, grazing land, and bushland (Ebabu et al., 2018). In all three sites, the cultivated area is larger than non-cultivated areas (grazing land and bushland) and the farming system is mixed crop–livestock; the cropping system is rainfed and continuous (Ebabu et al., 2018; Sultan et al., 2018).

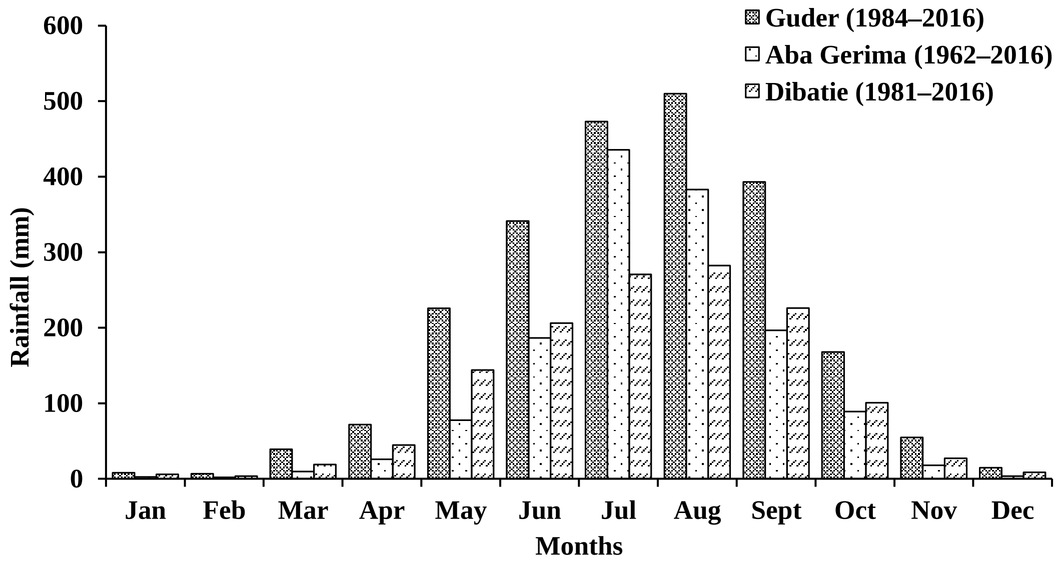

Figure 2. 1 Long-term average monthly precipitation in the three study sites.

In each site, paired micro-watersheds, Kasiry and Akusity in Guder, Kecha and Laguna in Aba Gerima, and Sahi and Bekafa in Dibatie, were selected for assessing the dynamics of gully erosion in agro-ecology settings characterized by different climatic conditions and landscape characteristics. Further, SWC measures have been implemented in only one of the watersheds in each paired watershed (Fig. 2.2): in the Kasiry (Guder), Kecha (Aba Gerima), and Sahi (Dibatie) watersheds, SWC measures have been implemented through regular extension programs of the national government. The traditional SWC technologies such as stone bund, drainage ditch and agroforestry and improved SWC technologies such as soil bund, *fanya juu*, stone-faced soil bund, and trenches are implemented by farmers. SWC interventions through community mobilization in the Kasiry area have also received support from the World Bank under its Sustainable Land Management Programme since 2008, and those in the Kecha area have also been supported by the Swiss Agency for Development and Cooperation since 2011 (Nigussie et al., 2017).

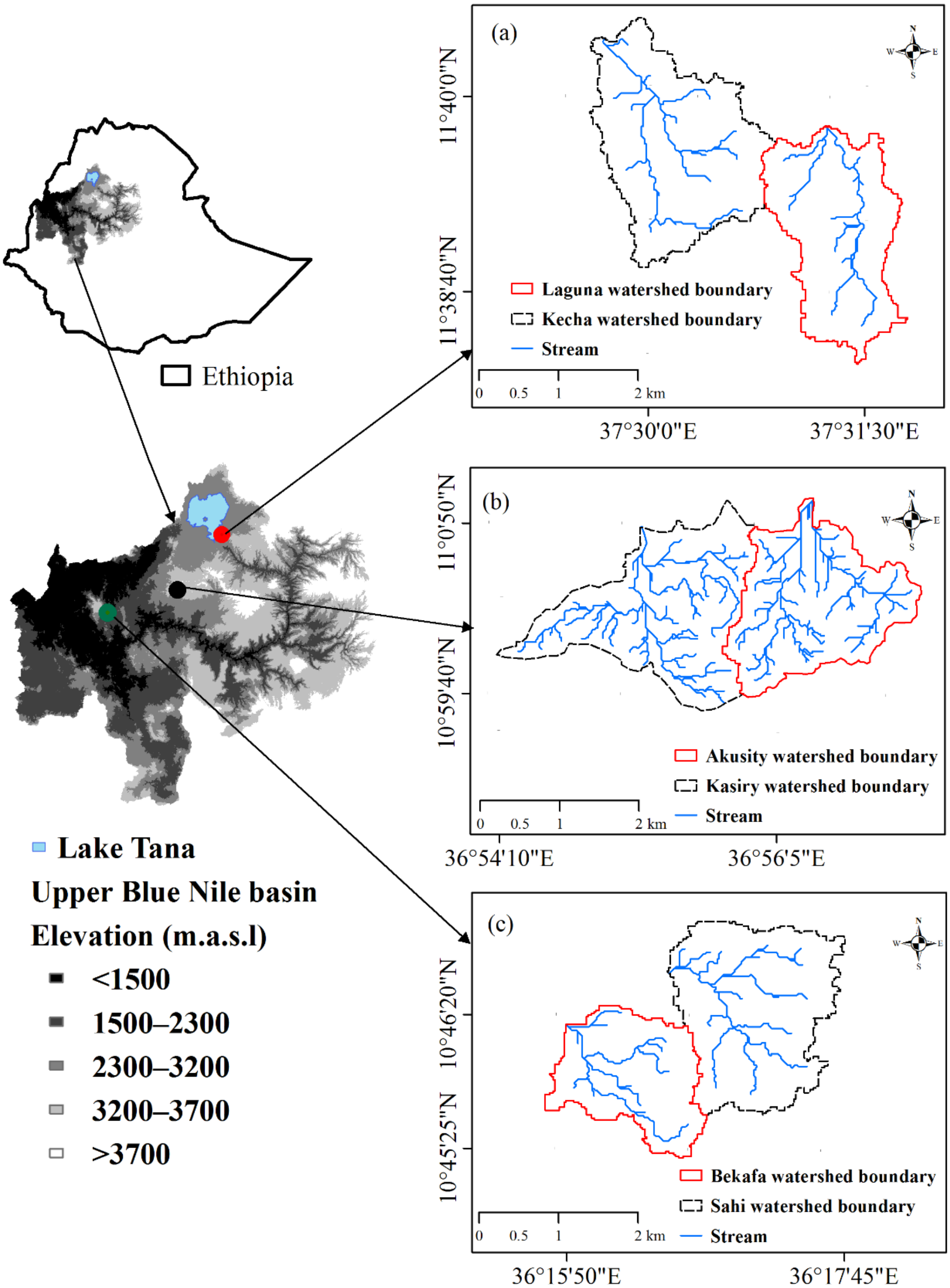

Figure 2. 2 Locations of the study watersheds in the Upper Blue Nile basin, Ethiopia: (a) Aba Gerima; (b) Guder; and (c) Dibatie.

Table 2. 1 Main characteristics of each watershed and agro-ecology.

Characteristics (unit)	Guder		Aba Gerima		Dibatie	
	Kasiry	Akusity	Kecha	Laguna	Sahi	Bekafa
Altitude (m.a.s.l)	2554–2882	2492–2880	1946–2222	1911–2116	1482–1704	1503–1706
Watershed outlet	11° 00′ 47″ E, 36° 55′ 11″ N	11°01′ 00″ E, 36°56′ 16″ N	11° 40′ 23″ E, 37°29′43″ N	11°39′ 19″ E, 37°31′ 26″ N	10°46′ 44″ E, 36°16′ 25″ N	10°46′ 19″ E, 36°15′ 53″ N
Total area (ha)	398	343	426	334	398	246
Drainage density (km km^{-2})	5.49	5.94	2.4	2.42	2.76	3.24
Major soil types[a]	Acrisols and Leptosols	Acrisols and Leptosols	Leptosols and Regosols	Luvisols and Regosols	Vertisols and Luvisols	Luvisols and Vertisols
Slope gradients (°)	0–39	0–32	0–36	0–28	0–28	0–21
Land cover classes (%)						
Cultivated land (CL)	41	39	64	67	50	56
Grassland (GL)	18	10	10	15	27	17
Forest (FL)	17	4	0	3	–	–
Degraded bushland (DBL)	14	17	–	–	–	–
Plantation (PL)	10	30	–	–	–	–
Degraded land (DL)	–	–	1	0	3	9
Village (VL)	–	–	2	3	2	0
Bushland (BL)	–	–	22	11	18	18
Soil bulk density (g cm^{-3})[b]	0.83–1.34		1.21–1.40		1.11–1.44	
Soil texture[b]	Clay loam		Clay		Clay	
Mean daily Temp. (°C)[b]	15–24		17–31		18–29	
Agro-ecology zone[b]	Moist subtropical		Humid subtropical		Tropical hot humid	
Major crops[b]	Barley, tef, wheat		Tef, finger millet, wheat		Finger millet, tef, maize,	
Major livestock[c]	Cattle, sheep, donkeys and horses		Cattle, sheep, goats and donkeys		Cattle, sheep, goats and donkeys	

Sources: [a], Mekonen (Amhara Design and Supervision Works Enterprise, Bahir Dar, Ethiopia, personal communication); [b], Sultan et al., 2018; [c], Nigussie et al., 2017.
Tef (*Eragrostis tef*); finger millet (*Eleusine coracana*); wheat (*Triticum aestivum*); maize (*Zea mays*); groundnut (*Arachis hypogaea*); barley (*Hordeum vulgare*); potato (*Solanum tuberosum*).

2.2.2 Data acquisition and image processing

Aerial photographs and VHR satellite images can be efficiently used to map and compare gully evolution during different time periods and in different locations (Daba et al., 2003; Frankl et al., 2011b; Kropacek et al., 2016; Mukai, 2017). However, it is difficult to use an automated pixel classification method for accurate identification of gullies and their features, because they may be masked by vegetation cover and because soil reflectances differ depending on soil properties such as organic matter and moisture contents (King et al., 2005; Stroosnijder, 2005).

To assess gully erosion in the three agro-ecologies, gully features in each site and watershed were determined for multiple years: Kasiry and Akusity watershed in Guder, 1957, 1982, 2006, 2012, and 2017; Kecha and Laguna watershed in Aba Gerima, 1957, 1982, 2005, and 2016; and Sahi and Bekafa watersheds in Dibatie 1957, 1982, 2006, 2011, and 2017. We obtained 38 black-and-white aerial photographs taken in 1957 and 1982 (scale 1:50,000) from the Ethiopian Mapping Agency, and used satellite images for the other years (Table 2.2). The aerial photographs were scanned at a geometric resolution of 600 dpi and radiometric resolution of 8 bit, gray scale and uncompressed. The photographs were acquired by a metric camera with a focal length of 153.046 mm for 1957 and 152.82 mm for 1982. We orthorectified the aerial photographs (1957, 1982) with a unique DEM from 30-m Shuttle Radar Topography Mission (SRTM); assuming that there is no any topographical elevations change during the study dates. This assumption is in accordance with Abate et al. (2015) and Mulatu et al. (2018). DEM data for 1957 and 1982 was not available to apply orthorectification processes. We orthorectified the aerial photographs in three steps: building the aerial photo interior orientation, building the aerial photo exterior orientation and orthorectification.

The interior and exterior orientation of each image was orthorectified by using ENVI version 4.3 image analysis software. The interior orientation of each aerial photograph was determined by using fiducial marks and focal lengths from camera calibration information. The exterior orientation was determined by using at least 10 ground control points (GCPs) which were collected churches and road curves. In some locations, the GCP coordinates and elevation data were collected in field surveys by using a Garmin Global Positioning

System instrument and by referring to topographic maps. Geometrically corrected satellite images (QuickBird, Worldview-2, SPOT-7, and IKONOS) were also used as reference images to determine GCP coordinates (eastings and northings). In addition, images were orthorectified by using 30-m Shuttle Radar Topography Mission (SRTM) data (http://dwtkns.com/srtm30m/) and then registered to the ENVI 4.3 coordinate and map projection system (UTM Zone37 North WGS84). Some orthorectified images showed relatively lateral displacements when overlapped to each other. This was done by using image-to-aerial photo registration of these layers to the recent high-resolution satellite images. The spatial accuracy was between 1.5 and 4.6 m, which is smaller than the pixel size of orthorectified images (5 m × 5 m). Finally, all orthorectified images were imported into ESRI ArcMap 10.4.1 software in GeoTIFF format for further analysis.

For VHR satellite images, we used Airbus Defence and Space satellite imagery products (Table 2.2). All images were radiometrically and geometrically corrected and registered to the UTM Zone37 North WGS84 projection system in GeoTIFF format. The average horizontal positional accuracies reported for all images were between 2.7 to 5.7 m and also all images excluding terrain distortion by using quality DEM and GCPs. Satellite image data were not available for Aba Gerima in 2011 or 2012. All images used, except the 1957 aerial photographs of Guder site, were acquired during spring, when weather conditions are dry and skies are clearer in the tropical highlands of Ethiopia, so that vegetation and cloud cover would not affect image quality and the identification of gullies and other landscape features (Mekuriaw et al., 2017).

Table 2. 2 Information about the aerial photographs and satellite images used in the study.

Raster image source	Date acquired (dd/mm/yyyy)	Resolution (m)	Spectral resolution
Aerial photographs	26/11/1957	2.1	Panchromatic
Aerial photographs	7/2/1982	1.9	Panchromatic
SPOT-7	26/03/2016	1.5	Multispectral
QuickBird	6/3/2005	0.65	Multispectral
IKONOS	6/4/2006	0.82	Multispectral
IKONOS	26/03/2006	0.82	Multispectral
Worldview-2	3/5/2011	0.46	Multispectral
Worldview-2	4/2/2012	0.46	Multispectral
Pleiades	11/1/2017	0.5	Multispectral

2.2.3 Mapping of gullies

All images were imported in GeoTIFF format into the ArcMap software for analysis. Gullies were delineated and mapped by stacking all the images of the same area from the different years. The general methodological approach is presented in (Fig. 2.3). Gullies length were obtained by manually digitizing the extension of the gully network by visual interpretation of each image using shape, shading, grey tones and texture, drainage patterns, and associated features (Hayas et al., 2017; Kropacek et al., 2016; Sonneveld et al., 2005). Gullies were mapped on images at resolutions of 1:1500 (SPOT-7), 1:1000 (QuickBird), 1:1500 (IKONOS), 1:1000 (Worldview-2), 1:1000 (Pleiades), and 1:2500 (aerial photographs). As necessary, the images were zoomed to larger scales to better distinguish details. Gully length was determined separately on aerial photographs and VHR satellite images by using the spatial analyst extension in the ArcMap software. Ephemeral gullies and those stabilized by vegetation and grass were excluded.

Although manual identification is time consuming, gullies and other landscape features could be easily distinguished from their surroundings. Field verification of the results of image interpretation was undertaken for the three paired watersheds within the different landscape positions. The visual interpretations were validated and gully distributions were confirmed by using detailed field survey data obtained from May to August 2017. The field verifications allowed evaluating the location of digitized gullies, recognizing the gully status, and gully management activities by local communities. In addition, this field verification showed that ephemeral gullies in cultivated lands and stabilized gullies were missed in the aerial mapping. To accurately map gullies on aerial photographs and satellite images, it is very important to understand the landscape topography and river network in each watershed so that permanent stream channels and other landscape features are not mistakenly interpreted as gullies. In additions, it was challenging to monitor gullies developing under forestlands and identify active and non-active gullies by using satellite remote sensing images. In addition, in the field surveys, we confirmed that gullies could form on many different land use types in the three sites (Fig. 2.4).

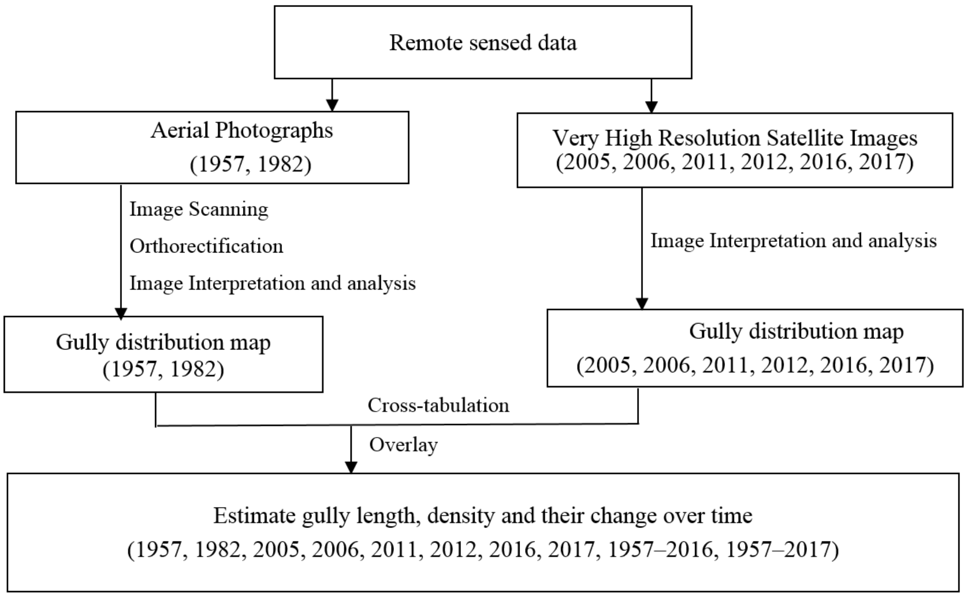

Figure 2. 3 Gully mapping methodology.

Figure 2. 4 Examples of active gullies developed on different land use types. (a) by roadside in Aba Gerima; (a) cultivated land and roadside in Dibatie; (c) grazing land in Aba Gerima; and (d) cultivated land in Dibatie.

The total length of all gullies L_t in each watershed was computed by summing the lengths of each gully identified on the images (Eq. 1) and gully density D_g in each watershed was calculated by dividing L_t by the watershed area (Eq. 2). The change in L_t over time, ΔL, in each watershed was computed by dividing L_t by the time period in years between the consecutive image (Eq. 3).

$$L_\mathrm{t} = \sum_{i=1}^{n}(L_i), \quad (1)$$

where L_t = total gully length (km), n = the number of individual gullies, and L_i = the length of each individual gully (km).

$$D_\mathrm{g} = L_{\mathrm{t}/A}, \quad (2)$$

where D_g = gully density (km km^{-2}) and A = watershed area (km^2).

$$\Delta L = L_{t/\Delta T} \, , \tag{3}$$

where ΔL = the change in total gully length (km yr^{-1}) and ΔT = the time between the consecutive images (yr).

2.3 Other data

Knowledge of the factors controlling gully erosion and their interactions is important for developing effective gully management strategies. Factors influencing the initiation and development of gullies include soil type, rainfall, slope gradient, land use type, lithology of the bedrock, and topography (Mukai, 2017; Poesen et al., 2003). In this study, we focused on land use type, slope gradient, and rainfall intensity. Changes in land use and cover were determined using data for different years in the three agro-ecologies (Guder, 1982, 2006, 2012, and 2017; Aba Gerima, 1982, 2005, and 2016, and Dibatie, 1982, 2006, 2012, and 2017). The land use and land cover map data are adapted from Berihun et al. (2019a). Maps of slope gradients were constructed by using SRTM elevation data (resolution, 30 m) and the ArcGIS spatial analyst tool extension. The slope classification was done based on FAO guidelines for soil description (Jahn et al., 2006). The spatial distributions of land use and slope gradients were considered in relation to gully density in 2016 or 2017 in the three agro-ecologies. The relationships between landscape features such as slope gradient and land use type and gully development were investigating by using the ArcGIS spatial tool.

Recent global-scale study showed that gully head retreat rates are very sensitive to rainfall intensity (Vanmaercke et al., 2016). However, in our study sites, detailed rainfall intensity data are unavailable. Hence long-term daily rainfall data were obtained from the nearest rainfall stations (i.e. Injibara Station for Guder, Bahir Dar Station for Aba Gerima, and

Bullen Station for Dibatie) were used for this study. To evaluate the effect of rainfall intensity on gully initiation and development, we tested two rainfall proxies: (1) “heavy-rainy” days with a precipitation amount >20 mm d^{-1}, a threshold for high erosive rainfall intensity established by Sultan et al. (2018) for our study sites and (2) long-term rainy day normal (RDN), calculated by dividing the average annual precipitation by the average number of rainy days in a year (Wilson and Jayko, 1997; Vanmaercke et al., 2016). Accordingly, the number of “heavy-rainy” days and RDN were calculated for Guder (1985–2016), Aba Gerima (1961–2016), and Dibatie (1980–2016) sites. Then we compared the respective proxies with gully densities observed during the corresponding five study years (1957, 1982, 2005/6, 2011/12, and 2016/17) for each site.

2.4 Results and discussion

2.4.1 Spatio-temporal distribution of gullies

The analyses of the aerial photographs and satellite images clearly showed the spatio-temporal distribution of gullies in the three study areas in the Upper Blue Nile basin (Fig. 2.5). Gully length varied greatly, and gullies were observed in many different locations in the paired watersheds of all three agro-ecologies. Similarly, Billi and Dramis (2003) reported that gullies can occur in any climatic, soil type, lithologic, and substratum setting in Ethiopia, with and Frankl et al. (2011b) found evidence that gully erosion has been occurring in the northern highlands of Ethiopia for over 10 decades. Natural and human factors inducing gully erosion since 1935 in northern Ethiopia include a land tenure system unconstrained by any land management policy, rapid population growth, land use and land cover changes, and high runoff from precipitation (Descheemaeker et al., 2006; Guyassa et al., 2018; Nyssen et al., 2009; Nyssen et al., 2014; Teka et al., 2013).

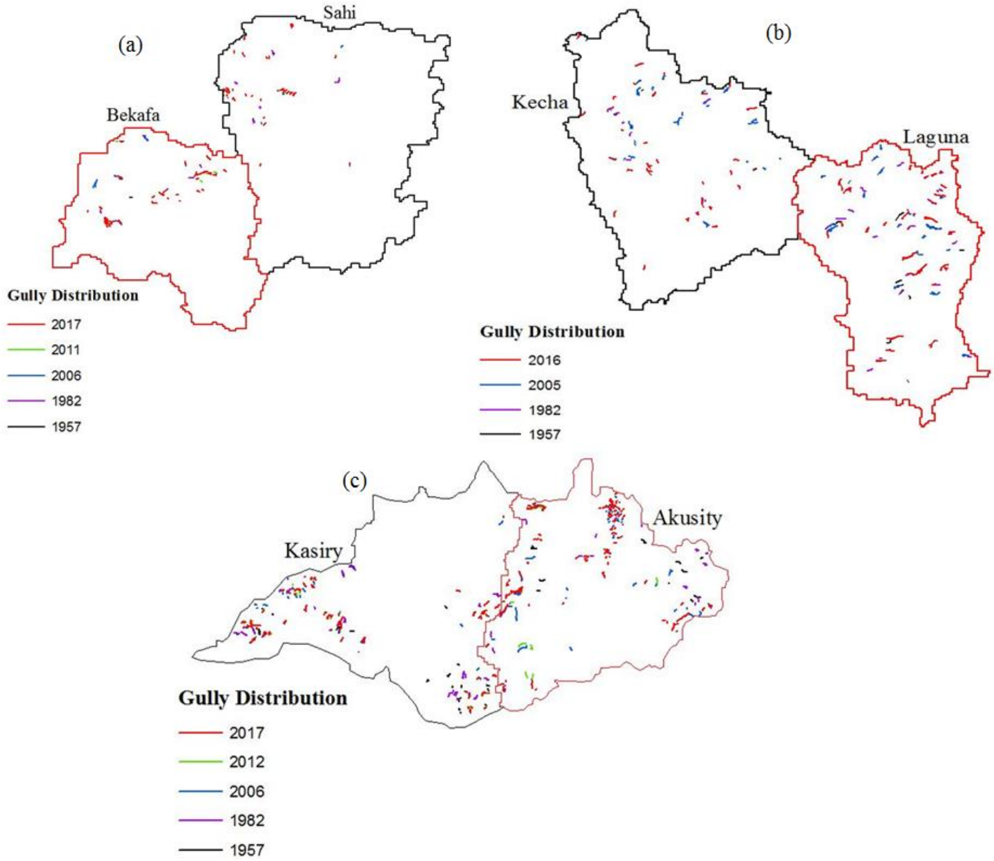

Figure 2. 5 Distribution of gullies in the paired watersheds in (a) Dibatie (lowland); (b) Aba Gerima (midland); and (c) Guder (highland).

2.4.2 Gully length

Total gully length L_t increased with time within each watershed and differed among the watersheds (Fig. 2.6). The minimum total length was 0.1 km in 1957 in Bekafa, and the maximum was 3.5 km in 2017 in Akusity. From 1957 to 2016 or 2017, L_t increased by 1.8 and 2.7 km in Kasiry and Akusity (Guder), respectively; by 1.6 and 2.4 km in Kecha and Laguna (Aba Gerima), respectively, and by 0.8 and 1.3 km in Sahi and Bekafa (Dibatie), respectively. Thus, although gully lengths increased considerably over time in all watersheds, in each paired watershed the increase in L_t was smaller in the watershed in which SWC measures have been implemented.

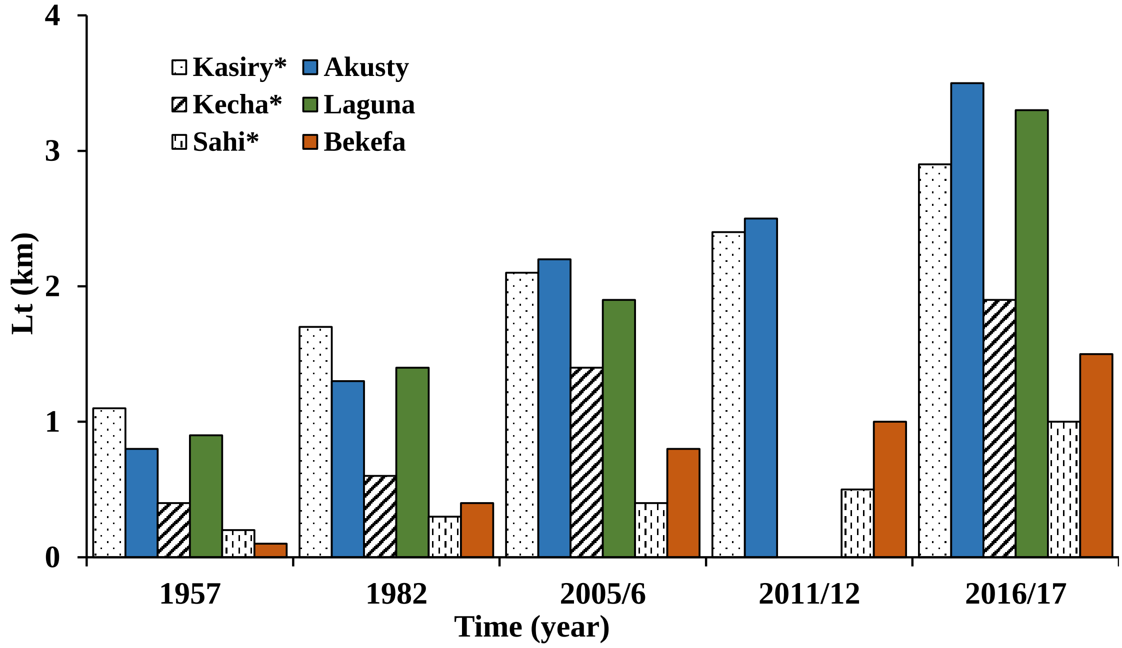

Figure 2. 6 Variation through time in total gully length (Lt) in each watershed. * SWC measures.

In all the watersheds, L_t increased exponentially with time (Fig. 2.6, Table 2.3), although the coefficients of the fitted equation differed among the watersheds, clearly reflecting differences in biophysical factors (rainfall, land use/cover distribution and change, and slope gradient) among them (Table 2.1 and Fig. 2.1).

$$Lt = ae^{bt} \tag{4}$$

Here, L_t is total gully length, t is time, and a and b are coefficients determined by the fitting. The fitted equations have high coefficient of determination (R^2) values, which indicates a strong relationship between gully length and time.

Table 2. 3 Fitted parameters of Eq. (4) for gully length in relation to time in each watershed.

	Guder		Aba Gerima		Dibatie	
	Kasiry*	Akusity	Kecha*	Laguna	Sahi*	Bekafa
a	1.12	0.77	0.36	0.86	0.18	0.11
b	0.02	0.02	0.03	0.02	0.02	0.04
R^2	0.97	0.97	0.97	0.94	0.81	0.98

* SWC-treated watershed

L_t increased more slowly in the watersheds with SWC measures, especially in Guder and Dibatie, than in the watersheds without SWC measures.

The finding that gully length increased over six decades in both watersheds of each paired watershed indicates that even when SWC measures were implemented, they were not completely successful in halting gully erosion. In the most recent decade, gully length in cultivated lands increased more in Dibatie than in Guder or Aba Gerima. The main reasons for this difference were attributed to expansion of cultivated land combined with inappropriate farming practices such as poor implementation of soil and water conservation structures (Fig. 2.13). In central Ethiopia, total gully length increased from 30.5 to 91.6 km over the period from 1965 to 2013 in a watershed with an area of 49.3 km^2 (Kropacek et al., 2016). Furthermore, an increase of gully length from 21.3 to 38.2 km between 1860 and 1920 in a 58 km^2 watershed in Hungary was attributed to vegetation removal (reductions of 30% in forest cover and 3.1% in shrub cover) and cultivation activities (Gábris et al., 2003). In contrast to our findings, Nyssen et al. (2006) reported an inconsistent gully development trend from 1960 to 2000 in the northern highlands of Ethiopia: although gully length increased from 1977 to 1990, major development of gullies ceased after 1995. Similarly, Frankl et al. (2011a) reported an increase in gully development from 1960 to 2000, and a decrease after 2000, which they attributed to gully management interventions. In general, the increasing trends in gully length in the three agro-ecologies in this study imply that land degradation increased from 1957 to 2016 or 2017.

The total number of gullies in each watershed (Fig. 2.7) varied from a minimum of 3 in 1957 in Bekafa to a maximum of 144 in 2017 in Akusity. The number of gullies increased from 1957 to 2016 or 2017 by 54 and 118 in Kasiry and Akusity, respectively, by 26 and

41 in Kecha and Laguna, respectively, by 35 and 37 in Sahi and Bekafa, respectively. The total number of gullies during the study period was highest in Guder and lowest in Dibatie. The severity of gully erosion and the state of land degradation at the three sites can be inferred by considering both the number of gullies and their total length. Although the total number of gullies in the most recent decade (2006–2016 or 2017) was similar for Dibatie and Aba Gerima, total gully length was greater in Aba Gerima (Fig. 2.7). The number of small sized gullies in the Guder site was greater compared to that in the Aba Gerima site. The number of longer gullies, however, was larger in the Aba Gerima site than in Guder. This difference is mainly related to the variation in topography, land use type, and rainfall characteristics between the sites (Table 2.1 and Figs. 2.10 and 2.14). Therefore, further study is crucial in consideration of comparing sediment loss rates and sediment connectivity from larger number of small sized gullies versus small number of longer gullies.

The topographical and human factors controlling gully formation and development vary spatially. During the last six decades, gully length and number were highest in Guder, indicating that the watersheds were highly dissected by gully erosion (Table 2.1). This result reflects the fact that drainage networks are more developed and slope gradients are steeper in Guder, with the result that runoff amounts are higher there than in Dibatie or Aba Gerima and gully formation is promoted on the gentle slopes (Table 2.1). In addition, rainfall is relatively high in Guder, compared with the other two agro-ecologies, so a high drainage density is necessary to drain the excess rain from farm fields, and this necessity can lead to gully initiation (Sultan et al., 2018).

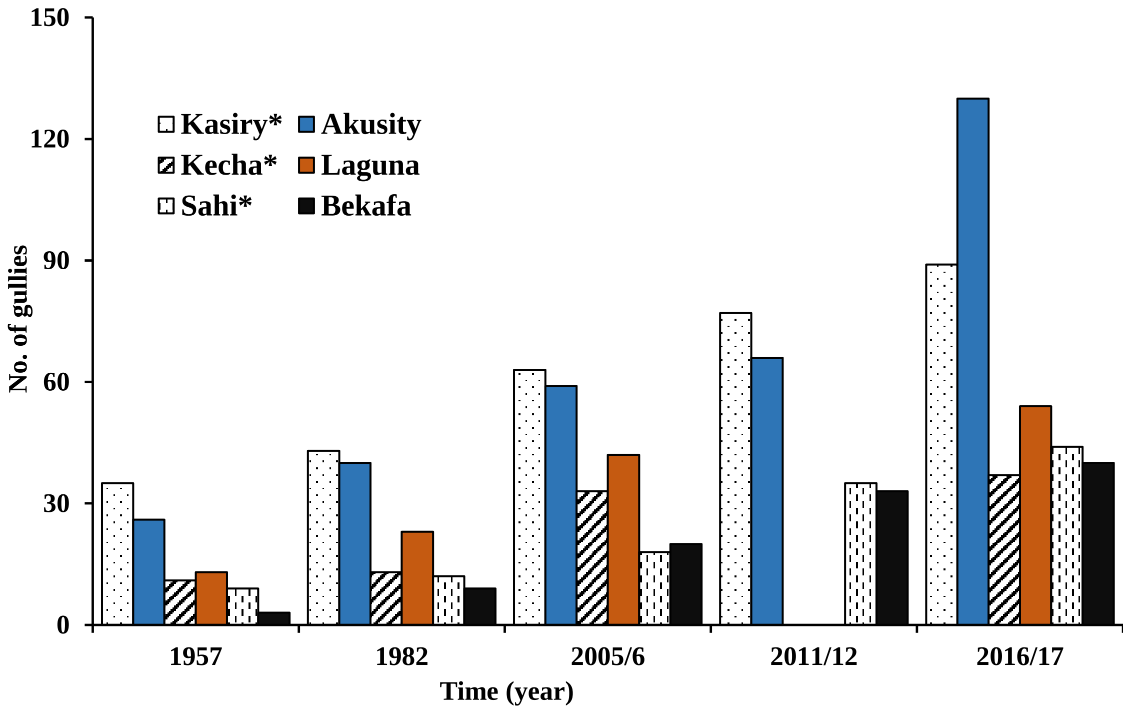

Figure 2. 7 Changes in the total number of gullies between 1957 and 2016 or 2017 in each watershed. *SWC measures.

2.4.3 Rates of change in gully length

Gully length increased at different rates in the different watersheds over the period from 1957 to 2016 or 2017 (Table 2.4). The maximum annual rate of increase in gully length of 182.7 m yr^{-1} was observed in Akusity watershed during 2012–2017, the highland watershed without SWC measures. The minimum rate of 1.5 m yr^{-1} was observed in Sahi watershed during 1982–2006.

Table 2. 4 Annual rates of increase in total gully length in each watershed.

Period (number of years)	Change in total length (m yr^{-1})					
	Guder		Aba Gerima		Dibatie	
	Kasiry*	Akusity	Kecha*	Laguna	Sahi*	Bekafa
1957–1982 (25)	24.9	22.1	9.5	20.2	2	10.7
1982–2005/2006 (24)	20.8	37.6	36.8	23	1.5	17.4
2006–2011/2012 (6)	30.2	49.8	–	–	40.5	32.8
2005–2016 (11)	–	–	42.5	125	–	–
2011/12–2017 (6)	91.6	182.7	–	–	106	97.1
1957–2016/2017 (60)	29.4	44.5	26.3	40.8	13.4	22.2

* SWC measures

The large differences observed in the rate of increase in gully length among the paired watershed and between members of each pair can be attributed to differences in daily rainfall amounts and tillage practices; gully length increases faster where daily rainfall is higher and where conventional tillage practices are followed. This finding is in agreement with the findings of Tebebu et al. (2010) and Zegeye et al. (2016), who showed that in sub-humid tropical areas, a rise in the groundwater table above gully bottoms due to high rainfall is a dominant cause of the expansion of gully erosion. Kropacek et al. (2016) reported annual rates of increase in total gully length (200, 1200, and 400 m yr^{-1} during the period 1967–1971/1972, 1971/1972–2006, and 2006–2013, respectively) in the central highlands of Ethiopia that are generally higher than the rates obtained in this study. The large difference in rates is mainly attributable to differences in watershed area (i.e., 4930 ha in their study versus 246–424 ha in our study).

Similar studies elsewhere show comparatively higher spatial variability. Gábris et al. (2003) reported in north-eastern Hungary, an annual rate of increase in gully length of 115 m yr^{-1} from 1860 to 1920, caused by land use changes, and Firth and Whitlow (1991) reported an annual rate of change of 2.9–12.3 m yr^{-1} during 1948–1973 in Zimbabwe. Therefore, the rate of gully development is highly likely to be influenced by the location and scale of the study area; hence, site-specific assessment is necessary to precisely determine temporal changes in gully features. The rates observed in this study are within the range of the annual gully head-cut retreat rates of 0.01 and 135 m yr^{-1} reported by Vanmaercke et al. (2016) based on data compiled for 933 individual and actively retreating gullies from more than 70 study areas worldwide.

2.4.4 Gully density

Gully density also varied between paired watersheds in the three agro-ecologies (Fig. 2.8). The maximum gully density was in Akusity (10.1 m ha^{-1}) in the highland, followed by Laguna (9.8 m ha^{-1}) in the midland, and the minimum densities were observed in Sahi (2.6 m ha^{-1}) in the lowland and Kecha (4.5 m ha^{-1}) in the midland. Gully density increased in all three paired watersheds during the study period, but in recent 10 years' watersheds with SWC measures had lower gully densities than those without such measures. Thus, the implementation of SWC practices appeared to reduce gully initiation and development across the three agro-ecologies.

During the last six decades (1957–2016 or 2017), gully density increased on average by 5.9 m ha^{-1} in Guder, 5.4 m ha^{-1} in Aba Gerima, and 3.7 m ha^{-1} in Dibatie. Over this time period, gully density tripled in Guder, quadrupled in Aba Gerima, and increased by a factor of eight in Dibatie. These results can be explained by differences in gully evolution among the agro-ecologies due to differences in biophysical factors such as drainage density, topography, soil type, rainfall amount and intensity, and land use distribution (Table 2.1 and Fig. 2.1). We examine the effects of slope gradient, land use, and rainfall in detail in section 4.2. As observed in the case of total gully length, gully density increased less and at a slower rate in SWC-treated watersheds in Aba Gerima and Dibatie sites (Table 2.5 and Fig. 2.8).

Table 2. 5 Fitted parameters of Eq. (4) for gully density in relation to time in the study watersheds.

	Guder		Aba Gerima		Dibatie	
	Kasiry*	Akusity	Kecha*	Laguna	Sahi*	Bekafa
a	2.85	2.24	0.75	2.5	0.5	0.53
b	0.02	0.02	0.03	0.02	0.02	0.04
R^2	0.98	0.98	0.99	0.94	0.62	0.99

* SWC measures

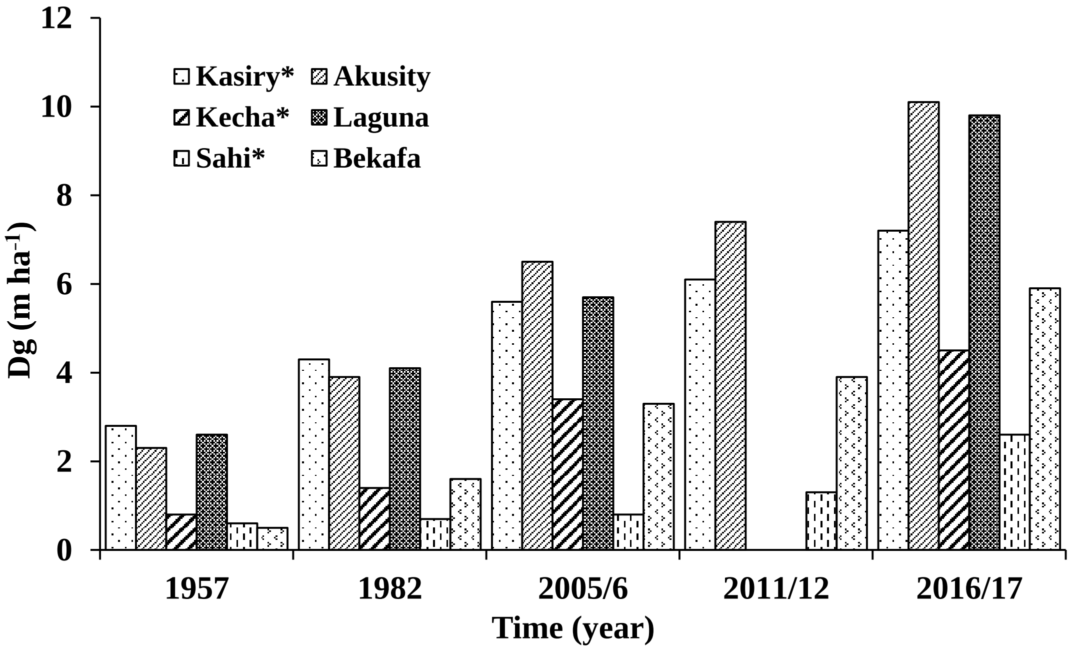

Figure 2. 8 Variation through time of gully density (Dg) in the study watersheds. * SWC measures.

We also found that the gullies were concentrated in a smaller portion of each watershed in the Guder and Dibatie agro-ecologies, whereas they were more scattered in Aba Gerima (Fig. 2.5). This heterogeneous distribution among the sites reflects differences in drainage density, soil type, rainfall amount and intensity, slope gradient, and land use/cover among the three agro-ecologies (Table 2.1 and Figs. 2.10 and 2.14). The high gully densities observed in Guder are linked to the more developed drainage networks (Table 2.1 and Fig. 2.2) and steeper slope gradients concentrate the runoff (Sultan et al., 2018) and thus promote gully formation on gentle slopes there more than in Aba Guder and Dibatie.

These findings are consistent with those of Kropacek et al. (2016) and Guyassa et al. (2018), who reported that gully density increased by 12.2 m ha^{-1} during 1965–2013 in the Ethiopian Rift valley and by 11.4 m ha^{-1} in 1935/1936 and 15.9 m ha^{-1} in 2014 in northern Ethiopia, respectively. Gully density increases in South Africa of 64 m ha^{-1} in 1981 (Garland and Broderick, 1992), and gully density increases in Zimbabwe from 20.0 m ha^{-1} in 1948 to 30.0 m ha^{-1} in 1973 (Firth and Whitlow, 1991) were caused by land use changes, from forest to cultivated and grazing lands. Our results are also similar to those of Zhang et al. (2015), who found that in Kebai Region in Heilongjiang Province, China, gully density increases depended on elevation differences within a watershed; they reported increases of 57.5% in a hilly watershed and of 52.9%, and 25.2% watersheds on a mesa and a plain, respectively, from 1945 to 2000. However, Sidorchuk et al. (2003) showed that gully density increases at a high rate during the gully initiation stage but then declines over time when gully management measures are implemented.

2.5 Controlling factors of gully erosion

2.5.1 Influence of slope gradient

Within each paired watershed, gullies were distributed in areas with similar slope gradients, but among the three agro-ecologies, the association of gully distribution with slope gradient varied (Fig. 2.9). Gully density tended to be higher on slopes with lower gradients (0–15°) in all three sites (Fig. 2.10). In all the watersheds, gullies were located mainly on gentle slopes with gradients of less than 15°, although in Guder, some gullies were located on steep slopes. In addition, gentle slopes (0–15°) accounted for most of the area in each watershed. In general, in the midland and lowland agro-ecologies, gully density increased as the slope gradient increased to 15° and then decreased at gradients greater than 15°.

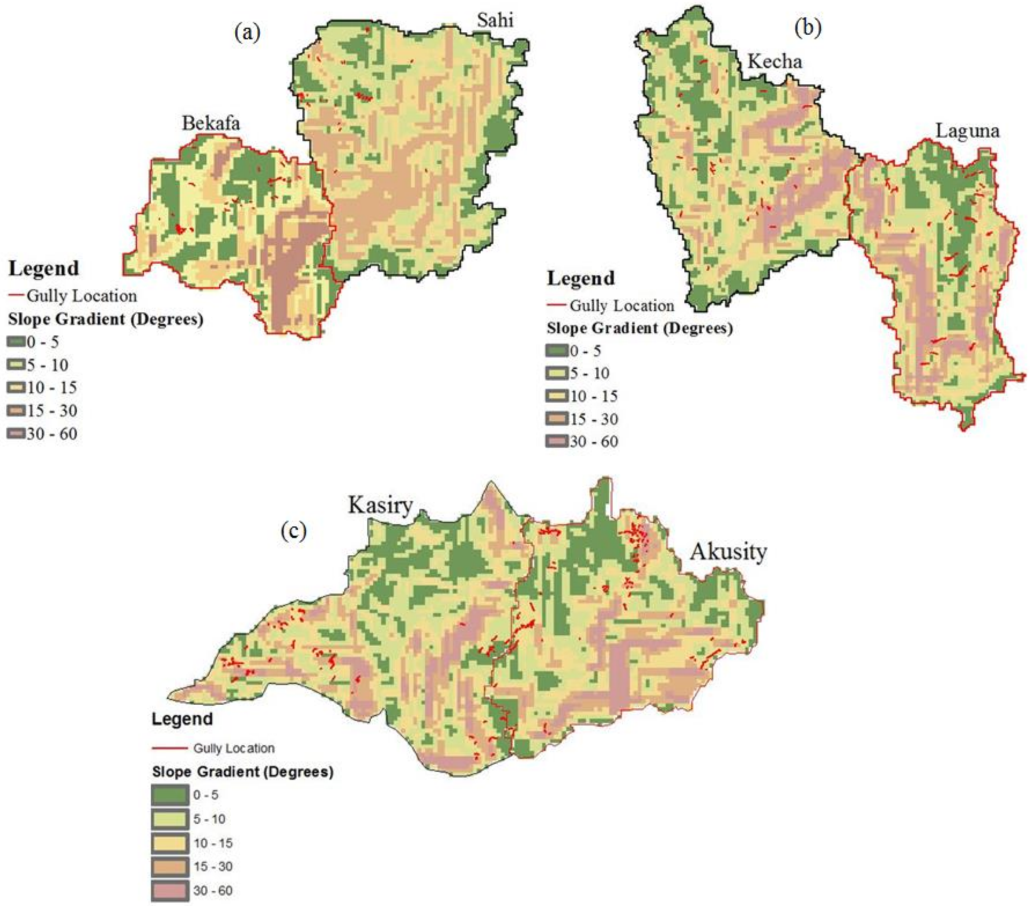

Figure 2. 9 Slope gradients and gully locations in the paired watersheds in (a) Dibatie, (b) Aba Gerima, and (c) Guder.

The higher gully density on gentle slopes can be explained partly by the concentration of runoff from continuously cultivated and grazed landscapes in the study watersheds (Sultan et al., 2018). Kropacek et al. (2016) also found that in the central highlands of Ethiopia gullies occur more extensively on gentle slopes. Poesen et al. (2003) showed that increases in the upslope drainage area can lead to higher runoff volumes and result in gully incision downslope. In South Africa, gentle slope gradients have also been found to be more susceptible to gully erosion because they are associated with an increased drainage area, which leads to higher runoff amounts and gully erosion in grazing and cultivated lands on gentle slopes (Kakembo et al., 2009; Laker, 2004; Le Roux and Sumner, 2012). Zhang et al. (2015) reported that in Kebai Region in Heilongjiang Province, China, the threshold gradient for gully formation was 3°.

Another possible explanation for the frequent occurrence of gullies on slopes with low gradients is that such slopes are commonly composed of colluvium deposits. These redeposited sediments are typically layered, which can cause vertical discontinuities in permeability. Thus, a perched water table might occur above a relatively impermeable deposit and the resulting water saturation of the surface soil might weaken soil strength, thus creating favourable conditions for the initiation of gully incision by runoff. A future study should collect the data necessary to test this hypothesis. This explanation is in line with the findings of Tebebu et al. (2010) and Bayabil et al. (2010), who found that in the northern highlands of Ethiopia, water infiltrates in upslope areas whereas erosion-inducing runoff occurs downslope; thus, excess water flows more rapidly to gentle slopes as lateral flow, leading to gully formation.

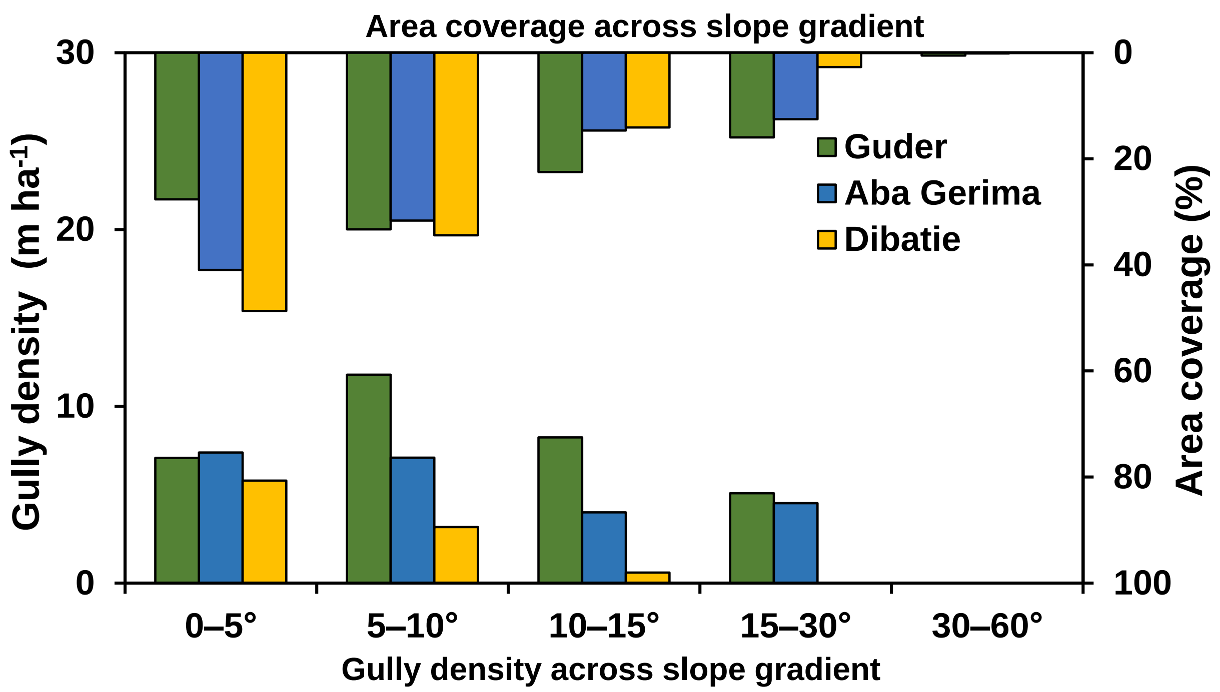

Figure 2. 10 Distribution of gully density for different slope gradient classes at the study sites.

Likewise, in northern Ethiopia severe gullying is observed on gentle slopes and gully density is lower on steep slopes (Tamene et al., 2006). One possible reason for this is that access is limited to steep areas, so they are less exposed to disturbances by humans and livestock. An additional factor that often limits the formation of gullies (and erosion on general) on steep slopes are the shallow soils and high rock fragment cover. Gully density and slope gradient are strongly related, but there exists a threshold gradient for gully formation (Poesen et al., 2003). Similarly, in China, gully density increases with slope gradients up to 3° and decreases as the slope gradient increases above that threshold (Zhang et al., 2015).

In contrast to our results, however, Guyassa et al. (2018) have reported that in northern Ethiopia more gullies develop on steeply sloping landscapes. Other studies have similarly found that gullies are common features in hilly regions with steep slopes because high runoff velocities lead to gully formation (Gábris et al., 2003; Valentin et al., 2005). Moreover, our results showed that the effect of slope gradient on gully formation and development differed among the three agro-ecologies implying that site and slope specific information on initiation of gully erosion is very crucial to propose appropriate management strategies.

2.5.2 Influence of land use distribution and change

In 2016/2017, gullies were distributed in areas with similar land uses types within each paired watershed, whereas their distribution showed more variation with respect to land use types among the three agro-ecologies (Fig. 2.11). Gullies in all watersheds were mainly located on cultivated and grazing lands. Gully density averaged 6.7 m ha^{-1} in Guder, 8.9 m ha^{-1} in Aba Gerima, and 7.7 m ha^{-1} in Dibatie in 2016/2017 (Fig. 2.12), and it was higher in cultivated lands in all three sites. In the highland and midland agro-ecologies the next most vulnerable land use types to gully erosion, after cultivated lands, were grazing lands and degraded bushlands (Fig. 2.12). In grazing lands, gully density averaged 36.1 m ha^{-1} in Guder and 6.4 in m ha^{-1} in Aba Gerima, whereas in degraded bushlands, it averaged 14.9 m ha^{-1} in Guder, 6.2 m ha^{-1} in Aba Gerima, and 2.2 m ha^{-1} in Dibatie.

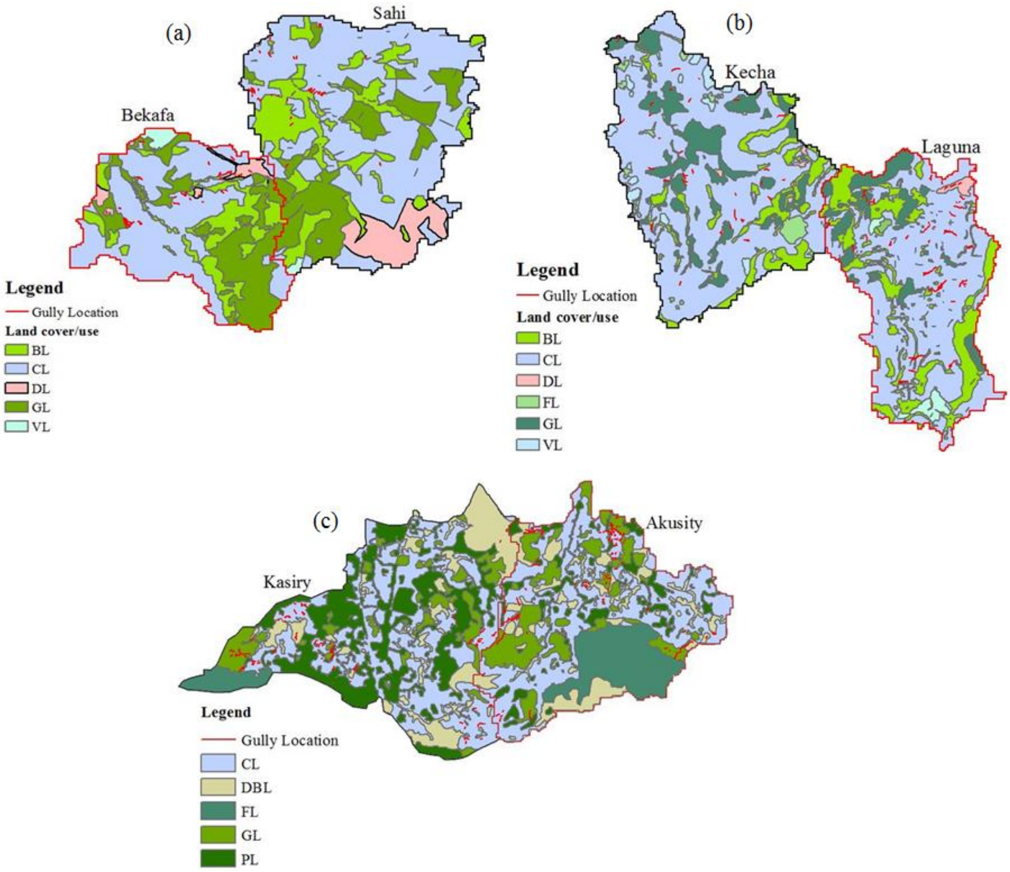

Figure 2. 11 Current (2016/2017) land use types and gully locations in the paired watersheds in (a) Dibatie, (b) Aba Gerima, and (c) Guder. CL, cultivated land; BL, bushland; GL, grassland; DL, degraded land; DBL, degraded bushland; PL, plantation; FL, forest; VL, village land.

Most importantly, our results indicate that cultivated lands are greatly vulnerable to gully erosion because of improper land management practices and poor vegetation cover. For instance, farmers usually construct drainage ditches parallel to the slope gradient in sloping cultivated lands to drain excess water from their fields. This design, however, concentrates the local flow and leads to gully formation (Fig. 2.13). Monsieurs et al. (2015) and Simane et al. (2013) also reported that improper design and construction of drainage ditches caused the initiation of gully erosion in the subhumid-tropical highlands of Ethiopia. Similarly, Casalı et al. (1999) showed that conventional farming practices (i.e., without SWC measures) and a lack of properly constructed channels for conveying excess water away from fields triggers gully formation.

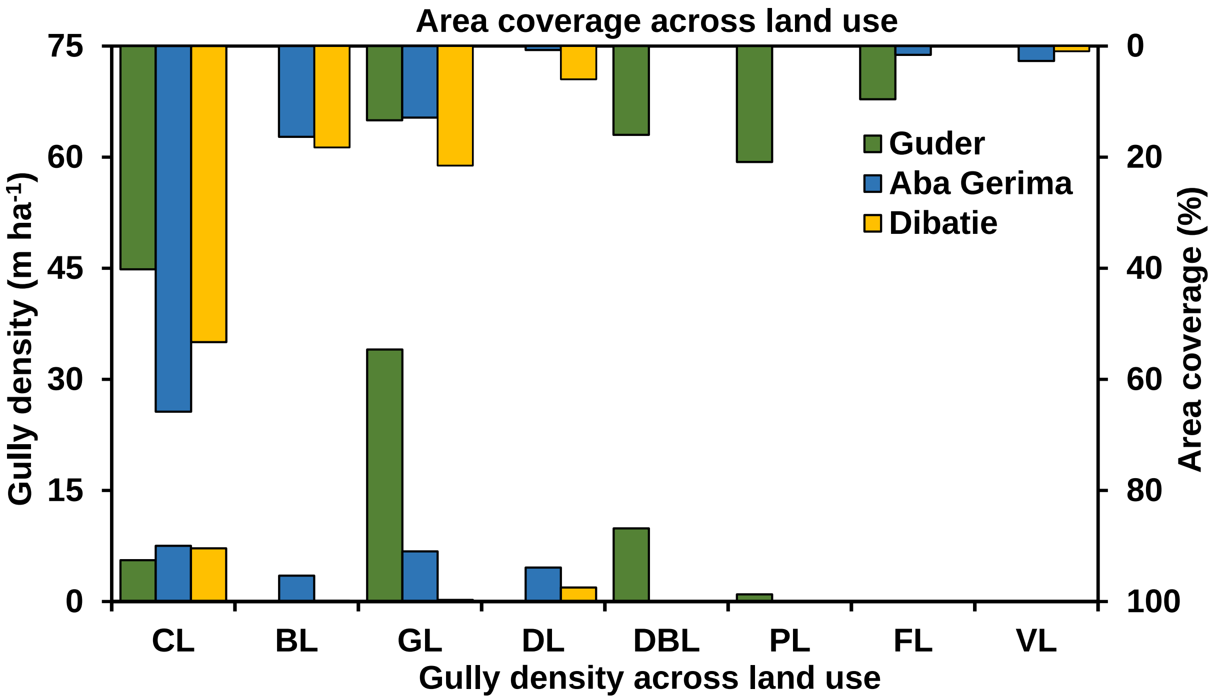

Figure 2. 12 Land use and gully density (Dg) in the three agro-ecologies. CL, cultivated land; BL, bushland; GL, grassland; DL, degraded land; DBL, degraded bushland; PL, plantation; FL, forest; VL, village land.

Our field observations also indicated that gullies formed as a result of incorrectly implemented SWC practices in cultivated lands in Dibatie (Fig. 2.13). For example, improper alignment of cutoff drains, waterways, and soil and stone bunds may lead to the concentration of runoff and the development of gullies downslope. Intensive use of agricultural lands, human settlement, and overgrazing cause land degradation through gully erosion in northern Ethiopia (Moges and Holden, 2008; Nyssen et al., 2009). Our study results provide an overview of the role that intensive use of agricultural lands and incorrectly implemented SWC practices plays in the formation and expansion of gully erosion in the Upper Blue Nile basin. Similarly, Avni (2005) reported that inappropriate land management practices can cause accelerated gully erosion. Poor cultivation practices can lead to gully erosion even in relatively flat areas (Kakembo and Rowntree, 2003; Sonneveld et al., 2005).

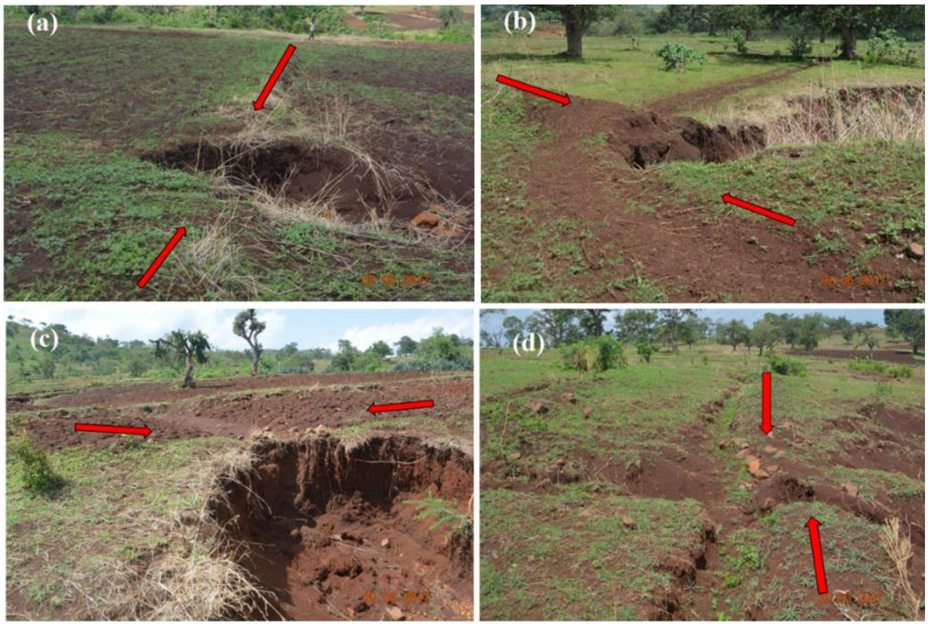

Figure 2. 13 (a-d) Examples of active gullies on farmland in Dibatie. Arrows show the direction of concentrated flow using water diversion channels which constructed by farmers from their farming lands and this is the main causes for gully development in Dibatie watershed.

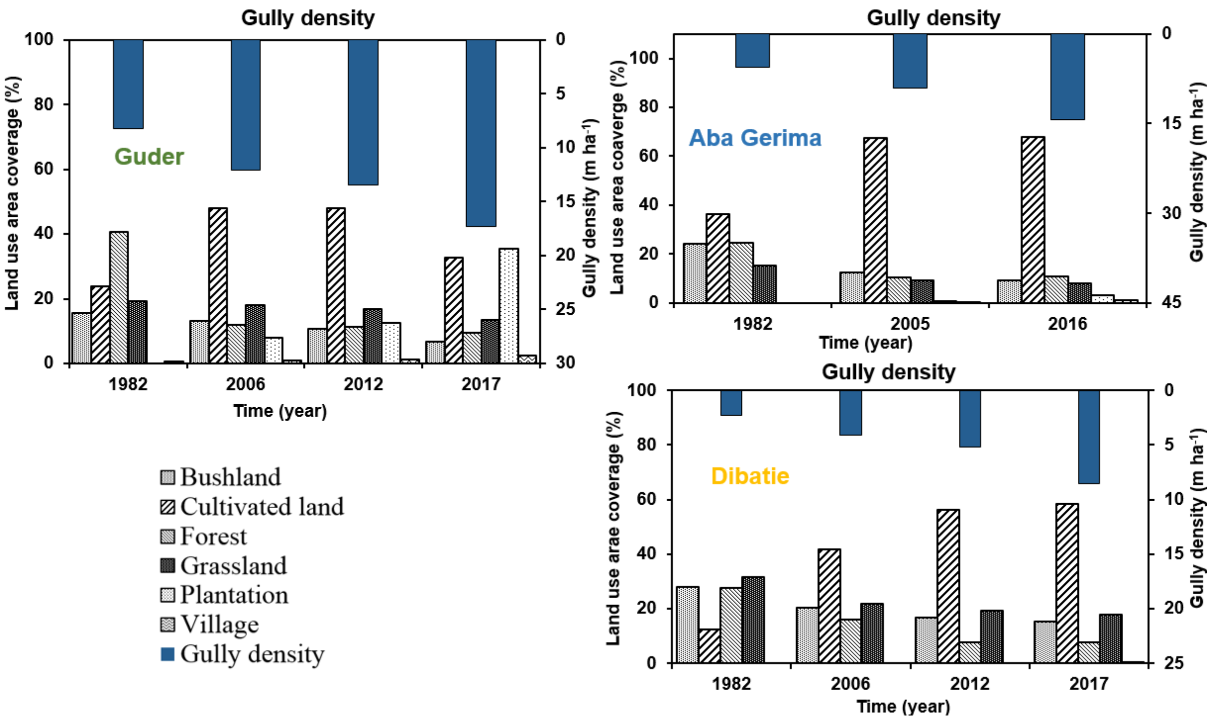

Figure 2. 14 Gully density (Dg) and land use changes between 1982 and 2016/2017 in (a) Guder, (b) Aba Gerima, and (c) Dibatie. BL, bushland; CL, cultivated land; FL, forest; GL, grassland; PL, plantation; VL, Village land.

The major reasons for gully formation in grasslands and degraded lands may be frequent soil disturbance by overgrazing and high stocking rates. Vegetation cover can reduce gully formation by increasing flow resistance and because plant roots bind the soil particles together. When the rainy season starts after the long dry season, gullies can easily develop on a disturbed surface. Sultan et al. (2018) reported that seasonal runoff from grazing lands on steep slopes was higher in Guder than in Aba Gerima and Dibatie; higher runoff in Guder was related to frequent soil trampling by animals, which reduced infiltration and thereby increased runoff, thus increasing the probability of gully formation.

In Ethiopia, gullies are common features in grasslands and rangelands because of overgrazing and soil trampling by cattle along cattle roads (Nyssen et al., 2004). In addition, it has been shown that vegetation disturbances are the major cause of the initiation of gully erosion after the introduction of livestock production in Australia and South Africa (Mararakanye and Sumner, 2017; Pringle et al., 2006). DeRose et al. (1998) showed that clearing forest to expand grazing lands accelerates gully erosion.

During the study period, both land use types and gully density changed in the three sites (Fig. 2.14). Gully density increased in all three agro-ecologies, whereas the main land use change was the conversion of forested lands and grasslands to cultivated land. In Guder, the cultivated land area increased by 24.4% from 1982 to 2006 and then decreased by 14.4% from 2012 to 2017. From 1982 to 2017, bushland and grassland decreased by 9.1% and 5.8%, respectively, in Guder, but plantation land (*Acacia decurrens*) increased by 35.4%. Likewise, in Aba Gerima, cultivated land increased by 31.8% from 1982 to 2016, whereas bushland and grassland decreased by 15.2% and 7.3%, respectively. In general, the expansion of cultivated lands was at the expense of other land uses (Fig. 2.14). From 1982 to 2017 in Dibatie, forest, bush, and grazing lands decreased by 19.9%, 12.8%, and

13.9%, respectively, and cultivated lands increased by 46%. The highest rate of land use change, which was observed in Dibatie after 1982, was due to the resettlement of people there from northern Ethiopia. In general, the cultivated land area increased and other land uses decreased between 1982 and 2016 or 2017 in the three sites. Cultivated lands are highly vulnerable to gully formation because the land is exposed and remains without protective vegetation cover for a long time because of tillage and other agronomic activities. In general, increases in the cultivated land area during the study period were strongly correlated with gully density in all three sites.

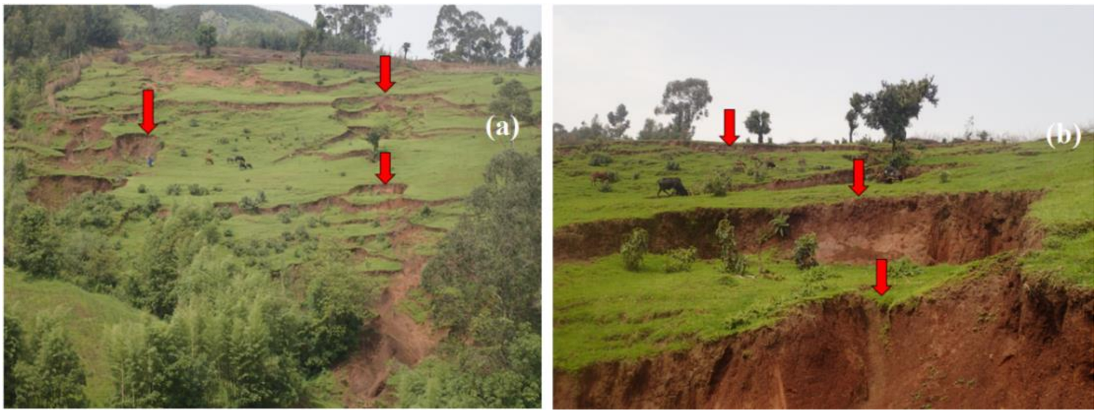

Figure 2. 15 (a and b) A land slump triggered by gully development on grazing land in Guder. Arrows indicate where gullies are eroding headward.

The increases in gully density and the cultivated land area were particularly higher in Dibatie than in the other sites because of a resettlement programme that began in the 1980s (Fig. 2.14c). According to the local district leaders, more than 60,000 people from drought-prone parts of northern Ethiopia were moved and resettled in Dibatie in 1980s as part of government-sponsored resettlement programs following a series of drought and famine events in the north and north-central Ethiopia (Comenetz and Caviedes, 2002; Meze-Hausken, E., 2000). The establishment of each settlement involved the clearing of forests and the introduction of crop cultivation and livestock farming. These land use changes may be a major cause of land degradation through gully initiation and expansion in Dibatie in recent years. Many studies in Ethiopia have shown that rapid gully development is related to land use changes, the frequent land distribution system to farmers, and inappropriate land management practices (Lanckriet et al., 2015; Moges and Holden, 2008; Nyssen et al., 2004). In addition, Gábris et al. (2003) noted that most gullies formed during periods of forest clearance and expansion of farming lands in north-eastern Hungary. In agreement with our findings, Descroix et al. (2008) reported that reductions in vegetation cover and overgrazing are the main factors causing rapid gully expansion in South Africa.

2.5.3 Influence of rainfall intensity

We examined changes in the number of intense daily rainfall events (>20 mm d^{-1}) in a year and in gully density during the corresponding five study years (1957, 1982, 2005/6, 2011/12, and 2016/17) in the three sites (Fig. 2.16). The long-term average number of intense daily rainfall events per year is an indicator of the frequency of extreme rainfall events, which can trigger gully development. On average, 36.7, 22.8, and 26.1 heavy-rainy days (rainfall > 20 mm d^{-1}) were recorded annually in Guder, Aba Gerima, and Dibatie, respectively, during the study period, and gully density showed an increasing trend over the six decades from 1957 to 2016 or 2017 across the three agro-ecologies. Although the number of intense rainfall events varied greatly across the three agro-ecologies, it showed a weak correlation trend, compare to the trend in gully density, in Guder. The increasing frequency of intense rainfall events may have been a major cause of land slumping and gully development in grazing lands, especially in Guder (Fig. 2.15). The slopes of the regression lines for Aba Gerima and Dibatie are small and negative, implying less variation in the annual number of intense daily rainfall events over the study period.

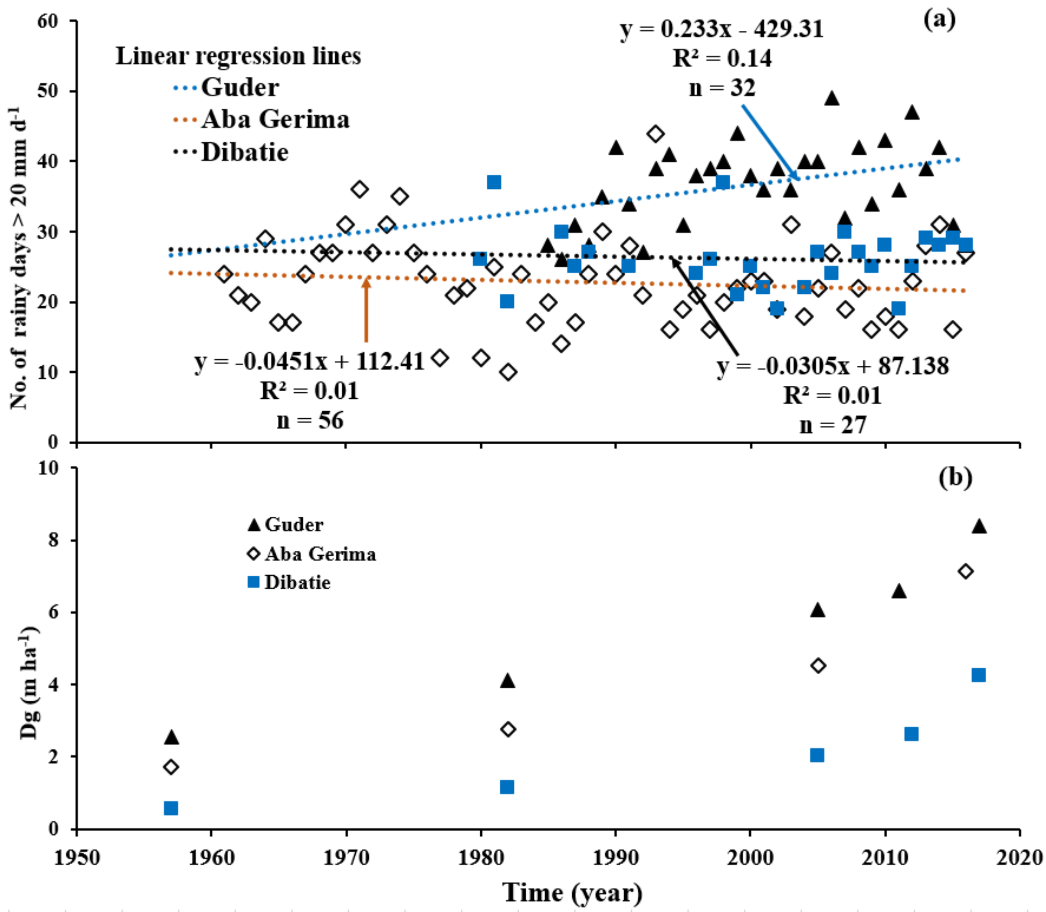

Figure 2. 16 (a) Number of intense daily rainfall events (>20 mm d–1) per year and (b) gully density (Dg) during 1957–2016/2017 in the three sites. n = numbers of years.

The rainy day normal (RDN) and gully density over the corresponding five study years (1957, 1982, 2005/6, 2011/12, and 2016/17) are presented in Fig. 2.17. Results show that gully density has weak correlation to the RDN (the long-term average annual rainfall depth divided by the average number of rainy days). The RDN clearly shows a weak correlation with gully density. Whereas, the RDN is highly varying across the three agro-ecologies during the study period, showing a relatively increasing trend with gully density in Guder site even though the trend is weak. Similar to "heavy-rainy" days the slopes of the regression lines for Dibatie and Aba Gerima are small and negative, implying less variation in RDN over the study period. However, a study done by considering worldwide gully data showed that gully head retreat has a positive relationship with RDN (Vanmaercke et al., 2016). In addition, Guzzetti et al. (2008) and Wilson and Jayko (1997) reported that RDN has strongly correlated to the occurrence of intense rainfall events that caused a landslide.

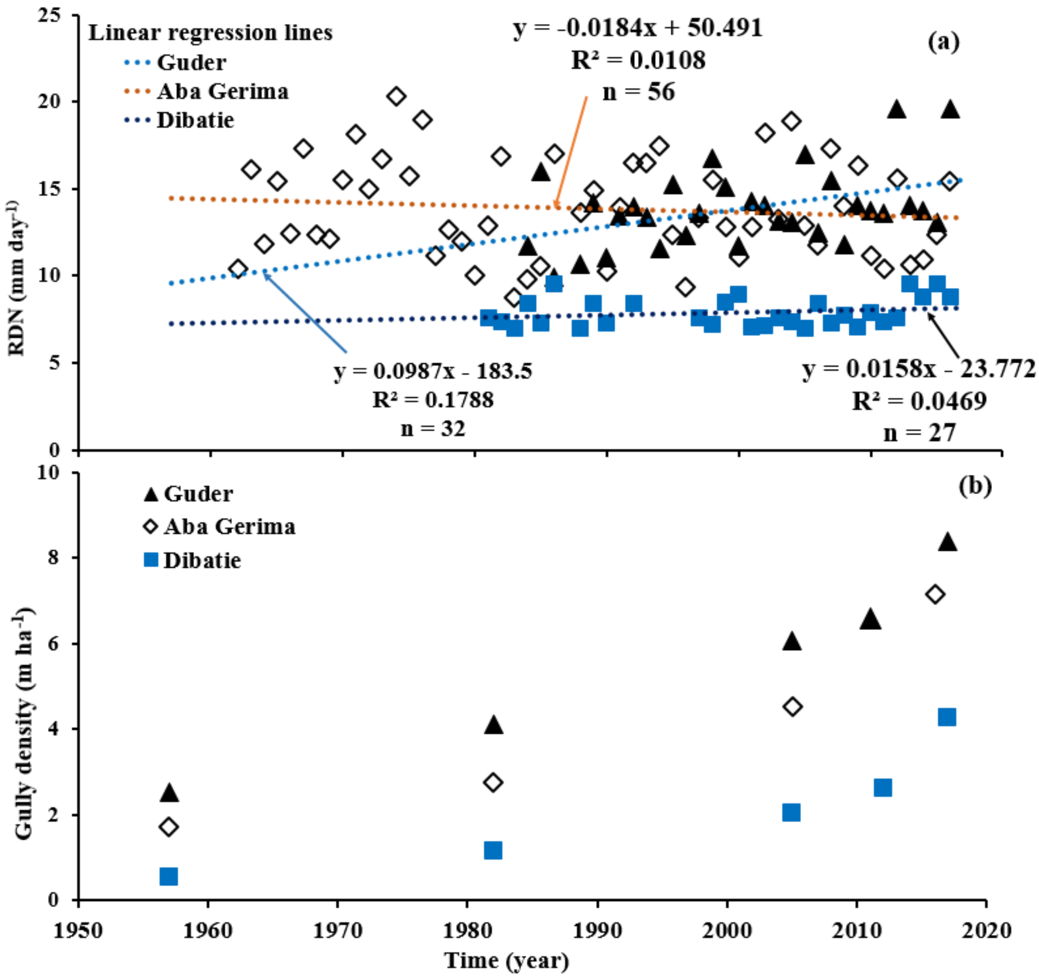

Figure 2. 17 Relation between the rainy day normal (RDN) (a) and gully density (1957–2016/17) (b) for the three sites.

Sultan et al. (2018) reported that the maximum daily rainfall intensity during 2015 was 97, 78 and 53 mm d^{-1} in Guder, Aba Gerima, and Debatie, respectively. Such high-intensity rainfall events may have had a major effect on gully initiation in the three sites. Rainfall erosivity varies according to the quantity, frequency, and intensity of precipitation events (Thiemann et al., 2005; Vanmaercke et al., 2016). Many studies have reported that ephemeral gully formation may occur during a single erosive event (Billi and Dramis, 2003). For example, the minimum conditions to initiate gully erosion in Navarra, Spain are a total rainfall depth of 17 mm and a peak rate of 54 mm h^{-1} (Casalı et al., 1999), whereas in a cropped area in Normandy, France, they are 21.6 mm and a maximum 6-min intensity of 98 mm h^{-1} (Cerdan et al., 2002). Likewise, Valentin et al. (2005) reported that extreme climatic events (i.e., heavy rainstorms) accelerated gully erosion, and Mararakanye and Sumner (2017) reported that watersheds with higher rainfall erosivity values have significantly more gully development in South Africa.

The high long-term average annual rainfall amounts (2495, 1343, and 1022 mm yr^{-1} in Guder, Aba Gerima, and Dibatie, respectively) may have been a major cause of gully formation and development because most rain events in these agro-ecologies occur after the long dry season, before vegetation cover has developed. Overall, both rainfall proxies ("heavy-rainy" days with a precipitation amount >20 mm d^{-1} and RDN), there is weak relationship between rainfall intensity and formation of gullies, in order to conclude that the increase in gully networks are due to climate change.

2.6 Conclusions

In this study, aerial photographs and VHR satellite images were used to assess the spatial and temporal dynamics of gully development in the Upper Blue Nile basin of Ethiopia over the last six decades. Our spatio-temporal analysis of gully erosion showed that it was generally higher in the highland (Guder) than in the midland (Aba Gerima) and lowland (Dibatie) agro-ecologies. This result can be attributed to variation in biophysical factors (rainfall characteristics, land use distribution and change, and slope gradient). Gully density increased by 5.9 m ha^{-1} in Guder, 5.4 m ha^{-1} in Aba Gerima, and 3.7 m ha^{-1} in Dibatie from 1957 to 2016 or 2017. Moreover, total gully length increased at a rate of 36.9 m yr^{-1} in Guder, 33.6 m yr^{-1} in Aba Gerima, and 17.8 m yr^{-1} in Dibatie over the last 60 years. Our results showed that total gully length and density varied temporally both within watersheds and among the three agro-ecologies. This variation suggests that the rate of gully development is greatly influenced by factors including rainfall, land use distribution and change, slope gradient, and the period of the study; hence, site-specific assessment is necessary to precisely determine spatio-temporal changes in gully development.

In the midland and lowland agro-ecologies, gully density was higher in cultivated lands, whereas in the highland agro-ecology, it was higher in grazing lands. In addition, gully density increased with increase in slope gradients up to 15° and then decreased as the gradients became greater than 15°. Gullies developed mainly in cultivated lands and grazing lands with gentle slope gradients in the three agro-ecologies. Moreover, although gully density showed increasing trends in the three paired watersheds during the study period, in recent years, watersheds with SWC measures had lower gully densities than those without such measures. Our results suggest that careful site-specific identification of factors controlling gully initiation and expansion is crucial for the development of appropriate gully erosion management strategies in the three study sites as well is in other area with similar agro-ecologies in Upper Blue Nile basin.

Chapter 3: Morphological characteristics and topographic thresholds of gullies in the Upper Blue Nile basin, Ethiopia

This chapter is published as:

Yibeltal, M., Tsunekawa, A., Haregeweyn, N., Adgo, E., Meshesha, D.T., Masunaga, T., Tsubo, M., Billi, P., Ebabu, K., Fenta, A.A. and Berihun, M.L., 2019. Morphological characteristics and topographic thresholds of gullies in different agro-ecological environments. Geomorphology, 341, pp.15–27.

3.1 Introduction

Gully erosion is a major cause of land degradation in many drought-prone regions of the world, including Ethiopia, and accounts for a large portion of the total soil loss at the catchment scale (Vandekerckhove et al., 2000; Zucca et al., 2006; Avni, 2008; Frankl et al., 2013, 2016). Indeed, gully erosion account for 60–90% of the total sediment production on agricultural lands in the hilly areas of the Loess Plateau, China (Li et al., 2003), and 70–90% of sediment production in catchments of northern Ethiopia (Bewket and Sterk, 2003; Zegeye et al., 2018). In northwest Ethiopia, gully erosion rates of 530 t ha^{-1} yr^{-1} over 17.4 ha are reported by Tebebu et al. (2010). Soil loss rates can result in both on- and off-site ecosystem damage. For instance, the large amounts of sediments released by gully erosion can contribute to the siltation of downstream lakes, reservoirs, and river channels. Gully erosion can cause catastrophic flooding and pollution, triggers landslides (Vandekerckhove et al., 2000b; Poesen et al., 2003; Haregeweyn et al., 2005), and gullies can devastate cultivated land, hinder mechanical tillage operations, and damage infrastructure such as roads, bridges and buildings (Frankl et al., 2016; Poesen, 2018; Wu et al., 2018).

In many cases, gully erosion is accelerated by overgrazing, land use change, extreme climatic events, inappropriate agricultural practices (Poesen et al., 2003; Valentin et al., 2005; Moges and Holden, 2008), and the diversion of concentrated runoff due to urbanization and construction (Nyssen et al., 2002; Poesen et al., 2003; Vanmaercke et al., 2016). Various studies (Vandekerckhove et al., 1998; Nyssen et al., 2002; Torri and Poesen, 2014) have shown that the slope at the gully head and the upslope drainage area are crucial topographic parameters determining the distribution and intensity of gully erosion. Patton and Schumm (1975) established an inverse relationship between slope and drainage area based on data derived from aerial photos and topographic maps and Montgomery and Dietrich (1988) and Vandaele et al. (1996) found an inverse relationship between the critical slope and the upslope drainage area. It is well understood that gully formation and evolution is largely controlled by runoff volume and relief energy when these variables exceed critical values (Begin and Schumm, 1979; Vandekerckhove et al., 2000a).

Many studies to determine the gully head retreat rates and to establish sediment budgets are based on repeated measurements over different time spans (e.g., Casalí et al., 2006; Capra et al., 2009; Castillo and Gómez, 2016) or on sequential series of aerial photographs (Daba et al., 2003; Frankl et al., 2012, 2013a). The most commonly measured parameters are gully width, depth, length, bottom gradient, slope, and ratios between these parameters (Casalí et al., 2015; Li et al., 2017; Wu et al., 2018). Geomorphic characterization of gully channels is important for determining gully head expansion rates and sediment budgets. The morphology of gully cross-sections (GCs) can be characterized by size parameters (average top and bottom width, maximum and mean depth, and surface area; Frankl et al., 2013b; Li et al., 2017) and proportionality parameters (e.g., the ratios of width to depth, average top width to maximum depth, and bottom width to top width; Zucca et al., 2006; Frankl et al., 2013b; Deng et al., 2015). Furthermore, upslope morphologic parameters significantly influence the threshold of gully formation (Poesen et al., 2003). Accurate measurement of gully geomorphic parameters is important not only for computing eroded volumes (Casalí et al., 2006; Frankl et al., 2013a; Castillo and Gómez, 2016) but also for understanding erosion dynamics (Zucca et al., 2006). Accurate GCs parameters are easily measured in the field using simple instruments, i.e., ruler, pole, tape, total station and laser distance meter (Casalí et al., 2006; Nyssen et al., 2006; Capra et al., 2009; Deng et al., 2015; Castillo and Gómez, 2016), or can be extracted from remotely sensed images (Daba et al., 2003; Frankl et al., 2013b; Li et al., 2017).

Although several studies exist on gully expansion and erosion rates, little is known about the formation mechanisms and the geomorphic characteristics of permanent gullies in the Upper Blue Nile basin, Ethiopia. Such studies are particularly important in areas like the Upper Blue Nile basin, where rainfall is intense and runoff occurs over highly erodible soils. The aim of this study was designed to provide site-specific information to improve the modeling of gully erosion-prone areas which, in turn, provides the basis for the development of gully erosion mitigation measures. The objectives of this study are (1) to quantify gully morphological characteristics and gully headcut retreat rates in areas of different land use and slope and (2) to estimate the topographic thresholds of gully formation in three different agro-ecologies of the Upper Blue Nile basin, Ethiopia.

3.2 Materials and methods

3.2.1 Study area

Our study area includes three sites in different agro-ecological zones (Bekele-Tesemma and Tengnäs, 2007) of the Upper Blue Nile basin, Ethiopia (Fig. 3.1): Guder (highland agro-ecology); Aba Gerima (midland agro-ecology); and Dibatie (lowland agro-ecology). The study sites are located between 10°46′12″N and 11°40′24″N and between 36°15′51″E and 37°29′49″E. Sheet, rill, and gully erosion continue to be major problems in the Upper Blue Nile basin (Haregeweyn et al., 2017; Ebabu et al., 2019; Yibeltal et al., 2019a) and have significant environmental impacts. The landscape of all study sites is fragmented as a result of different land use practices over many decades.

The major land use types in the study area are cultivated lands, grazing lands, and degraded bushlands (Table 3.1). In all sites, cultivated lands proportion is larger than grazing lands and degraded bushlands. The farming system is mixed crop-livestock, characterized by rain-fed and continuous cropping. Livestock types are more or less similar across the three sites, though the stocking rate and grazing intensity on non-cultivated lands is higher in Aba Gerima than in the other sites (Nigussie et al., 2017; Ebabu et al., 2018).

All three sites experience dry (November–April) and wet (May–October) seasons and rainfall distribution is highly variable throughout the year. More than 85% of the annual rainfall falls during the wettest months, especially during high-intensity summer rainstorms (June–August) (Ebabu et al., 2019; Yibeltal et al., 2019). The three sites have specific climate conditions, land use types, soil characteristics, topographical features, and management practices (Fig. 3.2, Table 3.1). Long-term daily rainfall data (1984–2016 for Guder, 1962–2016 for Aba Gerima, and 1981–2016 for Dibatie) were obtained from the nearest weather stations (Injibara station for Guder, Bahir Dar station for Aba Gerima, and Bullen station for Dibatie). The mean annual rainfall during those periods was 2454, 1343, and 1022 mm yr^{-1} for Guder, Aba Gerima, and Dibatie, respectively. The most active period of gully initiation and expansion in all sites is the main rainy season (May to September). Gullies are typically observed during field surveys regardless of topographical setting, land use types, and soil characteristics (Fig. 3.3).

Mekonnen (2016) summarized the four dominant FAO soil types of the study sites as follows: (1) Acrisols are soils with subsurface accumulations of low-activity (i.e., highly weathered) clays, low cation exchange capacity, and low base saturation; (2) Luvisols are very deep and well-drained soils that form on gentle slopes; (3) Leptosols are thin, degraded soils that developed from variable parent materials (including basic volcanic rocks and intrusive rocks) on steep slopes. As these soils are typically shallow, they do not efficiently store moisture; (4) Vertisols are soils with high concentrations of clay minerals that shrink and swell during dry and wet seasons, respectively. These latter soils are susceptible to physical crusting, sealing, and dispersion, particularly following disturbances such as plowing, cattle trampling, or the removal of ground cover and vegetation. All four soil types occur in Guder; Luvisols, Vertisols, and Leptosols are present in Dibatie (though Vertisols dominate); Luvisols and Leptosols occur in Aba Gerima.

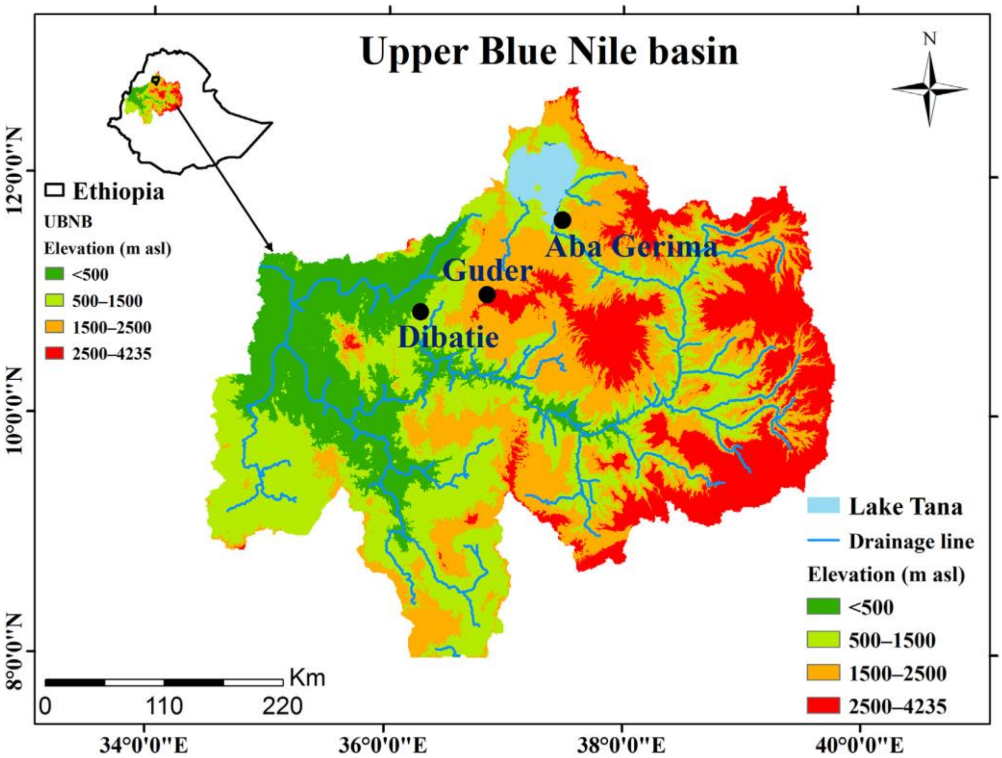

Figure 3. 1 Location map of the Upper Blue Nile basin, Ethiopia. The study sites are indicated by filled black dots.

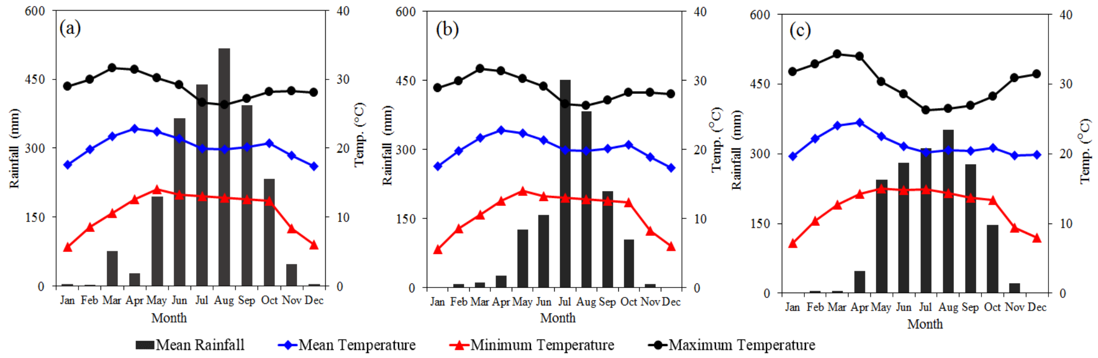

Figure 3. 2 Monthly mean rainfall (bars) and mean, minimum, and maximum temperatures (blue, red, and black curves, respectively) in (a) Guder, (b) Aba Gerima, and (c) Dibatie during 1999–2017.

Table 3. 1 Main characteristics of the three study sites.

Characteristics (units)	Guder	Aba Gerima	Dibatie
Altitude (m.a.s.l)	2492–2882	1911–2222	1482–1706
Total area (ha)	741	760	644
Annual rainfall (mm)	1951–3424	895–2037	850–1200
Drainage density (km km^{-2})	5.72	2.41	3.01
Major soil types[a]	Acrisols and Leptosols	Leptosols and Luvisols	Vertisols and Luvisols
Slope (°)	0–39	0–36	0–28
Major land use types[b]	Cropland, grazing land, degraded bushland	Cropland, grazing land, degraded bushland	Cropland, grazing land, degraded bushland
Soil bulk density (g cm^{-3})[a]	0.83–1.34	1.21–1.40	1.11–1.44
Primary soil texture[a]	Clay loam	Clay	Clay
Mean daily temp.(°C)	15–24	17–31	18–29
Agro-ecology zone[b]	Moist subtropical	Humid subtropical	Tropical hot humid
Major crops[c]	Barley, tef, wheat, potatoes	Tef, finger millet	Finger millet, tef, maize
Major livestock[c]	Cattle, sheep, donkeys, horses	Cattle, sheep, goats	Cattle, sheep, goats, donkeys

[a] Mekonnen (2016); [b] Sultan et al. (2018); [c] Nigussie et al. (2017).
Tef (*Eragrostis tef*); finger millet (*Eleusine coracana*); wheat (*Triticum aestivum*); maize (*Zea mays*); barley (*Hordeum vulgare*); potato (*Solanum tuberosum*).

Dominant tree and shrub species include *Acacia abyssinica*, *Erythrina brucei*, *Urtica simensis*, and *Justica schimperiana* in Guder, *Dodonaea angustifolia*, *Ficus thonningii B.*, *Acanthus sennii*, and *Solanum incanum* in Aba Gerima, and *Solanum marginatum*, *Datura stramonium L.*, *Albizia gummifera*, and *Ficus thonningii B.* in Dibatie. More detailed descriptions of the three sites can be found in previous studies (Nigussie et al., 2017; Ebabu et al., 2019; Yibeltal et al., 2019a).

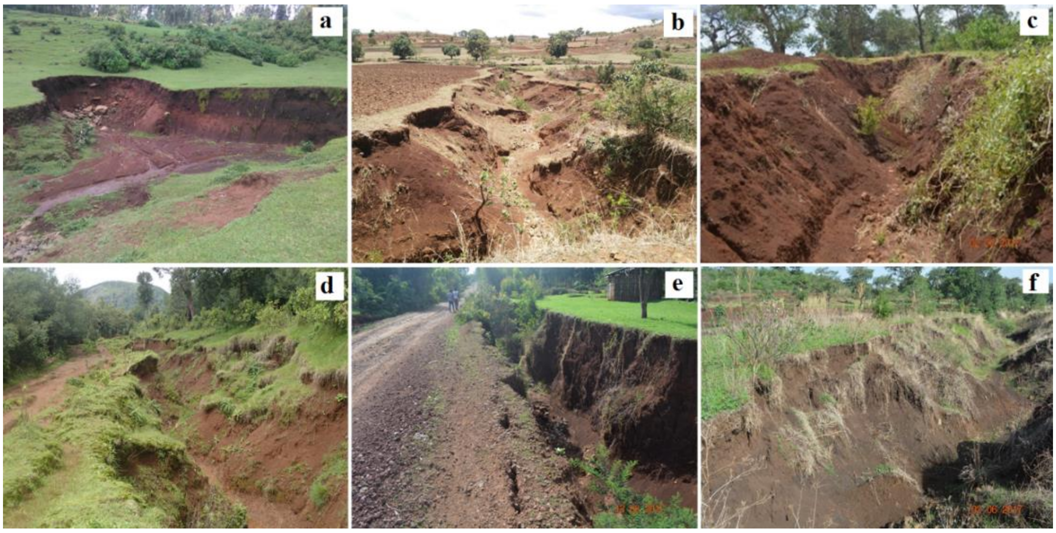

Figure 3. 3 Examples of active gullies in different land use types. (a) Gully in grazing lands (Guder); (b) gully in cultivated land (Aba Gerima); (c) gully in cultivated land (Dibatie); (d) roadside gullies (Guder); (e) gully between a road and a homestead (Aba Gerima), and (f) gully in cultivated land (Dibatie).

3.3 Field measurements

Inventory and measurement of permanent gullies in the three study sites were carried out from May 2017 to September 2018. Permanent gullies are channels cut into soil, colluvial deposits, regolith, and unconsolidated rock that are relatively narrow and deep (up to 25–30 m deep) and thus difficult to cross and erase with conventional tillage equipment (Poesen et al., 2003; Casalí et al., 2015; Zgłobicki et al., 2017). Cross-sectional measurements were obtained for 94 gullies (33 in Guder, 36 in Aba Gerima, and 25 in Dibatie). To assess gully locations and to measure the required parameters, we systematically walked along the different land use and slope gradients. The position of each gully head was recorded using a handheld Garmin GPSmap® 60 and measured using a 50-m-long surveyor's measuring tape to 1 cm scale. The accuracy of tape measurements was comparable to other methods and were within 0.03 m and 0.003 m of total station and laser distance meter measurements, respectively (Deng et al., 2015). To characterize the morphology of gullies in different locations, their width, depth, and length were recorded using well-tested methodologies (Ludwig et al., 1995; Casalí et al., 2006; Li et al., 2017; Wu et al., 2018). Multiple GCs were selected and measured to accurately describe the morphology of each gully.

Gullies were divided into representative segments and gully depth, top and bottom widths were measured for each segment length using a surveyor tape. Though gullies tend to develop trapezoidal cross-sections, their profiles may be highly irregular, therefore individual cross-sections were measured three to four times to improve the accuracy of cross-sectional area and gully volume calculation. The mean depth of each gully was calculated by averaging the individual segments depth. The field survey was performed during the dry season when vegetation and grass cover are minimal.

3.4 Satellite imagery

High-resolution satellite images were used to derive the rate of gully head retreat and to assess soil loss during the intervals 2005–2016 and 2006–2017. Spatial and spectral resolution and time of acquisition of the images are reported in Table 3.2. Different satellite images were used for the same sites due to the scarcity of available images. Gully head positions were extracted from the satellite images by visual interpretation.

Table 3. 2 Information about the satellite images used in the study.

Raster image source	Date acquired (dd/mm/yyyy)	Resolution (m)	Spectral resolution
SPOT-7	26/03/2016	1.5	Multispectral
QuickBird	6/3/2005	0.65	Multispectral
IKONOS	6/4/2006	0.82	Multispectral
IKONOS	26/03/2006	0.82	Multispectral
Pleiades	11/1/2017	0.5	Multispectral

3.5 Determination of gully headcut retreat rate and gully head drainage area

3.5.1 Gully headcut retreat rates

The length of gully headcut retreat over an 11-year period (2005–2016 for Aba Gerima and 2006–2017 for Guder and Dibatie) was assessed for 22 gullies in Guder, 18 gullies in Aba Gerima, and 16 gullies in Dibatie. The change in length was determined from the initial (2005/2006) to the current (2016/2017) position of the edge of the gully head. Gully head positions in 2005 (Aba Gerima) and 2006 (Guder and Dibatie) were first identified using satellite images. Then, the positions of the same gully heads were determined from satellite images acquired in 2016 (Aba Gerima) and 2017 (Guder and Dibatie). Finally, the linear, areal, and volumetric gully headcut retreat rates were determined from the difference between the initial and final images. The linear gully headcut retreat rate (m yr^{-1}) was calculated by dividing the retreat length by the duration of the observation period, i.e., 11 years for each site. The volumetric retreat rate (m^3 yr^{-1}) was calculated by multiplying the linear retreat rate by the average cross-sectional area of the incised gully. Volumetric retreat rates were converted into mass erosion rates (kg yr^{-1}) by multiplying the volumetric retreat with the average bulk density of the dry soil. Bulk densities were measured using undisturbed soil samples collected by means of a standard core sampler (volume = 100 cm^3). Average dry bulk densities of 1290, 1060, and 1170 kg m^{-3} for Guder

(23 samples), Aba Gerima (24 samples), and Dibatie (23 samples), respectively, were obtained.

3.5.2 Gully head drainage area

Gully head positions were recorded by GPS for the 94 studied gullies from June to September 2017. Areas contributing runoff to gully heads were measured by GPS and slopes were determined in the field. Topographical parameters, including the slope of the soil surface at the gully head, were determined with clinometers (Suunto type, 0.005 m m^{-1} error). The local slope of the soil surface nearest to the gully head was defined from locations within 5 m upslope and downslope of the cross-section (Rutherfurd et al., 1997; Nyssen et al., 2002). We assumed that a gully initiates at the steepest slope and that the maximum possible displacement of a gully head within a single storm is 5 m (Nachtergaele et al., 2001; Nyssen et al., 2002). The drainage area was defined as the area from which overland flow was assumed to reach the channel cross-section at the gully head position (Fig. 3.4). Finally, GPS positions were imported into ArcGIS and used to digitize topographic parameters and to calculate drainage areas.

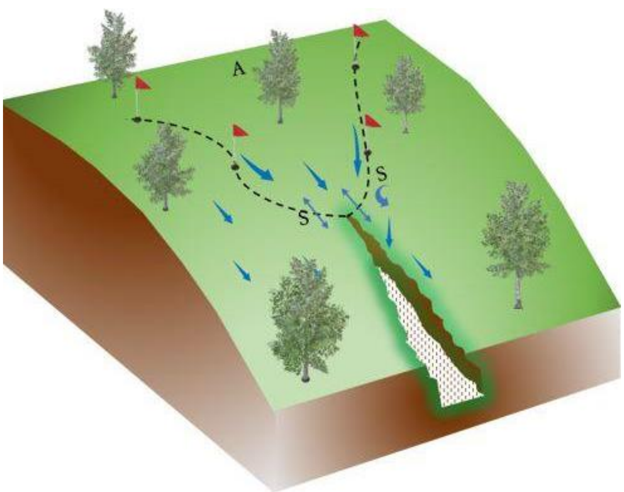

Figure 3. 4 Schematic representation of field survey techniques. Arrows indicate runoff directions, S is the local slope of the soil surface, and A is the runoff drainage area at the gully head, delimited by the red flags and inferred dashed line.

3.5.3 Land use, slope, and soil data

For this study, land use, slope, and soil data were generated to determine the development and morphological characteristics of gullies in the Upper Blue Nile basin. Land use and land cover data for the watersheds studied were obtained from Berihun et al. (2019a). Slope maps were constructed using SRTM elevation data (30 m resolution) and the ArcGIS spatial analyst toolbox. Slope classification was based on FAO soil description guidelines (Jahn et al., 2006). The spatial distributions of land use types and slopes were considered in relation to the morphological characteristics of the GCs in the three study sites. Soil data for the three sites were obtained from Mekonnen (2016).

3.6 Data analysis

3.6.1 Morphological and topographic characteristics of gullies

Gully morphological characteristics were investigated in the field by measuring GCs, their positions, and the area draining runoff to gully head. During the field survey, only clearly visible, large gullies (>5 m long and >0.8 m deep) were selected for detailed measurement. A total of 773 GCs (275 in Guder, 300 in Aba Gerima, and 198 in Dibatie) were measured. In addition, average depth (D, m), top width (TW, m), bottom width (BW, m), cross-sectional area (CSA, m^2), surface area (A_g, m^2), length (L, m), and volume ($V = L \times CSA$, m^3) of each gully section was calculated. GCs were assumed to be trapezoidal in shape and their areas was computed as $CSA = [(TW + BW)/2] \times D$. The ratios between bottom width and top width (BW/TW) and between gully top width and depth (TW/D) were calculated to represent the shape of GCs. The latter ratio, the top width and depth (TW/D) of a gully, reflects its cross-sectional size: higher TW/D values indicate that GCs are comparatively wide and shallow, whereas lower values indicate that they are narrow and deep (Wu et al., 2018). The reported mean morphological parameters were averaged from all GCs in each of the three sites.

3.6.2 Analysis of topographic thresholds for gully development

Topography is an important factor controlling gully erosion rates. The possibility of predicting the spatial occurrence of gullies from topographic attributes using a power function has been investigated by various researchers around the world (Nyssen et al., 2002; Torri and Poesen, 2014). In this study, the following general equation (reported also by Begin and Schumm, 1979 and by Vandaele et al., 1996), was used:

$$S = aA^{-b}, \qquad (1)$$

where S is the local slope (m m^{-1}), A is the drainage area (ha) upslope of the headcut, *a* is a coefficient and *b* is an exponent. Both *a* and *b* take different values under various environmental conditions. The values of *a* and *b* were derived from log-log scale plot of S versus A.

3.6.3 Statistical analysis

Parametric statistical tests could not be used for this study because all data sets were not normally distributed with square root and log transformations. Site characteristics of the three watersheds were compared using pooled *t*-tests or Wilcoxon rank-sum tests for normally and non-normally distributed data. Hence, a Kruskal-Wallis test was used to evaluate the significance of differences between the morphological parameters at the three sites. Descriptive statistical parameters (mean, median, standard deviation, minimum, maximum, skewness, kurtosis, and coefficient of variation) were calculated. Spearman's rank correlation coefficients were determined and regression analyses of the morphological parameters were performed to evaluate the statistical relationship between the datasets collected from the three sites. Data analyses were performed using RStudio (R Core Team, 2018), an interface for the R software program (3.4.4) and Microsoft Excel.

3.7 Results

3.7.1 Morphological characteristics of gully cross-sections

The morphological parameters of GCs are highly variable among the three sites (Table 3.3). TW varies from 2.77 to 13.45 m in Guder (median 6.54 m), 2.63 to 6.30 m in Aba Gerima (median 3.95 m), and 4.43 to 7.20 m in Dibatie (median 5.90 m); the highest, intermediate, and lowest site-averaged values are observed in Guder (highland), Dibatie (lowland), and Aba Gerima (midland), respectively. BW varies from 1.37 to 6.94 m in Guder (median 3.05 m), 2.07 to 4.90 m in Aba Gerima (median 3.10 m), and 1.17 to 2.07 m in Dibatie (median 1.53 m); the highest, intermediate, and lowest site-averaged values are obtained in Guder, Aba Gerima, and Dibatie, respectively. D varies from 1.05 to 4.01 m in Guder (median 1.92 m), 1.60 to 3.63 m in Aba Gerima (median 2.42 m), and 2.07 to 3.10 m in Dibatie (median 2.50 m); the highest, intermediate, and lowest site-averaged values are observed in Dibatie, Aba Gerima, and Guder, respectively. CSA ranges from 2.23 to 24.03 m^2 in Guder, 4.00 to 17.41 m^2 in Aba Gerima, and 6.23 to 14.16 m^2 in Dibatie (Table 3.3).

The variations in gully morphological parameters within and across the agro-ecological sites are presented in Table 3.3. The coefficient of variations (CVs) for the 10 gully parameter datasets ranges from 33.63 to 92.20% in Guder, 8.75 to 77.09% in Aba Gerima, and 14.55 to 30.48% in Dibatie. The highest and lowest CVs are found for V and BW/TW, respectively, in all sites.

Table 3.3 shows that TW, TW/D, and CSA are higher in Guder than in Dibatie and Aba Gerima. The site-averaged TW, BW, and CSA values in Guder are respectively 39.86%, 7.81%, and 18.09% higher than those in Aba Gerima and 12.34%, 55.29%, and 14.03% higher than those in Dibatie. The median TW/D values are 3.05, 1.62, and 2.29 in Guder, Aba Gerima, and Dibatie, respectively, indicating that gullies are comparatively wider in Guder and relatively deeper in Aba Gerima (though in absolute terms the deepest gullies are in Dibatie). The median BW/TW values are 0.54, 0.80, and 0.29 in Guder, Aba Gerima, and Dibatie, respectively, indicating that in Aba Gerima there is little difference between top and bottom width which implies more cohesive soils. The BW/TW values indicate that the study gullies cross-section is trapezoidal, though these parameters vary along the gully length in the three sites.

Table 3. 3 Morphological characteristics of gullies in the Guder, Aba Gerima, and Dibatie watersheds.

Site	Parameters	Mean	Median	Min.	Max.	SD	CV (%)	Kurtosis	Skewness
Guder (*n* = 33)	TW (m)	6.66	6.54	2.77	13.45	2.24	33.63	1.44	0.91
	BW (m)	3.47	3.05	1.37	6.94	1.42	40.92	–0.26	0.65
	D (m)	2.14	1.92	1.05	4.01	0.73	34.11	–0.19	0.58
	TW/D	3.38	3.05	1.63	9.03	1.56	46.15	5.23	2.05
	BW/TW	0.53	0.54	0.18	0.85	0.16	30.19	–0.24	–0.26
	CSA (m^2)	11.12	9.64	2.23	24.03	5.52	49.64	–0.55	0.56
	A_g (m^2)	102.5	79.46	20.4	330	76.29	74.4	1.72	1.39
	L (m)	19.35	15.6	5.2	55.5	11.92	61.6	2.27	1.53
	V (m^3)	233.2	148.4	26.2	981	215	92.2	3.56	1.8
	A (ha)	0.25	0.26	0.16	0.36	0.06	22.47	–0.72	–0.18
Aba Gerima (*n* = 36)	TW (m)	4.01	3.95	2.63	6.3	0.79	19.7	0.82	0.69
	BW (m)	3.2	3.1	2.07	4.9	0.64	20	0.14	0.45
	D (m)	2.49	2.42	1.6	3.63	0.48	19.28	0.13	0.44
	TW/D	1.64	1.62	0.84	2.33	0.33	20.12	0.78	0.07
	BW/TW	0.8	0.8	0.64	0.9	0.07	8.75	–0.59	–0.35
	CSA (m^2)	9.11	8.3	4	17.41	3.04	33.37	0.74	0.96
	A_g (m^2)	399.9	290.26	161	962.2	245.4	61.35	0.41	1.25
	L (m)	106.5	85.8	52	237	51.27	48.13	0.63	1.24
	V (m^3)	1052	660.54	280	3333	811.1	77.09	1.35	1.52
	A (ha)	0.32	0.32	0.21	0.51	0.08	24.48	–0.23	0.55

Dibatie	TW (m)	5.84	5.9	4.43	7.2	0.85	14.55	–1.09	0.25
(n = 25)	BW (m)	1.55	1.53	1.17	2.07	0.27	17.42	–0.94	0.34
	D (m)	2.57	2.5	2.07	3.1	0.38	14.79	–1.63	0.14
	TW/D	2.3	2.29	1.75	3.03	0.36	15.65	–0.73	0.49
	BW/TW	0.27	0.29	0.17	0.39	0.06	22.22	–1.11	–0.01
	CSA (m^2)	9.56	9.63	6.23	14.16	2.15	22.49	–0.80	0.28
	A_g (m^2)	278.7	298.8	154	356.3	58.28	20.91	–0.69	–0.63
	L (m)	75	76	52	95.03	11.66	15.55	–0.80	–0.27
	V (m^3)	727.5	758.44	324	1104	221.8	30.48	–0.93	–0.22
	A (ha)	0.29	0.27	0.2	0.47	0.08	28.39	0.01	0.47

SD = standard deviation; CV = coefficient of variation; TW = gully top width; BW = gully bottom width; D = gully depth; TW/D = gully top width-to-depth ratio; BW/TW = bottom-to-top width ratio; CSA = gully cross-sectional area; A_g = gully surface area; L = gully length; V = gully volume; A = upslope drainage area at the gully head; n = number of observations per site.

The respective values of L, A_g, and V varies from 5.20 to 55.50 m, 20.39 to 329.65 m^2, and 26.16 to 981.04 m^3 in Guder, from 52.0 to 237.0 m, 160.98 to 962.24 m^2, and 280.0 to 3332.9 m^3 in Aba Gerima, and from 52.0 to 95.0 m, 154.3 to 356.3 m^2, and 323.96 to 1104.38 m^3 in Dibatie. The shortest gullies in Aba Gerima and Dibatie are over ten times longer than the shortest gully in Guder. Site-averaged L, A_g, and V values are highest in Aba Gerima (midland), intermediate in Dibatie (lowland), and lowest in Guder (highland) (Table 3.3), and the average values of L and V are much higher in the midland than in the highland and lowland.

2.7.2 Relationships between gully morphological parameters

3.7.2.1 Depth and width

The observed relationships between maximum depth (D_{max}) and average top width (TW_{ave}) at each site are not statistically significant (Fig. 3.5), implying that both top width and the gully depth are controlled by different runoff processes and soil types. Top width is controlled mainly by bank failure, whereas maximum depth is affected by local factors including soil profile characteristics.

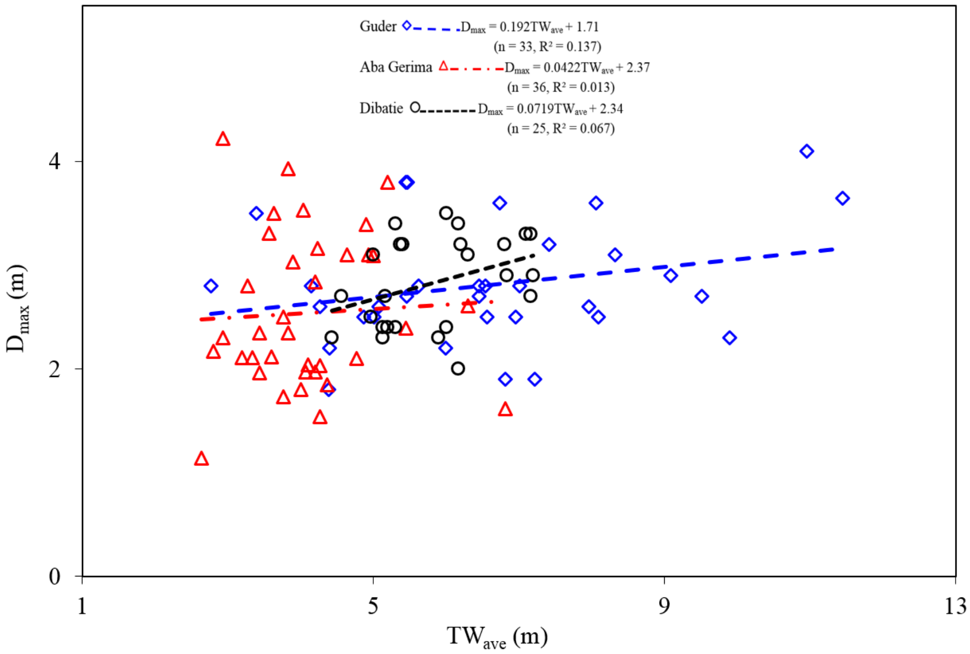

Figure 3. 5 Relationship between average top width (TWave) and maximum depth (Dmax) of gullies in the Guder (blue), Aba Gerima (red), and Dibatie (black) watersheds.

3.7.2.2 Establishing V-L and V-A_g relations

Spearman's correlation coefficients for the gully parameters relationships are reported in Table 3.4. The volume, V, is significantly and positively correlated with A_g, L, D_{ave}, and CSA_{ave} ($p < 0.001$), and A_g is significantly and positively correlated with L and D_{ave} ($p < 0.001$). The strongest relationship is observed between V and L (R^2 = 0.66, 0.83, and 0.68 for Guder, Aba Gerima, and Dibatie, respectively; $p < 0.001$; Fig. 3.6a). The relationship between L and V is likely influenced by the location and scale of the study area; hence, site-specific assessment is necessary to precisely determine the spatial variability of gully features. The significant power relationship between V and L, the weak relationships between V and TW and between V and BW confirm that gullying is mainly a longitudinal incision process. The covariations of V and L are best described by the power equation V

= aL^b, with a = 4.29 and b = 1.29 in Guder, a = 1.39 and b = 1.40 in Aba Gerima, and a = 0.37 and b = 1.75 in Dibatie. The general equation fitting all three sites is:

$$V = 8.097L^{1.032} \quad (2)$$

These power relations allow to assess gully volume from gully length measurements using aerial photographs or topographic maps in a cheap and quick way.

Table 3. 4 Spearman's correlation coefficients between gully morphological parameters (n = 94).

	V (m^3)	A_g (m^2)	L (m)	TW_{ave} (m)	BW_{ave} (m)	D_{ave} (m)	CSA_{ave} (m)
V (m^3)	1	0.965***	0.902***	0.047	0.037	0.637***	0.429**
A_g (m^2)		1	0.936***	0.093	0.011	0.454***	0.311*
L (m)			1	0.326*	0.107	0.403***	0.099
TW_{ave} (m)				1	0.069	–0.162	0.654***
BW_{ave} (m)					1	0.406	0.371*
D_{ave} (m)						1	0.733***
CSA_{ave} (m)							1

V = gully volume; A_g = gully surface area; L = gully length; TW_{ave} = average top width; BW_{ave} = average bottom width; D_{ave} = average depth; CSA_{ave} = average cross-sectional area.

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

The significant relationship is observed between V and A_g: ($V = 1.1138A_g^{1.1362}$, n = 33, R^2 = 0.86; P<0.001, Guder), ($V = 0.8971A_g^{1.1713}$, n = 36, R^2 = 0.93; P<0.001, Aba Gerima), and ($V = 0.3032A_g^{1.3791}$, n = 25, R^2 = 0.87; P<0.001, Dibatie) (Table 3.4, Fig. 3.6b). The relationship between V and A_g is stronger compared to the relationship between V and L. The general equation fitting all three sites is:

$$V = 1.048A_g^{1.15} \quad (3)$$

Equation (3) is useful for calculating gully volume from gully surface area measured in remotely sensed images.

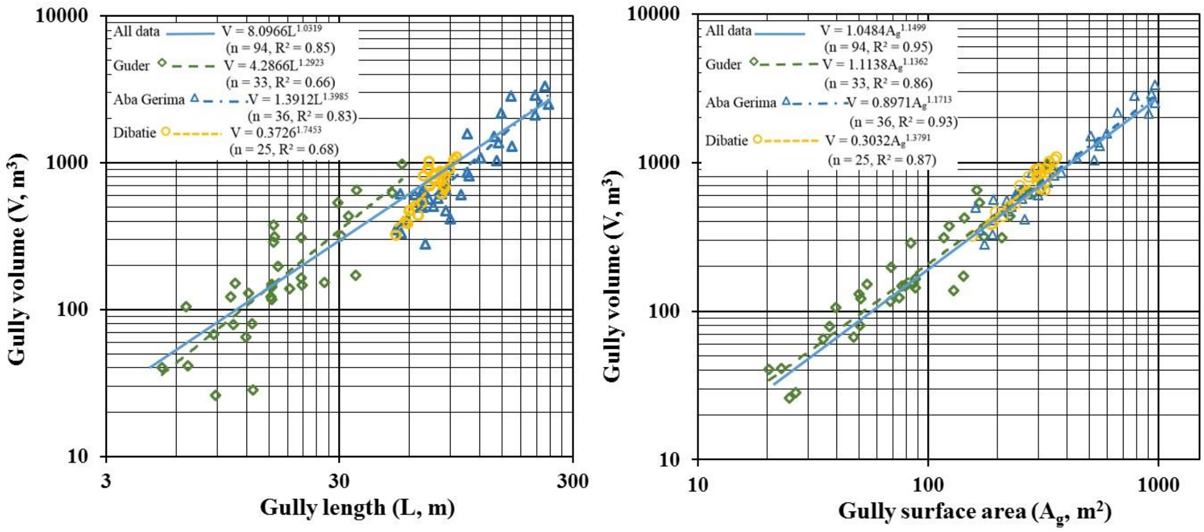

Figure 3. 6 Power law regression (a) gully volume (V) and gully length (L), and (b) V and gully surface area (Ag) on a double logarithmic scale for the Guder (Green), Aba Gerima (Blue), Dibatie (Yellow), and all data watersheds (light blue).

3.7.3 Gully headcut retreat rates and upslope drainage area characteristics

3.7.3.1 Gully headcut retreat rates

Table 3.5 presents the average annual linear (R_l), areal (R_a), and volumetric (V_e) gully headcut retreat rates measured at each study site. The mean (± standard deviation) R_l is 0.86 ± 0.64, 2.09 ± 0.74, and 3.42 ± 0.65 m yr^{-1} in Guder, Aba Gerima, and Dibatie, respectively (Table 3.5). The reduced gully head dynamics in Guder are rather surprising because this site receives the most annual precipitation and has the steepest slopes and the highest drainage density (Table 3.1). R_a is 9.72 ± 7.02, 9.76 ± 3.33, and 12.26 ± 3.08 m^2 yr^{-1} in Guder, Aba Gerima, and Dibatie, respectively (Table 3.5). The maximum V_e in Dibatie (42.16 m^3 yr^{-1}) and the minimum V_e in Guder (6.77 m^3 yr^{-1}) were measured at the same gully heads where the respective maximum and minimum R_l values were also measured. The gully volume retreat rates are similar with soil loss by gullying (SL_g) (t ha^{-1} y^{-1}) (Table 3.5), and the minimum (8.73 t ha^{-1} yr^{-1}) and maximum (49.33 t ha^{-1} yr^{-1}) rates occur in Guder and Dibatie, respectively.

Table 3. 5 Linear (Rl), areal (Ra), and volumetric (Ve) gully headcut retreat rates and soil loss (SLg) in the Guder, Aba Gerima, and Dibatie watersheds.

Site	No. of active gully heads	Mean R_l ($m\ yr^{-1}$)	Mean R_a ($m^2\ yr^{-1}$)	Mean V_e ($m^3\ yr^{-1}$)	Mean SL_g ($t\ ha^{-1}\ yr^{-1}$)
Guder	22	0.86 (±0.64)	9.72 (±7.02)	6.77 (±6.98)	8.73 (±9.01)
Aba Gerima	18	2.09 (±0.74)	9.76 (±3.33)	19.58 (±7.90)	20.76 (±8.37)
Dibatie	16	3.42 (±0.65)	12.26 (±3.08)	42.16 (±15.97)	49.33 (±18.68)

3.7.3.2 Topographic thresholds for gully initiation

From Fig. 3.7, it is evident that upslope drainage area and local slope gradient are the critical controls on gullying. Straight lines were drawn by aligning through the lowermost points of each dataset to approximate the slope-drainage area threshold for incision (Fig. 3.7). According to the data of Fig. 3.7, each of the study sites has a specific threshold for gully incision. Aba Gerima and Dibatie have relatively similar threshold condition for gully initiation as evidenced by their relatively similar exponent (0.234 and 0.216, respectively) of equation (1). On the other hand, Guder experiences a lower exponent (0.139) reflecting the lower dynamics of gullies in this site as also witnessed by the lower gully head retreat.

Though further studies are needed, Fig. 3.7 shows that gullying is not expected to occur in watersheds that fall below these thresholds in the absence of other factors promoting gully formation. These relationships indicate that, if we consider 0.1 ha as theoretically the minimum drainage area for gully initiation, the topographic thresholds for gully initiation at Guder, Aba Gerima, and Dibatie are local slopes of about 0.30, 0.23, and 0.18 $m\ m^{-1}$, respectively.

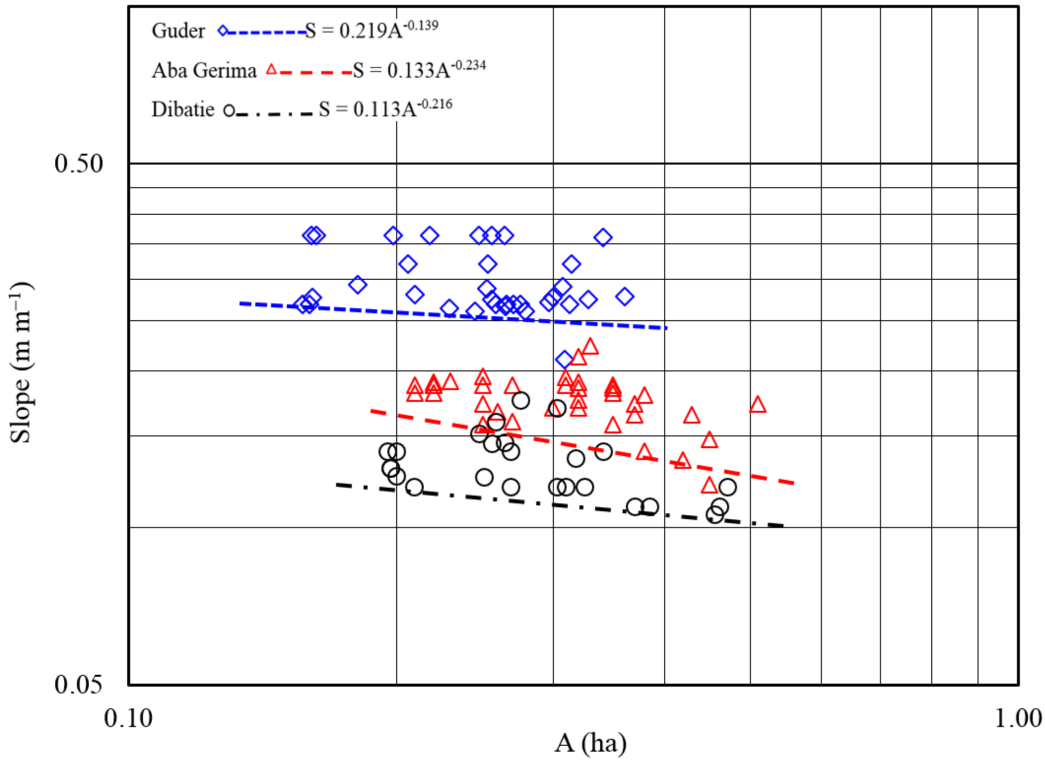

Figure 3. 7 Relationship between local slope of the soil surface at the gully head and upslope drainage area (A) for gullies in the Guder (blue), Aba Gerima (red), and Dibatie (black) watersheds. The lines were drawn through the lowermost data points for each site to approximate the slope-drainage area threshold for incision.

3.7.4 Factors affecting gully cross-sectional morphology

3.7.4.1 Land use type

Gully morphologies (TW, BW, and D) measured in the different land use types of the three agro-ecologies are presented in Fig. 3.8. The maximum TW values in Guder (7.2 m) and Aba Gerima (4.1 m) are associated with grazing (grass) lands, whereas that in Dibatie (6.1 m) is in cultivated land. The lowest TW values are in bushland in all three sites (Fig. 3.8a). The maximum BW in Guder (3.75 m) is observed in cultivated land, in Aba Gerima (3.2 m) in cultivated and grazing lands, and in Dibatie (1.8 m) in bushland, whereas the minimum BW values occur in grazing lands in Guder and Dibatie and in bushland in Aba Gerima (Fig. 3.8b). The maximum D in Guder (2.5 m) and Dibatie (2.7 m) are found in cultivated lands, and that in Aba Gerima (2.7 m) is in bushland (Fig. 3.8c). Gully depth varies minimally between cultivated and grazing lands, but the depth variation in bushland is high among the three sites.

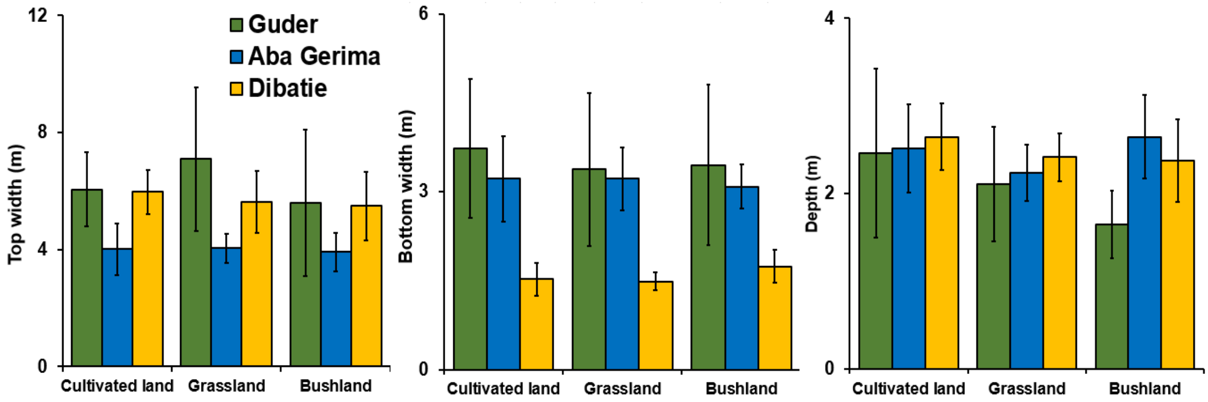

Figure 3. 8 Gully top width, bottom width, and depth distributions in the Guder, Aba Gerima, and Dibatie watersheds by land use type.

3.7.4.2 Slope gradient

Gullies are observed on varying slopes in Guder (0–20°), Aba Gerima (0–15°), and Dibatie (0–10°) (Fig. 3.9a–c), and gully TW, BW, and D vary with slope in the three study sites. Gully TW is similar on gentle slopes at each study site (0–10°), but increases on moderate to steep slopes (10–20°) in Guder (Fig. 3.9a). BW varies little with slope in each watershed; the maximum and minimum BW on all slope gradients are found in Guder and Dibatie, respectively (Fig. 3.9b). The maximum D in Guder is 2.21 m on a 15–20° slope, that in Aba Gerima is 2.70 m on a 10–15° slope, and that in Dibatie is 2.64 m on a 5–10° slope (Fig. 3.9c). The variability of D with slope is less than TW and BW in three sites.

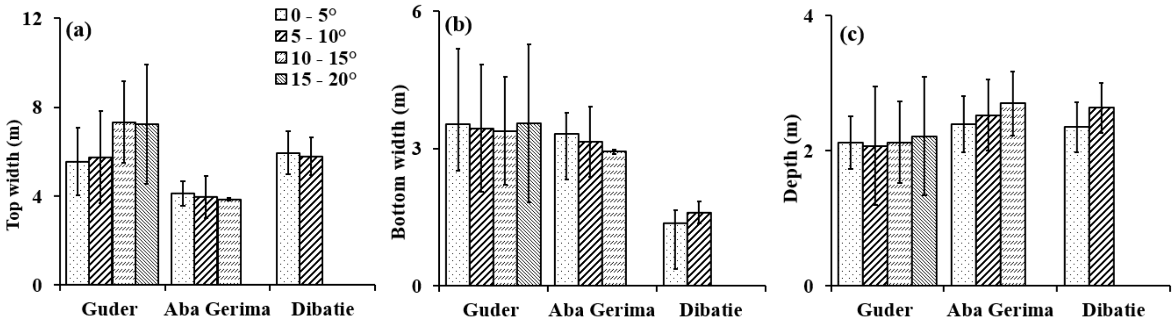

Figure 3. 9 Gully top width, bottom width, and depth distributions based on slope.

3.8 Discussions

3.8.1 Morphological characteristics of gully cross-sections

The widely varying morphological parameters of permanent gullies observed in this study are within the range of values reported by similar studies elsewhere. Our results are within the range of those of Frankl et al. (2013b) from semi-arid part of northern Ethiopia (TW = 0.35–31.90 m, BW = 0.10–19.50 m, D = 0.20–12.77 m, and CSA = 0.15–236.5 m^2). In their study areas mean annual rainfall ranges between 500 and 900 mm yr^{-1} and it is characterized by high rainfall intensity, though droughts are not infrequent (Frankl et al., 2013b). Similar studies in the Loess Plateau in China (e.g., Li et al.,2017) report TW = 2.5–22.5 m, BW = 0.01–17.5 m, D = 1.2–10.8 m, and CSA = 6–114 m^2, whereas Wu et al. (2018) report TW = 7.8–33.7 m (average 17.3 m), D = 3.8–13.7 m (average 8.2 m), and L = 33.6–88.9 m (average 58.4 m). In general, gullies in this study are smaller, although they are longer (in Aba Gerima and Dibatie).

The variability of V is not unexpected, as gullies may have formed at different times and their expansion rates may differ due to local conditions such as rainfall intensity, runoff volume, and soil characteristics (Zucca et al., 2006; Muñoz-Robles et al., 2010). In contrast, the variability of BW/TW reflects the predominance of different factors affecting the rates of bottom widening and bank erosion and failure. This latter process is mainly controlled by bank height and the geotechnical properties of the soil, provided bedrock does not crop out in the gully bottom (Zucca et al., 2006; Frankl et al., 2013b), but riparian vegetation and local slope may play a role as well (Radoane et al., 1995; Muñoz-Robles et al., 2010; Frankl et al., 2013b). In principle, under stable conditions, in trapezoidal cross-section the deeper the gully is the wider TW will be but, in deep gullies, high banks are more subjected to bank failure. The engineering characteristics of the soils in the study sites are not known in detail but, given that the average gully depth is similar among the three study sites, one important factor to account for the variability in the BW/TW ratio can be found mainly in the physical properties of the soils and in the occurrence of vertic characteristics and soil slumping. Vertic characteristics are present mainly in Dibatie where, in fact, Vertisols are very common. Obviously, other factors such as vegetation cover and rainfall intensity and amounts cannot be excluded. Rainfall is an important factor in determining the initiation of a gully but its role in contributing to shape the gully cross-section is only indirect and through runoff. Unfortunately, in this study no data about runoff is available but the hydraulic efficiency of runoff in gully bank undermining need to be further investigated.

Frankl et al. (2013b) report similar TW/D and BW/TW values in semi-arid northern Ethiopia, whereas Li et al. (2017) report wider ranges for TW/D (0.98–7.72) and BW/TW (0.01–0.82) in the Loess Plateau. Frankl et al. (2013b) report higher TW/D values for soils containing shale than those containing volcanic rocks, suggesting the importance of lithology in determining gully shape. Studies in different regions have indicated that gully morphologies are highly variable. For example, Li et al. (2017) report that L varies between 7.6 and 41.4 m (average 19.6 m) and V from 37.0 to 2589.3 m^3 (average 566.4 m^3) in 44 permanent gullies in the Loess Plateau; Kompani-Zare et al. (2011) report that L varies between 12 and 28 m (average 14.95 m) and V from 15 to 151 m^3 (average 67.18 m^3) in 146 permanent gullies in the Fars Province, Iran. Dong et al. (2013) report that L and V range from 1.34 to 24.22 m and 4.12 to 187.12 m^3, respectively, in the Yuanmou Dry-hot Valley, SW China. The gullies of this study show wider ranges of L and V, probably due to the larger number of gullies investigated and their rapid expansion, rather than their older ages. In Ethiopia, gullies are reported to develop very quickly (Billi, 2017) due to the monsoon-type rainfall pattern, high rainfall intensities, vulnerable soils, and poor soil and land management practices.

3.8.2 Relationships between gully morphological parameters

The relationships between maximum depth (D_{max}) and average top width (TW_{ave}) is similar to the weak relationships between gully depth and top width reported by Wu and Cheng (2005) and by Li et al. (2017). In contrast, Jetten et al. (2006) find a strong relationship between maximum gully depth and gully width, which they attribute to the increased influences of bank and bed erosion. The relationships between gully top width and depth reflect the environmental setting (climate, topography, soil, and vegetation) of the area for which gully developed (Li et al., 2017). In addition, the variability in gully channels depth is controlled by the runoff discharge (Frankl et al., 2013) and by the physical properties of the soil sublayers. For instance, hard sublayers such as calcrete concentration may offer substantial resistance to bottom erosion (Billi, 1998).

The covariations of V and L are best described by the power equation $V = aL^b$, with a = 4.29 and b = 1.29 in Guder, a = 1.39 and b = 1.40 in Aba Gerima, and a = 0.37 and b = 1.75 in Dibatie. Compared to other regions around the world, the exponent b in our study is large (probably due to greater rainfall intensities and more vulnerable soils commonly affected by tunneling processes), but consistent with previous studies reporting b to range between 0.8 and 1.43 (Nachtergaele et al., 2001; Zucca et al., 2006; Kompani-Zare et al., 2011; Frankl et al., 2013b). The relationship between V and L in equation (3) is similar to those of Kompani-Zare et al. (2011) and Dong et al. (2013), and thus can be used to quantitatively estimate gully erosion. As indicated by Woodward (1999) and Capra et al. (2005), such empirical relations are more suitable and simpler to apply to predict gully volumes than more complex models.

3.8.3 Gully headcut retreat rates

R_l varies between 0.76 and 3.42 m yr^{-1}, i.e. within the ranges obtained by Vanmaercke et al. (2016) (0.01–135.2 m yr^{-1}), Oostwoud Wijdenes and Bryan (2001) (0.8–15 m yr^{-1}), and Wu and Cheng (2005) (0.16–2.02 m yr^{-1}). Our results are similar to those obtained by Frankl et al. (2012), who report a short-term average of 0.34 ± 0.49 m yr^{-1}, a medium- to long-term average of 3.8 ± 4.7 m yr^{-1}, and 21.3 m yr^{-1} due to road construction. Radoane et al. (1995) report similar gully headcutting rates over 1.5 m yr^{-1} for gullies cut in sandy deposits and under 1 m yr^{-1} for gullies cut in marls and clays. Gully head retreat rate can be varied in watersheds due to the difference in resolution of satellite images used for this study.

The rates measured in this study are within the range of 0.002–430 m^3 yr^{-1} reported by Vanmaercke et al. (2016) based on data compiled for 933 individual and actively retreating gullies from more than 70 study areas worldwide. Our results are also similar to those of Frankl et al. (2012), who report short-term and medium- to long-term averages of 5.2 ± 5.1 and 47.7 ± 96.5 m^3 yr^{-1}, respectively. Vandekerckhove et al. (2003) report a similar rate (17.4 m^3 yr^{-1}) for 12 permanent gullies in Southeast Spain, but over a 40–43 year interval. Ghimire et al. (2006) estimate much higher V_e values of 731 (±57) to 2793 (±201) m^3 yr^{-1} over a period of two years in the Siwalik Hills, Nepal, though the environmental setting there is rather different from ours.

Among the study sites, in Guder, a reduced gully head dynamics was measured. This result is rather surprising because this site receives the highest annual precipitation and its gullies are the shortest. Moreover, the difference in slopes is negligible with Aba Gerima, whereas in Dibatie it is a little lower. Usual factors such as soil physical properties and land use/cover can play an important role in affecting the slower growing rates in the Guder site (e.g., in Dibatie Vertisoils and soil slumping are rather common processes).

The gully volume retreat rates are in good agreement with soil loss by gullying (SL_g) (t ha^{-1} y^{-1}) (Table 3.5) and the minimum (8.73 t ha^{-1} yr^{-1}) and maximum (49.33 t ha^{-1} yr^{-1}) values are similarly recorded in Guder and Dibatie, respectively. These results are in agreement with average soil loss values of 12.28 and 6.3 t ha^{-1} y^{-1} reported for areas underlain by shale and volcanic rocks, respectively (Frankl et al., 2013a).

The most active gully head dynamics is measured in Dibatie and it is accounted for by the extensive occurrence of Vertisols and soil tunneling. Vanmaercke et al. (2016) report that gully headcut retreat rates are well correlated with gully runoff drainage area, rainfall intensity, and other local factors (e.g., land use, soil characteristics, and topography). In general, our results indicate that the gully headcut retreat rate varies with agro-ecology and, thus, site-specific investigation of the controlling factors is crucial to understand the driver(s) of gully headcut advancement and to determine appropriate mitigation measures.

3.8.4 Topographic thresholds for gully initiation

The topographic thresholds for gully initiation at Guder, Aba Gerima, and Dibatie are local slopes of about 0.30, 0.23, and 0.18 m m^{-1}, respectively. Alternatively, a slope of 0.035–0.088 m m^{-1} is often considered as the threshold for the initiation of rill erosion for the European loam agricultural lands (Sun et al., 2013). In Guder, the data shows that the site with the steepest slopes, the slope threshold is higher for a comparable drainage area, confirming the results of Poesen et al. (2003) who explain the runoff drainage area decreases as the landscape steepens. Based on the topographic thresholds, overland (surficial) flow seems to be the dominant gully development process on cultivated lands in Dibatie and Aba Gerima whereas subsurface (subsurficial) flow is dominant in Guder watershed. Similar studies in other parts of the world (Vandekerckhove et al., 2000a; Morgan and Mngomezulu, 2003) indicate that values of the exponent $b \geq 0.2$ in equation (1) often reflect the dominance of Hortonian overland flow, whereas $b < 0.2$ may indicate subsurface processes and mass movement (Wu and Cheng, 2005; Dong et al., 2013). In Guder incipient landslides are very common (much more than in the Aba Gerima and Dibatie) (Yibeltal et al., 2019a) and the b exponent is 0.139, i.e. less than 0.2 as suggetsed by Vandekerckhove et al. (2000a). However, subsurface processes are not so common as in Dibatie where Verisols and soil tunneling (Fig. 3.11e) are very common, implying a predominant role of overland flow in gully development. In Aba Gerima the b exponet is 0.234 and subsurface processes and landsliding are uncommon, confirming the interpretation of Vandekerckhove et al. (2000a).

Fig. 3.7 indicates also that in the three study sites a minimum upslope drainage area of about 0.15 ha is necessary to start a gully. This value is larger than that of 0.05–0.40 ha reported by Montgomery and Dietrich (1992) for a semi-arid study area in California. The *b* exponent of Fig. 3.7 equations is in the range of those reported by Vandekerckhove et al. (2000a). Also, Wu and Cheng (2005) obtain a critical relationship for gully formation ($S = 0.1839A^{-0.2385}$) very similar to those of Fig. 3.7. The studies of Wu and Cheng (2005) and Li et al. (2004) are carried out in the Loess Plateau of China where the soil characteristics are rather different from those of our study sites and erosion rates are among the highest in the world.

The topographic thresholds for gullying in various environments is presented in Fig. 3.10. The threshold for gullying in the Guder watershed is among the highest observed globally. This is likely due to either the lower soil erodibility or greater grass cover compared to

Aba Gerima and Dibatie. In the latter site, Vertisols and soil tunneling are very common and a predominant role of subsurface processes in gully development is expected.

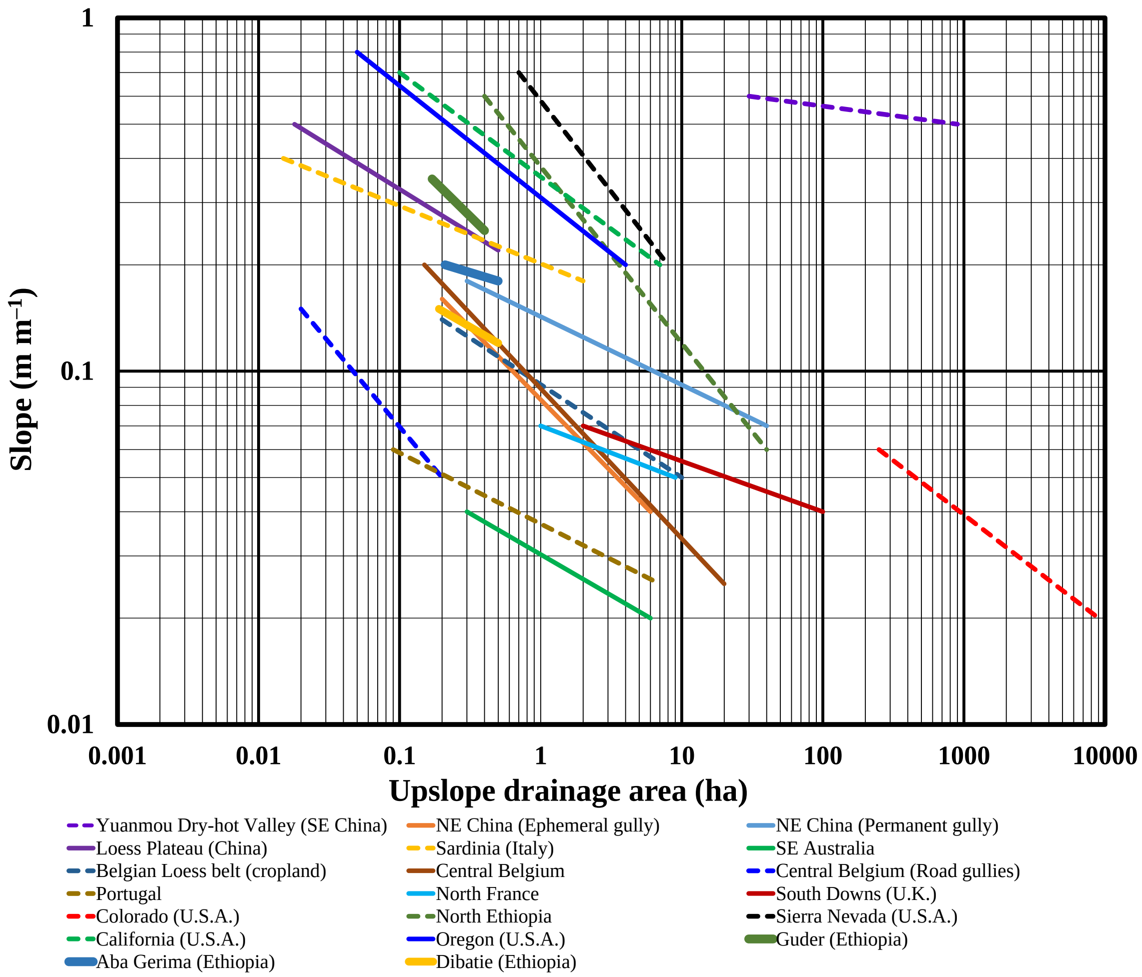

Figure 3. 10 Slope-drainage area thresholds for the initiation of gullying in the Upper Blue Nile basin, Ethiopia (Guder, Aba Gerima, and Dibatie; this study) compared to other results elsewhere in the world.

References are: Yuanmou Dry-hot Valley (Dong et al., 2013); NE China (Ephemeral and permanent gully) (Zhang et al., 2007); Loess Plateau of China (Wu and Cheng, 2005); Sardinia (Italy) (Zucca et al., 2006); SE Australia (Muñoz-Robles et al., 2010); Belgian Loess belt (cropland) (Nachtergaele et al., 2001); Central Belgium (Road gullies) (Vanwalleghem et al., 2003), and Other sources (Vandaele et al., 1996).

Nevertheless, factors such as land management practices, low ground cover which affect soil crusting, and high intensity storms may also have a strong affect on gullying (Patton and Schumm, 1975; Vandekerckhove et al., 2000a). Moreover, Gutiérrez et al. (2009) report that land uses that increase vegetation cover can increase gully development thresholds, whereas reduced vegetation cover (through increases in cultivated areas, conversion of forests to pasture, and overgrazing) tends to reduce the thresholds and increase the risk of gully erosion.

The concept of topographic thresholds provides a physical basis for gully initiation, and it is thus useful to predict where gully channels may develop for a given land use and location. Therefore, it is important to estimate topographic thresholds in different agro-ecologies and regions to identify areas susceptible to gully erosion and develop appropriate management practices.

3.8.5 Factors affecting gully cross-sectional morphology

The results indicate that land use type has some impact on gully development among the three sites. Gully bank collapse dominates in Guder and Dibatie, but has less impact in Aba Gerima (Fig. 3.9a). BW and TW can be influenced by external factors like physical soil property (soil texture), soil piping, and rainfall intensity, whereas gully depth is governed by the hardness/compaction of soil and rock layers and subsurface flow (Fig. 3.11e). The major reason for top-widening in grazing lands compared to bushlands is the minor effectiveness of grass roots, compared to bush roots (Fig. 3.11b), in binding the soil and preventing collapse (De Baets et al., 2007). This conclusion is supported by Billi and Dramis (2003) and Dong et al. (2013), who reported the role of gully bank vegetation in reinforcing soils and intercepting runoff and sediment.

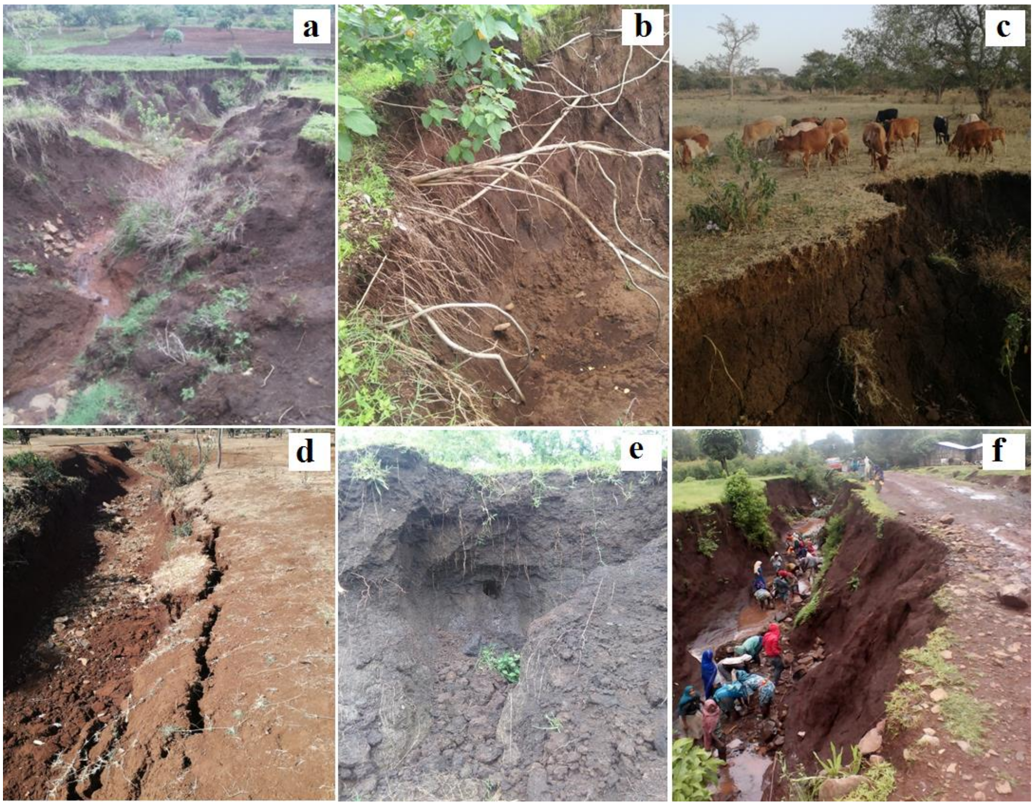

Figure 3. 11 Examples of active gullies observed in different land use and soil types. (a) Gully head and bank incised in Vertisol in cultivated land (Dibatie); (b) vegetation roots reinforcing a gully head and bank in bushland (Guder); (c) overgrazing at a gully he ad in grazing land (Dibatie); (d) gully bank cracks during the dry season in grazing land (Aba Gerima); (e) subsurface piping in grazing land (Dibatie); and (f) gully bank collapse blocking a rural gravel road (Aba Gerima).

The observed differences between sites must, therefore, be mainly induced by other factors such as soil type and land management practices (Table 3.1). Complementary to agricultural land use, the occurrence of infrastructure, such as irrigation canals, and especially roads and footpaths (Fig. 3.11f), can concentrate runoff, thus favoring the development of new gullies and increasing the expansion rates of existing ones (Fu et al., 2010; Verbist et al., 2010). In addition, TW increases with soil slumping, tunneling, and shallow mass-movements which may be triggered/favoured by subsurficial runoff (Tebebu et al., 2010; Addisie et al., 2017).

TW moderately increases with increasing slope only in the Guder watershed and remains nearly constant in the other sites. BW is very little affected by slope in the three study sites, but decreases slightly with increasing slope in Aba Gerima. Gully depth moderately increases with slope in Aba Gerima and Dibatie. Our data show that slope has little effect on gully cross-sectional morphology, though it strongly influences gully formation and development (Fig. 3.9).

3.9 Conclusions

This study investigated the morphological characteristics and topographic thresholds of gullies, and estimated the headcut retreat rates in three agro-ecologies of the Upper Blue Nile basin, Ethiopia. Gully morphological parameters are highly variable across the three agro-ecologies and are mainly related to varying local factors (e.g. land use).

Gully length and volume are generally much greater in midland than in highland and lowland agro-ecologies. This study also shows significant and positive correlations between gully morphological parameters (V, L, and A_g). A significant, general power equation to calculate the gully volume from gully length is obtained ($V = 8.097L^{1.032}$, $R^2 = 0.902$). The significant relationship between V and L, the weak relationships between V and TW, and between V and BW confirm that gullying is mainly a longitudinal incision process. This relation can be used whenever it is necessary to make an overview on gullying at regional level and to identify areas more or less prone to gully erosion simply by comparison of aerial photos or satellite images taken at different time interval in a relatively quick and cheap way. This method may find its best application also in remote and difficult to access areas. These results can be used to monitor changes in gully volume and related parameters affected by remedial measures implemented to control and/or reduce gully expansion.

This study demonstrated that the threshold of gully initiation in the highland (Guder site) is among the highest observed worldwide. This is probably due to the high grass cover that increases the soils' resistance to concentrated flow erosion and allows for infiltration. Thus reducing the runoff volume and shear stress and this cause potential subsurficial runoff. The gully initiation threshold is moderate in Aba Gerima (midland) and low in Dibatie (lowland). Based on these topographic thresholds, the dominant gully development process on cultivated lands of the Dibatie and Aba Gerima watersheds is overland flow, whereas subsurface processes affect the Guder watershed. Soil loss is more severe from lowland than from highland and midland gullies. Thus, unexpected result can be account for the highly erodible nature of Vertisols that occur at large in Dibatie.

The dominant local factor affecting gully cross-sectional morphology in the three agro-ecologies was land use. This suggests that biophysical factors can strongly impact gully morphological characteristics and topographic thresholds in different environmental settings. This study also shows gully headcut retreat rates vary based on agro-ecology, and thus site-specific investigations are crucial to understanding the major local drivers of gully headcut advancement.

This study provides useful information on the regional importance of gully erosion and draws attention to the need for conservation measures, especially in gully prone areas. Our results can be used to identify areas for gully initiation and estimate the contribution of gully erosion to soil loss. These applications are important for devising appropriate control measures for our study sites and areas with biophysical settings similar to the Upper Blue Nile basin, Ethiopia.

Chapter 4: Effects of hydrological processes on gully headcut retreat in a tropical highlands of Ethiopia

4.1 Introduction

Gully erosion is one form of accelerated soil erosion and its occurrence is often associated with extreme conditions of land degradation (Dotterweich et al., 2012; Poesen, 2018), and unsustainable land management (Castillo and Gómez, 2016; Haregeweyn et al., 2015; Haregeweyn et al., 2017). Gully erosion rates are typically high in the highlands of Ethiopia and other similar environments, but are also characterized by large spatial and temporal variability (Yibeltal et al., 2019a). Soil loss due to gully head retreat rate varies within agro ecological zones: the annual soil loss rates were estimated at 8.73 t ha^{-1} yr^{-1} in highland, 20.76 t ha^{-1} yr^{-1} in midland, and 49.33 t ha^{-1} yr^{-1} in lowland (Yibeltal et al., 2019c). Gully erosion accounts for 70–90% of sediment production in catchments of northern Ethiopia (Bewket and Sterk, 2003) and 60–90% of the total sediment production of agricultural lands in the hilly areas of the Loess Plateau, China (Li et al., 2003). Gully erosion can contribute to the siltation of lakes, reservoirs, and river channels (Haregeweyn et al., 2006; Haregeweyn et al., 2005; Poesen et al., 2003) and can lowers groundwater tables (Daba et al., 2003; Tebebu et al., 2010). It can cause catastrophic flooding and pollution, triggers landslides (Costa and Bacellar, 2007; Poesen et al., 2003) and gullies can devastate cultivated land and reduce crop yield, obstruct bridges and mechanical tillage operations damage infrastructure such as roads and buildings (Frankl et al., 2016; Nyssen et al., 2004; Yibeltal et al., 2019b).

Gullies can form in natural environments, but they are much more common when the landscape has been disturbed by anthropogenic factors (Frankl et al., 2012; Poesen, 2018) such as the diversion of concentrated runoff due to urbanization and construction activities (Nyssen et al., 2006; Poesen, 2018; Vanmaercke et al., 2016), changes in soil physical properties (Zegeye et al., 2018) and in the size of the upslope contributing area (Torri and

Poesen, 2014; Yibeltal et al., 2019b), especially in combination with high rainfall intensities (Vanmaercke et al., 2016). Active gully networks are commonly found in the saturated valley bottomlands (Tebebu et al., 2010; Yibeltal et al., 2019a). Soil saturation by a rising water level decreases the soil shear strength and therefore destabilizes the gully banks (Addisie et al., 2017; Tebebu et al., 2010). In the north-western highlands of Ethiopia, soil becomes saturated around the middle of the main rainy season and remains saturated until the beginning of the dry season. Gully formation is initiated with the occurrence of convergent shallow subsurface flow that leads to seepage-induced erosion of surface soils, gully heads and sidewalls (Vanmaercke et al., 2016; Zegeye et al., 2016). In pasture bottom lands of sub-humid high rainfall Ethiopian highlands, piping is also an important processes leading to development of permanent gullies (Zegeye et al., 2016). During intense rains, overland flow infiltrates through the pipes, thus increasing the lower soil horizon's vulnerability to gully erosion or favouring shallow landslides.

A major process of gully expansion occurs by gully-head retreat (e.g., Oostwoud Wijdenes and Bryan, 2001; Vandekerckhove et al., 2003; Yibeltal et al., 2019b). As a result of tumbling flow undermining, gully head moves upslope, releasing sediment to the channels and exposing new channel walls to erosion. Many studies to determine the rates of gully head retreat and to calculate sediment budgets are based on repeated measurements over different time spans (e.g., Capra et al., 2009; Castillo and Gómez, 2016) or on the analysis of aerial photographs sequential series (Daba et al., 2003; Frankl et al., 2012). The most commonly measured parameters are gully width, depth, length, gully bottom gradient, upstream supplying area slope and ratios between these parameters (Casalí et al., 2015; Li et al., 2017; Wu et al., 2018).

A few studies (e.g. Tebebu et al., 2010) have shown that the amount of surface flow and subsurface flow in the humid regions is different from that in the arid and semiarid regions.

The subsurface flow is a major contributory factor in the formation and development of gullies in the sub humid Ethiopian highland (Addisie et al., 2017; Tebebu et al., 2010; Zegeye et al., 2016). In the arid part of northern Ethiopia, Frankl et al. (2013) found that about 25% of the study gully sections were stabilized by siltation behind check dams. However, such physical structures have been ineffective in controlling gully erosion in the (sub) humid Ethiopian Highlands, where gullies are formed in gentle slope areas and where water often bypasses the check dams (Dagnew et al., 2015) and interflow elevates subsurface water level in the valley bottom, which promote gully formation and expansion (Tebebu et al., 2010; Yibeltal et al., 2019a). Though it was recognized that subsurface flow plays an important role in gully formation and expansion (e.g. Castillo and Gómez (2016)), limited information exists on the effects of soil water table changes on gully erosion under field conditions (Fox et al., 2007).

So far, limited field study has been carried out to understand the influence of subsurface flow processes in the initiation and development of gully erosion in the sub-humid Ethiopian Highlands (high rainfall areas). This study was aimed to better understand gully erosion processes and factors in the initiation and development of gullies in the Upper Blue Nile basin (UBNB), Ethiopia. The main aim of this work is to investigate the role of subsurface flow in gully formation and expansion in the sub-humid northern highlands of Ethiopia and, specifically, to relate hydrological and morphological features with gully head retreat rates. Three specific research objectives were identified: (1) to assess gully-head retreat rates in selected gullies and to evaluate sediment loss from paired watershed; (2) to understand the relationship between daily rainfall and subsurface water level; (3) to identify the main gully erosion controlling factors in the sub-humid highlands of Ethiopia.

4.2 Study area

The study was conducted in two small watersheds within the headwaters of the Upper Blue Nile basin, Ethiopia (10° 57′ 23″ to 11° 11′ 21″ N latitude and 36° 40′ 01″ to 37° 05′ 21″ E longitude). The watersheds (Akusity and Kasiry) are specifically located in Fagita Lekoma district, Awi Zone 114 km from Bahir Dar city, Amhara National Regional State, Ethiopia (Fig. 4.1). The topography of the study area is characterized by irregular morphology with medium to steep slopes and rugged and undulating landscape. The landscape is fragmented as a result of different land use practices over many decades. In the study area, with population growth, agropastoral communities have intensified land use over the past decades. To halt the degradation of the natural environment, soil and water conservation (SWC) structures were implemented (especially trench) on steep slopes. On most steep slopes of the study area, trenches were constructed to trap water and sediment and to improve infiltration (Ebabu et al., 2018; Sultan et al., 2018a). In areas with high densities of trenches, the increased rate of infiltration resulted in gully development on foot slopes. In spite of the efforts made, gully erosion continues to be major problems in the study area (Yibeltal et al., 2019a; Yibeltal et al., 2019b) and has significant environmental impacts.

The most active period of gully initiation and expansion is the main rainy season (May–October). The study area can be described as a sub-tropical moist agro-ecological zone with long cool and rainy summer, which corresponds to *Dega zone* (highland) (Ebabu et al., 2018). Based on the record period 1999–2018, measured at Ingibara Meteorological station, which is located about 5 km far from the study area, the average daily temperature ranges between 9.4 and 25°C. Mean annual rainfall is 2454 mm yr^{-1}, about 86% of which falling in the rainy season from May to October (Fig. 4.2). Rainfall distribution varies widely with high-intensityand erosive potential rainstorms occurring during summer (June–August) (Ebabu et al., 2018). During the main rainy season, the sediment yield of the study watersheds ranges from 7.6 to 71.2 t ha^{-1} (Ebabu et al., 2018). The area is subjected also to dry period (November–April) and a secondary wet season (May–October). Annual average potential evapotranspiration is about 1160 mm and maximum potential evapotranspiration occurs in March (Fig. 4.2).

The gently sloping areas (0–10°) (which are mainly in grazing lands) are saturated for long periods and affected by active gully networks, in places also related to landslides (Yibeltal et al., 2019a). Free grazing is common on most of the grazing lands, both on gentle and steep slopes. Livestock densities are amongst the highest in the region (Leta and Mesele, 2014), resulting in high risk of overgrazing.

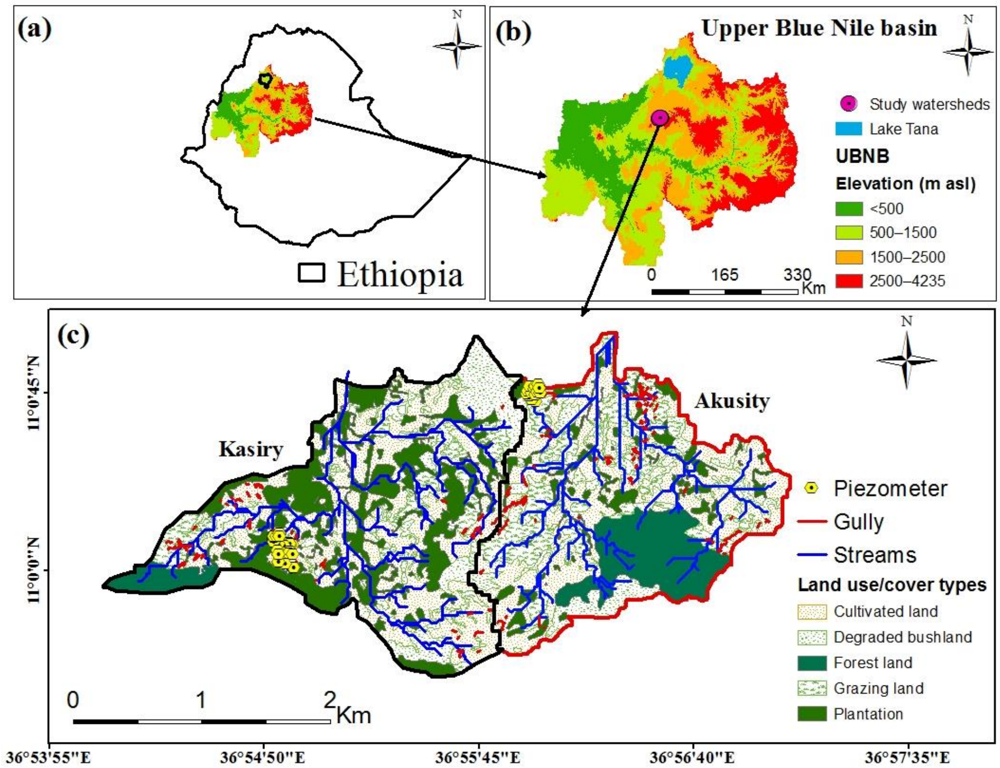

Figure 4. 1 Maps of the study area. (A) Location of the Upper Blue Nile basin (UBNB) within Ethiopia. (B) Topography and locations of the Kasiry and Akusity watersheds within the UBNB. (C) Land use/cover types, gullies distribution in 2017, piezometers location, and stream networks.

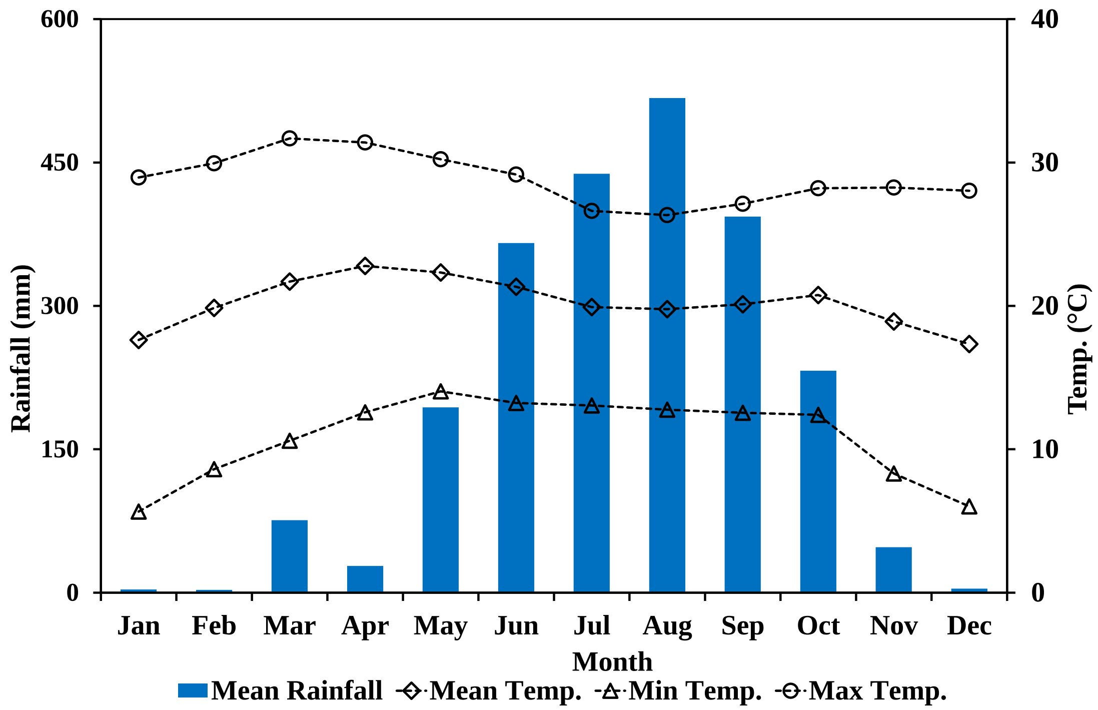

Figure 4. 2 Monthly mean rainfall and mean, minimum, and maximum air temperatures in Guder during the 1999–2018 interval.

During the field survey we noticed the colluvial deposits in the gully profile with piping flow triggering gully bank collapse (Fig. 4.3c), termite effect (Fig. 4.3b), and several landslides induced gullies (Fig. 3a). Colluvial deposit can be highly permeable due to interconnected pores formed at the time of sedimentation processes. The study area is underlain by recent (Quaternary) fissural and volcanic basalts (Abbate et al., 2015) on which colluvial deposit, resulting from accumulation of weathering products, including redeposited soil, rest. The expansion of the gully network in the paired watershed highly impacted the grazing land (Fig. 4.3).

Figure 4. 3 Gully headcut related to landslide (a), termite effect (b), and Colluvial deposit (c).

The dominant FAO soil types of the study site are Luvisols in sloping areas and Vertisols in valley bottoms (Mekonnen, 2016). Most of the soil texture in the paired watersheds are clay dominated (Table 4.1). The textural analysis was done from different soil layers along the profile of the sidewalls near the gully head (the number of layers varied from three to five depending on the gully depth and the deposition history in case of colluvial deposits). Luvisols are very deep and well-drained soils that form on gentle slopes and Vertisols are soils with high concentrations of smectite-type clay minerals that shrink and swell under dry and wet conditions, respectively (Mekonnen, 2016). These soils are susceptible to physical crusting, sealing, and dispersion, particularly following disturbances such as plowing, cattle trampling, or the removal of ground cover and vegetation. Ten soil profiles were analyzed to understand the soil physical properties in different soil layers of the paired watersheds (Table 4.1).

Table 4. 1 Physico-chemical properties of soil samples at different horizons of 10 selected profiles (Pedons) in different land use types of the study area.

Site	Soil type	Land use type	Pedon No.	Horizon	Depth (cm)	Particle size (%)			Textural class	BD (g cm^{-1})
						sand	Silt	Clay		
Akusity	Luvisols	Grazing land	1	Ap	0–25	45	40	15	Loam	1.25
				AB	25–60	49	36	15	Loam	1.33
				B	60–80	43	32	25	Loam	
		Grazing land	2	Ap	0–20	35	38	27	Loam	1.32
				AB	20–45	43	34	23	Loam	1.35
				Bt1	45–110	41	36	23	Loam	
				Bt2	110–195	31	50	19	SL	
		Grazing land	3	Ap	0–26	69	18	13	SL	1.3
				AB	26–53	53	32	15	SL	1.35
				Bt1	53–80	21	32	47	C	
				Bt2	80–140	21	30	49	C	
		Plantation	4	Ap	0–14	12	38	50	C	1.22
				AB	14–55	14	30	57	C	1.28
				Bt1	55–90	12	24	64	C	1.34
				Bt2	90–135	13	23	64	C	
				Bt3	135–200	10	28	62	C	
Kasiry	Vertisols	Cultivated land	2	Ap	0–18	36	24	40	C	1.39
				AB	18–47	38	12	50	C	1.41
				Bt1	47–79	39	25	36	CL	
				Bt2	79–114	36	28	36	CL	
		Plantation	3	Ap	0–20	20	26	54	C	1.3
				AB	20–81	41	15	44	C	1.35
				Bt1	81–111	35	25	30	C	
				Bt2	111–190	31	25	44	C	
		Grazing land	4	Ap	0–23	39	18	43	C	1.38
				AB	23–62	30	25	45	C	1.42
				Bt1	62–97	36	29	35	CL	
				Bt2	97–170	35	31	34	CL	
	Luvisols	Cultivated land	1	Ap	0–17	52	28	20	SL	1.2
				AB	17–51	78	18	4	LS	1.3
				Bt1	51–103	30	24	46	C	
				Bt2	103–162	76	20	4	LS	
				Bt3	162–200	42	26	32	CL	
		Grazing land	5	Ap	0–35	32	20	48	C	1.23
				Bt1	35–70	26	20	54	C	1.27
				Bt2	70–150	22	20	58	C	
		Grazing land	6	Ap	0–26	69	18	13	SL	1.3
				AB	26–53	53	32	15	SL	1.35
				Bt1	53–80	21	32	47	C	
				Bt2	80–140	21	30	49	C	

Source: (Mekonnen, 2016).

OC = organic carbon; TN = total nitrogen; C: N = carbon to nitrogen ratio; BD = dry bulk density; BS = base saturation; C = clay; CL = clay loam; LS= loamy sand; SL= silt loam.

The major land use/cover types in the study area are cultivated lands, grazing lands, bushlands, plantation, and homesteads (Table 4.2). Cultivated lands comprise a larger proportion of the land use than grazing lands and bushlands and the farming system is mixed crop-livestock, characterized by rain-fed and continuous cropping. The major crops produced in this area are include: *tef* (Eragrostis tef), barley (Hordeum vulgare), wheat (Triticum aestivum), and potato (Solanum tuberosum) (Nigussie et al., 2017b; Yibeltal et al., 2019a). The direction of the tillage practice is across the slope of the cultivated land. The farmers locally used animals to compact the soil to make a favourable condition, especially for *Tef* cultivation. Dominant tree and shrub species include *Acacia abyssinica, Erythrina brucei*, *Urtica simensis,* and *Justica schimperiana*. The main farming practice is several ploughing using horse driving equipment's to a depth of about 40 cm from March to July before sowing in summer (June to August). Eucalyptus trees are planted throughout the watersheds but mainly around homesteads. Recently, large portions of the watersheds are predominately cover by *Acacia dicurence,* for it is the most economical tree in the area (Nigussie et al., 2017a). More detailed descriptions of the study area can be found in previous studies (Berihun et al., 2019a; Berihun et al., 2019b; Ebabu et al., 2018).

Table 4. 2 Main characteristics of the Akusity and Kasiry watersheds.

Watershed characteristics (units)	Akusity	Kasiry
Elevation (m.a.s.l)	2554–2882	2492–2880
Total area (ha)	398.3	343.7
Total number of households	56	105
Slope range (°)	0–32	0–39
Drainage density (km/km^2)	5.94	5.49
Land use / cover (%):		
Cultivated land	19	21
Grazing land	10	14
Degraded bushland	4	17
Tree plantation[a]	42	40
Forest	25	8
Major soil types	Luvisols	Luvisols and Vertisols
Major livestock	Cattle, sheep, donkeys and horses	
Major crops	Barley, *tef*, wheat and potato	
Temperature (°C)	9.4–25	
Annual rainfall (mm yr^{-1})	2454	
Agro-ecological zone	Sub-humid tropical	

Source: (Berihun et al., 2019a; Ebabu et al., 2018; Mekonnen, 2016; Yibeltal et al., 2019a). [a]planted tree species is Acacia dicurrens; Tef (*Eragrostis tef*); wheat (*Triticum aestivum*); maize (*Zea mays*); barley (*Hordeum vulgare*); potato (*Solanum tuberosum*).

4.3 Materials and methods

4.3.1 Monitoring gully headcut retreat and sediment yield rates

To investigate the medium-term gully head expansion, we measured 11 gullies for 11-year period (2006–2017). We estimated the extent expansion of gullies and associated sediment yield from the paired watersheds using the data from previous work by Yibeltal et al. (2019a). The change in length was determined from the initial (2006) to the current (2017) position of the edge of the gully head. Gully head positions in 2006 were first identified using satellite images. Then, the positions of the same gully heads were determined from satellite images acquired in 2017. High-resolution satellite images were used to derive the rate of gully head retreat and to assess soil loss during the 2006–2017 interval. IKONOS images from 26 March 2006 and Pleiades images from 11 January 2017 were used. The spatial resolutions of the different satellites are 0.82 m for IKONOS and 0.50 m for Pleiades. Different satellite images were used for the same sites due to the scarcity of available images. Gully head positions were extracted from the satellite images by visual interpretation. Gully length was determined separately on very high resolution satellite images by means of the spatial analyst extension in the ArcMap software, which was also used to calculate the surface area and the length of each gully. Since gully volume could not be obtained from aerial measurements, it was derived from the digitized gully length and gully surface area using the correlation model developed by Yibeltal et al. (2019b). In addition, to assess the sediment yield (SY) from the two paired watersheds during the study periods, we adopted length and volume relationship developed for this study site.

The direct measurements of short-term retreat rates of 16 gullies were carried out over a 2-year period (2017 and 2018). The gully heads advancement was monitored on a monthly basis from June to November during both the 2017 and 2018 rainy season. For 16 gullies, we measured (1) the headcut retreat; (2) gully widening; (3) the gully expansion rates and (4) associated amount of soil loss. To assess gully expansion and the amount of soil loss from the total gully reach, four gully profile measurement (before and after the rain phases of 2017 and 2018) were conducted. Gully cross-sectional geometry was surveyed by dividing the cross section into trapezoidal segments at abrupt changes in the ground profile and then measuring maximum depth (D, in meters), top width (TW, in m) and bottom width (BW, in m) of the bankfull channels at each segment. Where the gully cross-sectional shape was trapezoidal (which is in most of the cases), [(TW+BW)/2] x D gave the cross-section area (CSA) (in m^2). In other cases, additional measurements of the channel dimension were done. The linear gully headcut retreat rate (m yr^{-1}) was the retreat length by the duration of the observation period, i.e., 2 years. The volumetric retreat rate ($m^3 yr^{-1}$) was calculated by multiplying the linear retreat rate by the average cross-sectional area of the incised gully before and at the end of the rainy season. Volumetric retreat rates were converted into mass erosion rates ($t\ yr^{-1}$) by multiplying the former by the average bulk density of the dry soil. Bulk densities were measured using undisturbed 23 soil samples collected from different soil layers along the profile of the sidewalls and at gully heads using a standard core sampler (volume = 100 cm^3).

4.3.2 Subsurface water level monitoring

Subsurface water level is one of the most important factors for gully formation and gully head and bank instability in high rainfall sub-humid regions highlands of Ethiopia (Addisie et al., 2017; Zegeye et al., 2016). To investigate the role of subsurface water level on gully head retreat or gully bank collapse, piezometers were installed near the heads and in the runoff contributing area above the gully heads. The piezometers were made from PVC pipes with a diameter of 5 cm. The bottom end of the pipes was perforated along a length of 40 cm with 1 cm diameter. Intrusion of silt and sand to the piezometers was prevented by covering filter fabric around the 40 cm long screened bottom end, while the top end of the piezometers was covered by a removable plastic cap to prevent the entrance of surface runoff, rainfall, sediment and any physical damage. The pipe height above the ground surface was 25 cm and considered adequate to prevent the entrance of surface runoff, sediment and to protect from physical damages. Subsurface water level elevations were measured by a tape meter twice a day in the morning (8:00–9:00 AM local time-LT) and in the evening (3:30–10:30 PM LT).

A total of 34 piezometers (20 in Kasiry and 14 in Akusity) were installed in the gully's contributing area above each gully head for the rainy seasons of 2017/18 and 2018/19.

Piezometers depth in the Akusity watershed varies from 1.7 to 2.87 m with an average depth of 2.48 m near SWC structures (trench) and gully heads. We installed piezometers near the trenches to understand the effect of SWC practices in promoting water infiltration and in increasing subsurface water level. By using a hand auger, each piezometer installed in the Kasiry and Akusity watershed around the actively eroding gully have a depth of 1.15 to 4.05 m with an average depth of 2.62 m. For some piezometers, the installation depth was limited due to the difficulty of drilling. An individual recording of all water levels in all the piezometers was completed in one hour to minimize any discrepancy in water level depths due to different survey time variations. For this purpose, two data collectors were hired for daily measurement.

A wood pin was installed as a benchmark below and above each gully head to measure change in bed depth and distance to the edge of the gully head. Wood pins 50 cm long were driven into the bed and head of the gully at the beginning of the study period in June 2017 and 20 cm wood pin were inserted to the soil surface. The length of the exposed end of the wood pins were measured at the beginning and end of the monitoring period to estimate gully head retreat length during the measuring period (2017 and 2018).

We conducted a comprehensive study of the dynamics of 16 gully headcut (GH 1_Ka to GH 9_Ka in Kasiry and GH 1_Aku to GH 7_Aku in Akusity), as well as the factors controlling it. Gullies are located in different locations of the pair watersheds and many gullies are located on gentle slope (Fig. 4.4). Gully heads GH15_Ka and GH16_Ka in Kasiry and GH12_Aku, GH13_Aku, and GH14_Aku in Akusity are located in the flat bottom of the watershed. Gully heads GH3_Ka, GH4_Ka, and GH14_Ka in Kasiry and GH8_Aku and GH12_Aku in Akusity are located on the medium slope area of the watershed and gully heads GH8_Ka, GH10_Ka, GH11_Ka, and GH12_Ka in Kasiry and

GH3_Aku and GH6_Aku in Akusity are located on the steep slope area of the watershed (Fig. 4.4). All gullies in both watersheds are located on communal grazing lands (Fig. 4.4).

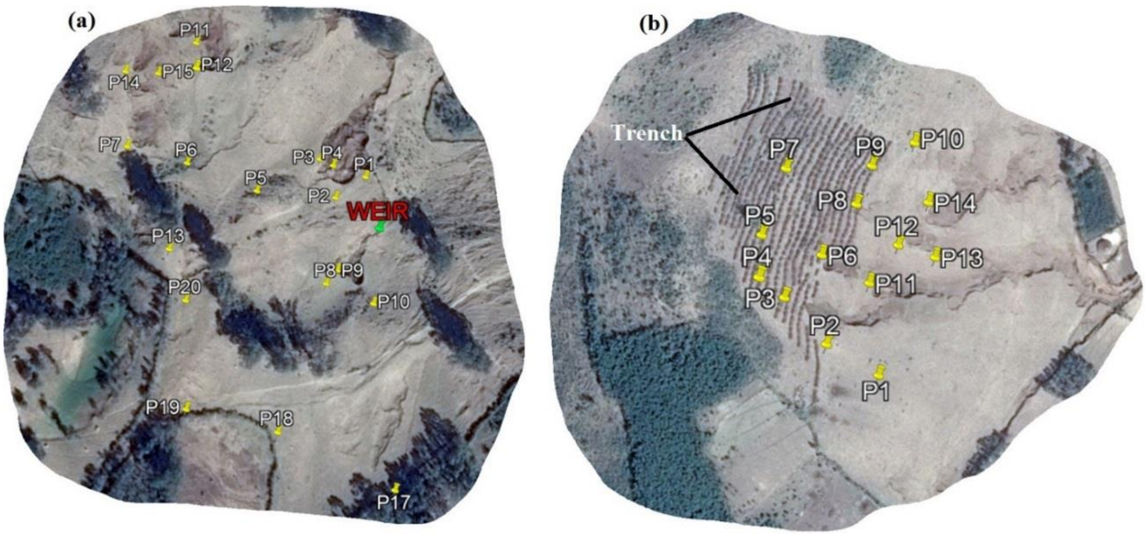

Figure 4. 4 Location of piezometers and trenches in Kasiry (a) and Akusity (b) watersheds.

Precipitation in rainy season was measured daily using manual and tipping-bucket rain gauges from May to December during the study period (2017 and 2018). We used the minimum and maximum temperatures for 2017 and 2018 to calculate a daily average temperature, which was used to calculate potential evapotranspiration.

4.3.3 Sediment yield measurements

Sediment transport from selected gully during rainy seasons in 2017 and 2018 was measured using weir structure (Fig. 4.5). This measurement was used to understand the relationship between gully headcut retreat and sediment yield during rainy period. Weir was constructed below the two gullies to understand the sediment transport from gully cross-section during the gully headcut retreat monitoring period (Fig. 4.4a).

Figure 4. 5 Weir structure to monitor sediment yield from gully cross-section.

4.3.4 Electrical conductivity measurement for piping flow and surface runoff

The electrical conductivity (EC) of the surface runoff at the gully head during the rainy events and of subsurface water flow (piping flow) from gully bottom was measured using Milwaukee MW 802 pH/EC/TDS Meter. A total of 51 samples for surface runoff and 51 for piping flow were measured to understand EC difference between piping flow and surface runoff and to attempt to identify the source of piping flow. Yet, this helps to understand the source of the piping flow at the gully bottom either from direct rainfall or subsurface flow (Fig. 4.6) and to understand the piping flow effect on bank collapse and gully headcut retreat.

Figure 4. 6 Field electrical conductivity measurement; Piping flow (a) and surface runoff (b).

4.4 Results

4.4.1 Dynamics of gully head retreat

4.4.1.1 Medium-term gully expansion rates and soil loss (2006–2017)

Table 4.3 presents the linear, areal, and volumetric gully headcut retreat rates. The minimum and maximum gully head retreats are 10.1 m in Kasiry and 11.9 m in Akusity, respectively, over the 2006–2017 intervals. The mean (± standard deviation) longitudinal retreat and lateral retreat are 10.97±0.69 m and 4.87±1.03 m, respectively. The average surface area increase varies from 37.38 to 84.78 m^2, with average of 53.49 (±12.83) m^2 (Table 4.3). The maximum and minimum volumetric gully headcut retreat (V_e) value is 15.72 m^3 yr^{-1} and the minimum is 6.21 m^3 yr^{-1}. The average volumetric expansion rate of the 11 gullies is 8.62±0.70 m^3 yr^{-1} and 9.35±2.58 m^3 yr^{-1} using gully volume and gully length and surface area relationships, respectively. The minimum and maximum volumetric rates are between 85.11 and 105.21 m^3 and between 68.19 and 172.87 m^3 using gully length (V, $m^3 = 4.2866L^{1.2923}$) and surface area (V, $m^3 = 1.1138Ag^{1.1362}$) relationship, respectively (Yibeltal et al., 2019b) (Table 4.3). The corresponding soil loss from these gullies between 2006 and 2017 is 11.12±0.90 t yr^{-1} and 11.34±1.94 t yr^{-1} by using gully volume and length and surface area relationships, respectively (Table 4.3). The coefficient of variations (CVs) ranges from 8.12 to 27.59%.

Table 4. 3 Rates of gully headcut and soil loss from Kasiry and Akusity watersheds.

No.	L (m)	W (m)	Ag (m^2)	V (m^3) = 4.2866 $L^{1.2923}$	V(m^3 yr^{-1})*	V (m^3)= 1.1138 $Ag^{1.1362}$	V(m^3 yr^{-1})**	Ton/yr*	Ton/yr**
GH1_Ka	11.8	5.04	59.97	104.11	9.36	116.64	10.6	12.34	13.68
GH3_Ka	10.5	4.96	52.1	89.49	8.14	99.41	9.04	10.5	11.66
GH4_Ka	10.4	5.6	58.21	88.39	8.04	112.77	10.25	10.37	13.22
GH10_Ka	11.5	5.4	62.13	100.66	9.15	121.44	11.04	11.8	14.24
GH11_Ka	10.8	4.83	52.13	92.81	8.44	99.49	9.04	10.88	11.67
GH12_Ka	11.2	3.34	37.38	97.28	8.84	68.19	6.21	11.41	8
GH15_Ka	10.1	4.69	47.41	85.11	7.74	89.31	8.12	9.98	10.47
GH6_Aku	11.7	7.25	84.78	102.93	9.36	172.87	15.72	12.07	12.34
GH11_Aku	10.5	4.24	44.5	89.49	8.14	83.1	7.55	10.5	9.75
GH12_Aku	10.2	4.34	44.24	86.2	7.84	82.56	7.51	10.11	9.68
GH14_Aku	11.9	3.83	45.58	105.21	9.56	85.41	7.76	12.34	10.02
Average	10.97	4.86	53.49	94.8	8.62	102.84	9.35	11.12	11.34
Stdev	0.69	1.03	12.83	7.69	0.7	22.37	2.58	0.9	1.94
CV	6.28	21.2	23.99	8.16	8.12	21.75	27.59	8.12	17.11

L = gully length (m); W= gully width (m); A_g= gully surface area (m^2); V= volume (m^3); V_e= volumetric rate (m^3 yr^{-1}); SL= sediment loss (ton yr^{-1}); GH_Ka = Gully head retreat in Kasiry watershed; GH_Aku = Gully head retreat in Akusity watershed; * (V, $m^3 = 4.2866L^{1.2923}$); ** (V, $m^3 = 1.1138Ag^{1.1362}$) Yibeltal et al. (2019b).

4.4.1.2 Gully erosion dynamics and sediment loss from paired watersheds (2006–2017)

Total gully length increased within each watershed between 2006 and 2017 (Table 4.4). Based on the digitized high resolution satellite images of 2006 and 2017, we found that the number of gullies increasing in length from 2006 to 2017 are 26 and 85 in Kasiry and Akusity watersheds, respectively. The total length of the gully network increased from 2.1

km in 2006 to 2.9 km in 2017 in Kasiry (343.7 ha) and 2.2 km in 2006 to 3.5 km in 2017 in Akusity (398.3 ha) (Table 4.4). From 2006 and 2017, the total gully length increased by 800 and 1300 m in Kasiry (343.7 ha) and Akusity (398.3 ha), respectively. Mean annual volumetric rate is 2199.80 m^3 yr^{-1} in Kasiry and 4119.73 m^3 yr^{-1} in Akusity. The soil losses are 8.26 t ha^{-1} yr^{-1} and 13.34 t ha^{-1} yr^{-1} in Kasiry and Akusity watersheds, respectively (Table 4.4).

Table 4. 4 Medium-term sediment loss from Kasiry and Akusity watersheds.

Watershed	Year	No. of gullies	L (km)	ΔL (m)	V* (m^3) = $4.2866L^{1.2923}$	Ve (m^3 yr^{-1})	SL (ton yr^{-1})	SL (ton ha^{-1} yr^{-1})
Kasiry	2006	63	2.1	800	24197.81	2199.8	2837.74	8.26
	2017	89	2.9					
Akusity	2006	59	2.2	1300	45317.08	4119.73	5314.46	13.34
	2017	144	3.5					

L = L = gully length (m); W = gully width (m); A_g = gully surface area (m^2); V = volume (m^3); V_e = volumetric rate (m^3 yr^{-1}); SL= sediment loss (ton ha^{-1} yr^{-1}); *(V, m^3 = $4.2866L^{1.2923}$) Yibeltal et al. (2019b).

4.4.1.3 Measuring gully widening and headcut retreat (2017 and 2018)

The short-term gully head retreat is analyzed by the variables listed in Table 4.5. The headcut retreat over the 2-year monitoring period in the rainy season for the 16 headcut is shown in Table 4.5. During the two years, only 8 of the 16 gullies (GH8_Ka, GH12_Ka, GH16_Ka, GH3_Aku, GH11_Aku, GH12_Aku, GH13_Aku, and GH14_Aku) were actively expanded. The gully head retreat during the 2017 and 2018 rainy season varied from 0.24 to 1.93 m, with mean (± standard deviation) value of 0.96±0.55 m, depth of the gully heads varied between 1.07 and 3.42 m, with a mean value of 2.06±0.68 m, and the widths varied between 2.07 and 7.04 m, with an average value of 4.72±1.34 m (Table 4.5). The shallowest gully is 1.07 m, GH2_Ka, and the deepest gully is 3.42 m deep, GH12_Aku. The surface slope above the gully head was also greater than gully channel slopes (Table 4.5). Width depth ratio (WDR) varies between 1.48 and 6.56 m, with mean value of 2.52±1.24 m, indicating that gullies expansion occurred mainly as gully widening rather than gully bottom erosion. The average cross-sectional area varies from 4.09 (GH14_Aku) to 19.9 m^2 (GH13_Aku), with an average of 8.50± 4.44 m^2. The average gully headcut volumetric retreat (V_e) values during the 2017 and 2018 rainy seasons varied from 2.67 (GH10_Ka) to 30.18 m^3 (GH13_Aku), with a mean value of 8.58±7.06 m^3 (Table 4.5). The soil loss of the individual gullies ranged from 3.45 (GH10_Ka) to 38.94 t yr^{-1} (GH13_Aku). During 2017–2018, the average soil loss due to gully headcut is 11.06±9.11 t yr^{-1}.

Table 4. 5 Short-term sediment loss from the Kasiry and Akusity watersheds.

Gully ID	Mean head retreat (m)	Mean width (m)	Mean depth (m)	WDR	Surface slope above gully head (m m^{-1})	Channel slope (m m^{-1})	CSA (m^2)	Volumetric soil loss (m^3)	Soil loss by weight (ton yr^{-1})	RCA (ha)
GH3_Ka	0.68	7.04	1.07	6.56	0.26	0.13	10.1	6.81	8.79	0.2
GH4_Ka	0.49	3.82	1.85	2.06	0.26	0.12	8.81	4.33	5.59	0.25
GH8_Ka	1.67	5.02	1.93	2.61	0.17	0.11	4.17	6.95	8.97	0.26
GH10_Ka	0.71	5.05	2.86	1.77	0.18	0.11	3.77	2.67	3.45	0.16
GH11_Ka	0.25	4.08	2.61	1.57	0.16	0.12	12.3	3.07	3.96	0.16
GH12_Ka	0.74	3.54	2.14	1.65	0.14	0.12	11.5	8.48	10.94	0.24
GH14_Ka	1.13	4.96	2.39	2.08	0.26	0.14	5.87	6.61	8.52	0.26
GH15_Ka	0.28	7.37	2.68	2.75	0.16	0.12	14.7	4.17	5.38	0.37
GH16_Ka	1.93	3.45	1.78	1.93	0.26	0.13	10.5	20.27	26.15	0.22
GH3_Aku	1.43	2.07	1.08	1.92	0.16	0.12	10	14.28	18.42	0.34
GH6_Aku	0.84	3.96	1.64	2.42	0.18	0.13	5.95	5.1	6.45	0.31
GH8_Aku	0.68	4.24	2.86	1.48	0.17	0.11	5.07	3.46	4.47	0.26
GH11_Aku	1.71	4.47	1.71	2.61	0.17	0.11	4.48	7.65	9.86	0.27
GH12_Aku	1.13	5.38	3.42	1.58	0.17	0.12	4.86	5.49	7.08	0.16
GH13_Aku	1.52	5.72	1.62	3.52	0.16	0.13	19.9	30.18	38.94	0.26
GH14_Aku	1.91	5.45	1.42	3.84	0.16	0.12	4.09	7.81	10.07	0.16
Average	1.07	4.73	2.07	2.52	0.19	0.12	8.5	8.58	11.06	0.24
Stdev	0.55	1.29	0.66	1.24	0.04	0.01	4.41	7.06	9.11	0.06

WDR = width depth ratio; CSA = cross-sectional area (m^2); RCA = Runoff contributing area (ha); GH_Ka = Gully head retreat in Kasiry watershed; GH_Aku = Gully head retreat in Akusity watershed.

The runoff contributing area of each gully head is minimum and it related to the topography of the watersheds. The runoff contributing area for the studied gully heads varied from 0.16 to 0.37 ha with an average value of 0.24±0.06 ha (Table 4.5). The average gully channel slope is minimum (0.12 m m^{-1}) when compare to surface slope at gully head (0.19 m m^{-1}).

The subsurface water level measurements, which started in mid July 2017 and 2018, showed that the soil was slowly wetting up and eventually became saturated (Fig. 4.7). This process was extended to the end of the rainy season. The measured water level depths at each gully site were between 40.36% and 63.57% above the gully bottom during 2017 and 2018, respectively. At the end of October, when the rainfall amounts had decreased, the water level slowly decreased.

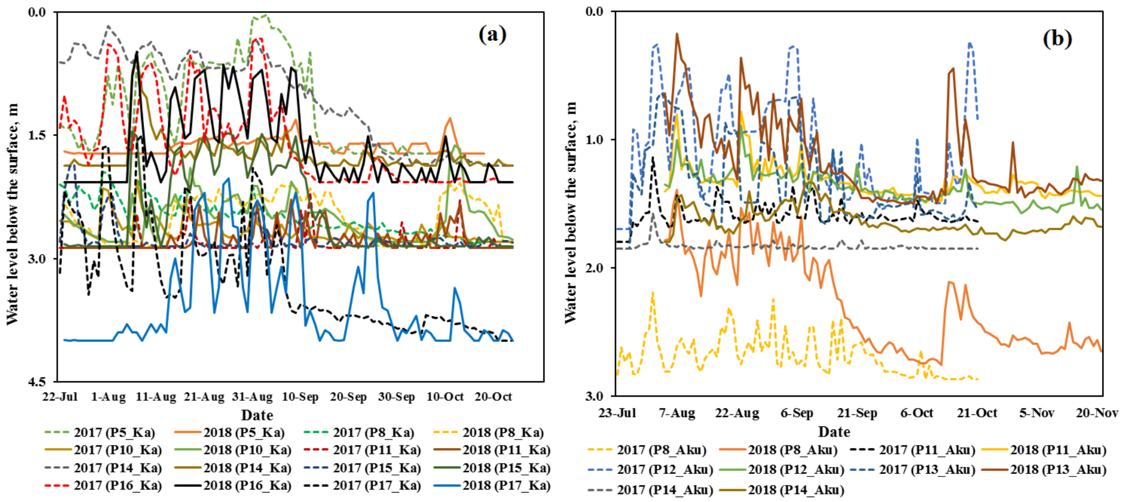

Figure 4. 7 Trends in subsurface water level measured during the period 2017 and 2018 in Kasiry (a) and Akusity (b) watersheds.

The linear retreat of the 19 gully heads in 2017 and 2018 was compared with average subsurface water level (Fig. 4.8). In Kasiry watershed, the maximum and minimum gully head retreat was 68 cm (G2_Ka) and 22 cm (G12_Ka) in 2017 and 62 cm (G10_Ka) and 23 cm (G3_Ka) in 2018, respectively. The subsurface water level was between 281 cm (P11_Ka) and 133 cm (P3_Ka) in 2017 and between 277 cm (P11_Ka) and 105 cm

(P3_Ka) in 2018 (Fig. 4.8). In Akusity watershed, gully head retreat was between 76 cm (G14_Aku) and 28 cm (G3_Aku) in 2017 and between 86 cm (G14_Aku) and 28 cm (G3_Aku) in 2018. The subsurface water level was between 269 cm (P14_Aku) and 89 cm (P3_Aku) in 2017 and between 228 cm (P14_Aku) and 78 cm (P3_Aku) in 2018 (Fig. 4.8). The relationship between subsurface water level and gully head retreat showed to be moderate at watershed scale. The higher gully head retreat and subsurface water level occurred at similar gully locations in Akusity watershed. The linear headcut retreat showed a moderate relationship with subsurface water level (Fig. 4.8). This clearly indicates that subsurface water level, and thus gradual wetting and saturation of the soil, is an important factor for headcut retreat. The elevated water level appears to facilitate the slumping of gully walls (Fig. 4.8), which causes the gully to migrate up the hillside and to widen. The piezometric data showed that, in the actively eroding sections of the gully, water level was above the gully bottom and, in stable gully sections, the water level was below the gully. Such field evidence suggests that the elevation of subsurface water level played an important role in gully expansion.

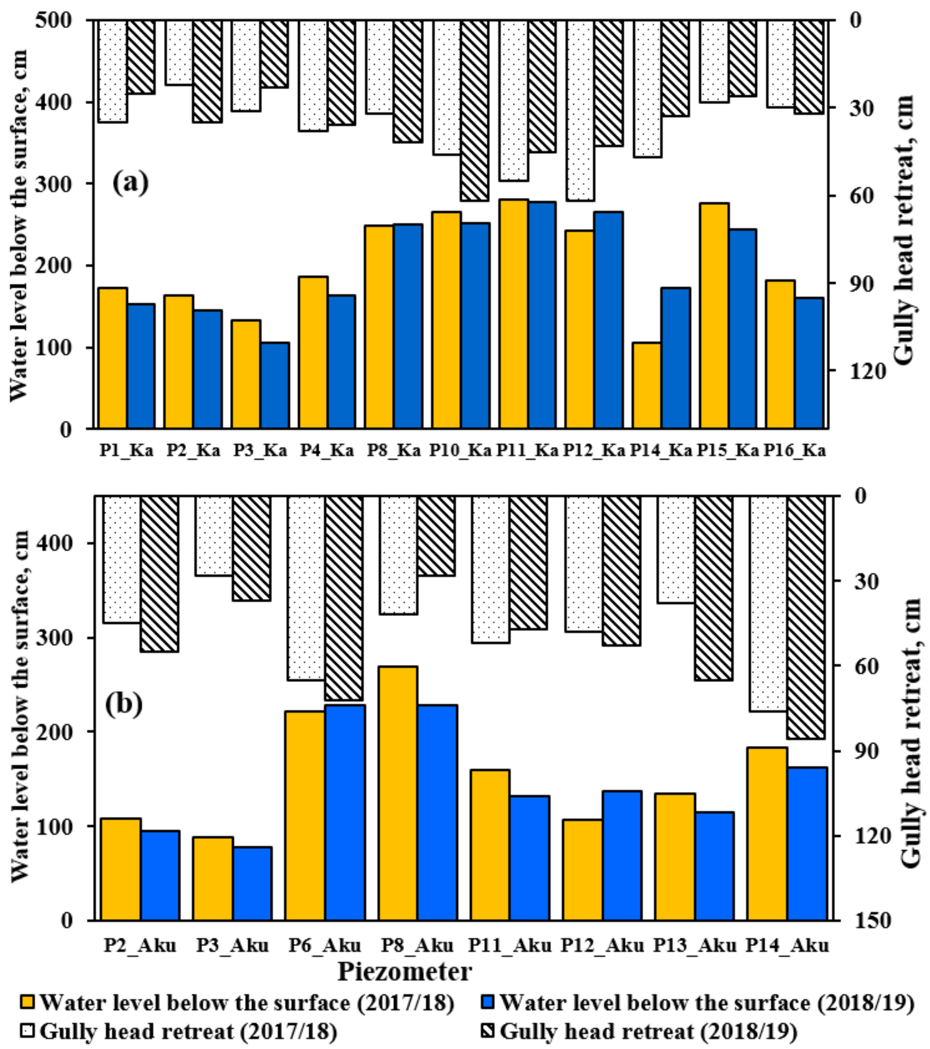

Figure 4. 8 Mean annual subsurface water level and gully headcut retreat for selected gullies; Kasiry (a) and Akusity (b).

4.4.1.4 Sediment yield and gully headcut retreat relationships

The relationship between the linear retreat of the two gully heads (GH8_Ka and GH10_Ka) and sediment yield in 2017 and 2018 was measured (Fig. 4.9). The relationship indicates both gully head retreat and the sediment amount measured in rainy season. The higher amount of sediment yield and gully head retreat mainly occurred at the beginning of the main rainy season (Fig. 4.9). In both years, the trend is similar for gully headcut retreat at both gully heads and sediment yield. Figure 4.9 indicated that the main controlling factor for higher gully sediment yield and headcut retreat is not linked with high subsurface water level that occurred late rainy seasons (2017 and 2018). Both higher gully headcut and sediment yield observed before the subsurface water is approaching to gully head and bank.

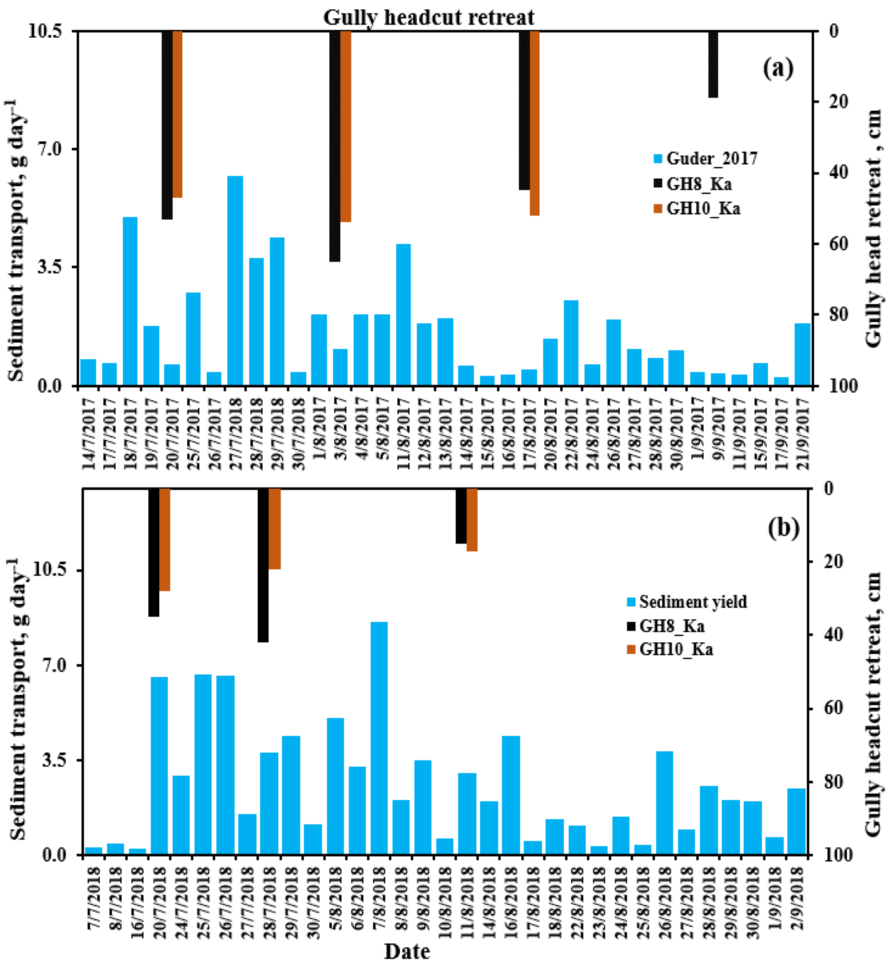

Figure 4. 9 Sediment yield and gully headcut retreat relationship on specific gully head (a) 2017 and (b) 2018.

4.4.2 Factors influencing gully head retreat

4.4.2.1 Effect of rainfall on subsurface water level depth

The recorded precipitation during the 2017 rainy season (136 days of rainfall) is1722 mm and in 2018 rainy season (112 days of rainfall) it is 2017 mm. Figure 4.10 shows the water level rose above the gully bottom for 19 gullies during the rainy season, which indicates mostly saturated gully head and bank soils. The water level decreased between morning and evening readings on average by 0.4±3.0 cm. The greatest water level fluctuations were observed at P4_Ka in 2017 and P13_Aku in 2018 (Fig. 4.8). The average PET is 4.04±0.38 mm day^{-1} in 2017 and 4.23±0.37 mm day^{-1} in 2018. Since the study area is humid and receives high rainfalls, potential evapotranspiration is higher and similar magnitude during the study seasons.

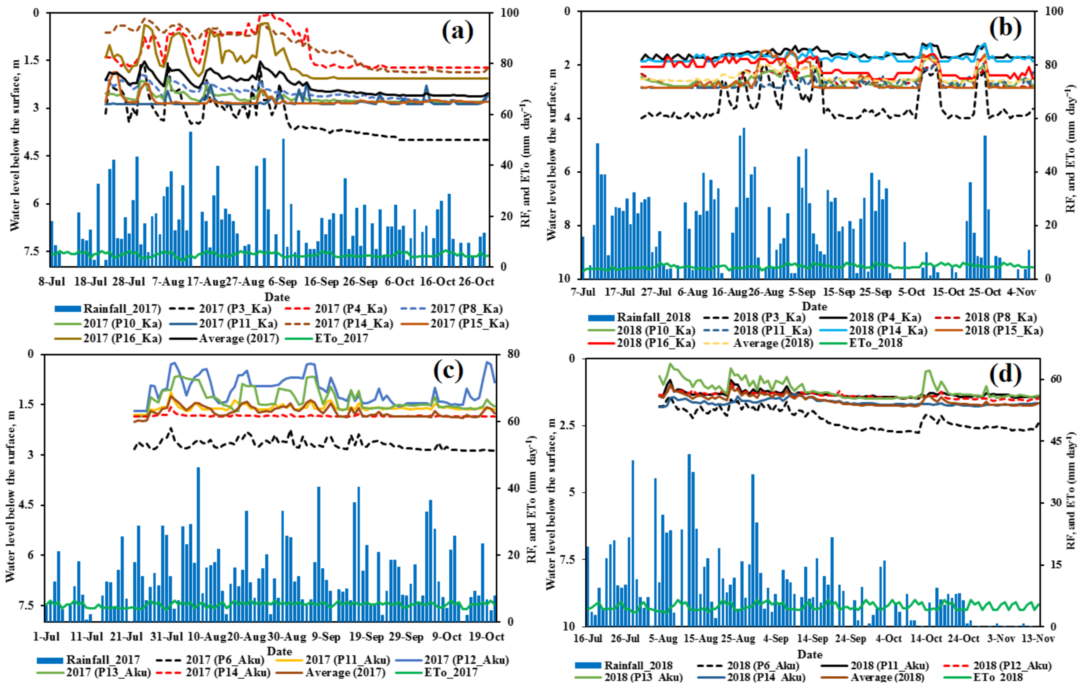

Figure 4. 10 Subsurface water level for selected piezometers in and around the active gully section. Precipitation and PET during the period is also shown: (a and b) Kasiry and (c and d) Akusity.

The linear headcut retreat showed a good relationship with subsurface water level (Table 4.6). In fact, gully headcut and bank collapse was severe in locations where the subsurface water level saturated almost entirely the exposed profiles of gully heads and banks (Fig. 4.10). The subsurface water level close to the ground surface causes a decrease in shear strength and an increase of the gully bank material unit weight which, combined with the undermining of the headcut and banks by tumbling and bottom flow and the suction process during the receding gully flow (especially where soil piping density is high), result in a marked unbalance among the bank stability forces, thus facilitating the bank collapse.

Table 4. 6 Power-type regression equation of the longitudinal headcut retreat, L, with the controlling factors, X. The goodness of the fit is represented by the coefficient of determination, R2.

Controlling factors (X)	$L = aX^b$		
	a	b	R^2
Subsurface water level	0.14	0.11	0.61
Gully headcut depth	0.25	-0.08	0.02
Runoff contributing area	0.23	0.03	0.13

The subsurface water level fluctuations were found to be wider in the piezometers located at higher topographic elevations in both watersheds (Fig. 4.11). Piezometers in the lower elevated sites receive a continuous water supply from upper catchment and, therefore, the water level variation is minimum.

In general, the piezometers with lower water level are found where a large proportion of water drainage occurs through piping flow.

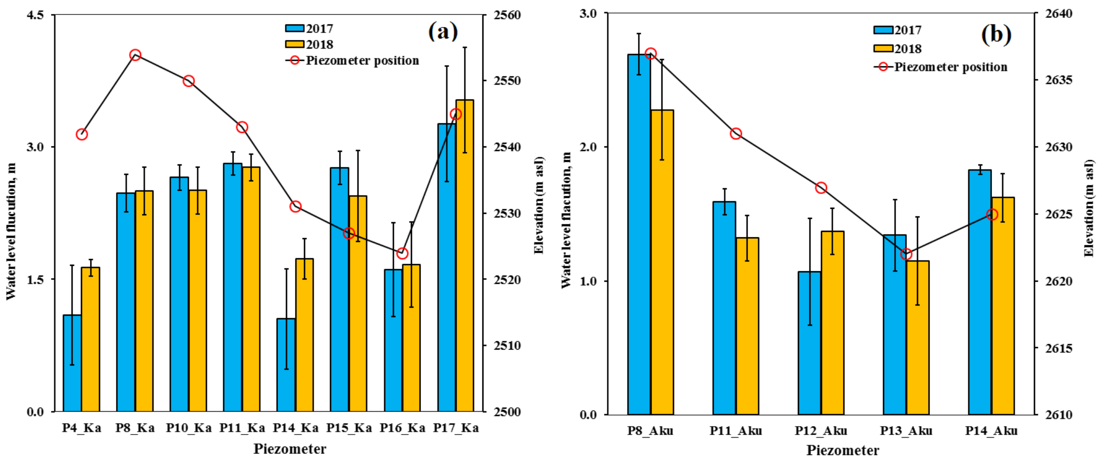

Figure 4. 11 Subsurface water level fluctuation for selected piezometers around the active gully heads for 2017 and 2018 in Kasiry (a) and Akusity (b).

4.4.2.2 Electrical conductivity of surface runoff and piping flow

Figure 4.12 presents the electrical conductivity (EC) of surface runoff (measured during rainfall) and piping flow water samples. The result indicates that the EC of piping water is constantly higher than in surface runoff. In fact, the maximum value (0.09 mS cm^{-1}) of EC in surface runoff flow is less than the minimum value (0.10 mS cm^{-1}) for piping flow.

The average EC values of surface runoff and piping flow were 0.06±0.02 and 0.13±0.02 mS cm^{-1}, respectively. The maximum and minimum values were 0.09 and 0.03 mS cm^{-1} and 0.16 and 0.10 mS cm^{-1} in surface runoff and piping flow, respectively.

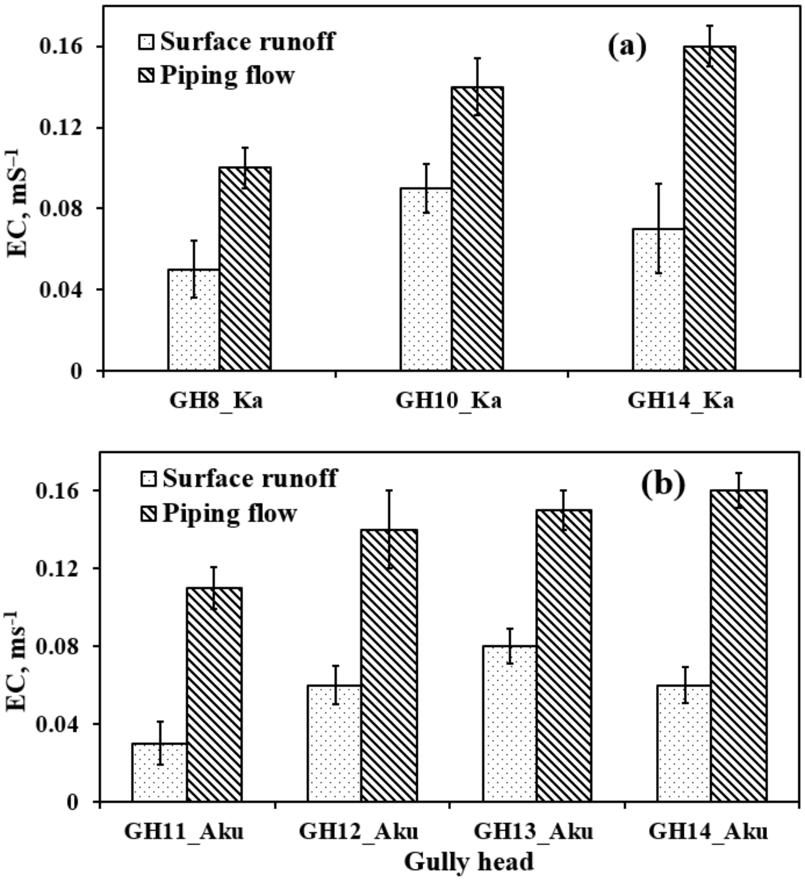

Figure 4. 12 EC of piping flow and surface runoff in Kasiry (a) and Akusity (b).

4.5 Discussion

4.5.1 Headcut retreat rate and sediment loss

The headcut retreat over the 2-year monitoring period in the rainy season for the 16 headcut is shown in Table 4.5. The gully head retreat during the 2017 and 2018 rainy season varied from 0.25 to 1.93 m, with mean (± standard deviation) value of 1.07±0.55 m (Table 4.5). The gully headcut retreat rate within the ranges obtained by Vanmaercke et al. (2016) (0.01–135.2 m yr^{-1}), Oostwoud Wijdenes and Bryan (2001) (0.8–15 m yr^{-1}), and (Wu and Cheng, 2005) (0.16–2.02 m yr^{-1}). The rates reported in this study are approximately similar to that of the semi-arid Ethiopian highlands with increases in length of 0.34 m yr^{-1} and in surface area of 1.70 m^2 yr^{-1} (Frankl et al., 2012). Both short-term and medium-term gully head retreat rates in the paired watersheds are minimum as compare to other similar works in the sub-humid Ethiopian highlands like Addisie et al. (2017) and Tebebu et al. (2010). Table 4.4 indicates that the gully contribution for the total sediment loss (between 8.26 and 13.34 t ha^{-1} yr^{-1}) is minimal. The watershed scale seasonal sediment yields in the study site during rainy season are between 7.6 and 71.2 t ha^{-1} yr^{-1} (Ebabu et al., 2018).

WDR varies between 1.48 and 6.56 m, with mean value of 2.52±1.24 m, indicating that gullies are comparatively wider and relatively minimum depth. This result indicates that gullies bank collapse dominates for gully expansion. Gully bottom and top width can be influenced by external factors like physical soil property (Table 4.1), soil piping (Fig. 4.6a), and rainfall intensity, whereas gully depth is governed by the hardness/compaction of soil and rock layers and subsurface flow (Addisie et al., 2017; Yibeltal et al., 2019b). The headcut retreat of each gully varied (Table 4.3 and 4.5). This variation should, therefore, be explained by other factors, including subsurface water level, soil physical properties (texture, bulk density, and porosity), gully head height, and drainage area. In general, our results indicate that the gully headcut retreat rate varies with gully head, and thus is crucial to understanding the driver(s) of gully headcut advancement and determining appropriate mitigation measures.

4.5.2 Factors influencing gully headcut retreat

4.5.2.1 Rainfall and subsurface water level

The field measurement during two rainy seasons (2017 and 2018) showed that daily rainfall has a marked influence on subsurface water level at gully heads (Fig. 4.8). The elevated water level appears to facilitate the slumping of both the gully headcut and walls (Fig. 4.3c). Saturation of the gully banks is principally responsible for their destabilization. In the fairly good relationship between gully head retreat and daily rainfall an important role is played also by the bank saturation, in addition to well know factors such as soil properties, drainage area size, etc. (see (Castillo and Gómez, 2016), for a comprehensive review on this topic) is likely caused by daily rainfall and saturation of the soil surrounding the gully. The large differences observed in the rate of gully head retreat among the study watersheds can be attributed to differences in daily rainfall amounts and in land use type (Yibeltal et al., 2019a). Thus rainfall plays a major role in soil erosion and gully development (Valentin et al., 2005) not only for runoff generation, but also for affecting changes in the subsurface water level. Since the study area is subjected to a monsoon-type climate with high rainfall during the summer season, the effect of evaporation on subsurface water level is negligible (Berihun et al., 2019b).

This study showed that gully head slumping was facilitated by saturation of gully headcut top soil. This result is in agreement with the findings of Tebebu et al. (2010) and Zegeye et al. (2016), who showed that in sub-humid tropical areas, a rise in the subsurface water level above gully bottoms due to high rainfall is a dominant cause of gully expansion. Gullies are characterized by bank widening due to the presence of cracks and a high water level (Tebebu et al., 2010). Our field data indicated that a high subsurface water level was the main cause of gully expansion, especially in flatter, lower elevated area, where the subsurface water level fluctuations are modest, and confirmed the findings of Kirkby and Chorley (1967) and the observations of Zegeye et al. (2016) and Addisie et al. (2017) and that active gully networks are predominantly found in the saturated flat areas (Addisie et al., 2017; Zegeye et al., 2016). In this study area, soil becomes saturated around the middle of the rain season and then remain saturated until the end of the rain season (Okoyeh et al., 2014). In the valley bottom, ground water tables rising to the surface proved to aggravate slumping of gully heads and banks by increasing pore water pressure that decreases soil strength (Tebebu et al., 2010). The presence of the many, though temporary, springs during the rainy season in the gentle slope in this study site is indication of the high permeability of the underlying rocks (John, 2016). In the study watershed, low permeability colluvial deposits can affect the hydrology upslope, forcing subsurface flow to the surface resulting in saturated source areas, in a downslope increase of overland flow and in for piping flow (Jiang et al., 2018; Nash and Dale, 1984).

In addition, Fox and Wilson (2010) demonstrated the role of subsurface flow on gully formation using laboratory experiments. The seepage forces caused by the hydraulic gradient in the gully walls produce piping and tunneling that undermine the gully walls and activate their retreat (Fox et al., 2007). Additional factors, such as the gully headcut height and the size of the runoff contributing area, which were considered by several authors (see Castillo and Gómez (2016), for a complete review on this topic) as important factors in gully expansion proved to be though poorly related with bank collapse (Table 4.6).

Figure 4.9 indicated that the main controlling factor for higher gully sediment yield and headcut retreat is not linked with high subsurface water level that occurred late rainy seasons. Both higher gully headcut and sediment yield observed before the subsurface water is approaching to gully head and bank. In many gullies the subsurface water level was near the ground surface (Fig. 4.6) but, this has less impact on gully bank collapse and headcut retreat was limited. This indicates that even under high subsurface water level conditions, vegetation with dense root systems can reduce headcut retreat (De Baets et al., 2006; De Baets et al., 2008; Yibeltal et al., 2019b).

Electrical conductivity of piping flow at gully bank and bed seem to suggest that the piping flow sources are not directly related with immediate surface runoff due to rainfall event. However, the prolonged weathering processes within the soil cavities during the dry season can provide a sufficient amount of salts to account for the higher EC of piping flow. This process is enhanced by the fact that pipe water travel long distance within the soil, as compare to surface runoff. Though runoff flows in contact with the soil, the area covered by vegetation reduces the contact of overland flow with the bare soil. Moreover, the occurrence of high levels of organic matter in the top soil (Table 4.1) contributes to the formation of soil particle aggregates and thus reduces the dissolution of salt into the runoff. This result may help to develop alternative gully bank collapse management strategies due to tunneling erosion. When the rainy season starts after the long dry season, gullies can easily develop on a disturbed surface.

The study gullies were stable during the dry season because the soil profile is saturated and collapsed at the beginning of rainy season and surface runoff was zero or minimal. Planting suitable vegetation on regressing gully slopes can decrease the risk of bank failure by reducing pore-water pressures and reinforcing the soil. A management practice that is relatively low cost and easily implemented in the Ethiopian highlands would be to plant eucalyptus trees on locations where the original forest was removed, which would increase evapotranspiration and lower the water level (Lane et al., 2004). Finally, any management practices capable to decrease the subsurface water level would remarkably reduce the risk of slumping of gully heads and banks.

Physical gully management structures e.g. stone and wood check dams and other SWC like trench measures cannot be effective to control gully initiation and development in the high rainfall Ethiopian Highlands, where through flow rises subsurface water level in the gentle slopes that promote gully head and bank collapse and, hence, expansion (Tebebu et al., 2010). Trenches promote infiltration and are effective on the hillsides where rainfall water can infiltrate (Dagnew et al., 2015; Ebabu et al., 2019; Sultan et al., 2018a), but on the gentle slope, that become saturated with and high rainfall amount and the continuous water supply from upslope, infiltration is limited and conservation practices may become conduits conveying excess rainfall. This causes the initiation of gullies in the saturated gentle slopes (Dagnew et al., 2015) and triggers shallow landslides (Yibeltal et al., 2019a). Though trenches are usually recommended mainly in arid and semi-arid regions for the purpose of soil and moisture storage, these structures are common also in the study area site. A trench is a short ditch dug along the contour (i.e. across the slope) to trap runoff water in dry and moist deficit areas and particularly useful to help rehabilitate degraded lands.

Installation of upland SWC practices that reduce runoff (and increase infiltration) are expected to decrease gully formation (Wilson et al., 2008) but, as shown in Fig. 4.3a of this study, the increasing infiltration might increase landslide and caused the initiation of gullies in several occasions in the saturated bottomlands. Infiltration furrows were effective on the hillsides where rain water could infiltrate, but on the flat bottom lands that become saturated with the progress of the monsoon rain, infiltration was restricted and conservation practices became conduits for carrying excess rainfall. More importantly, this can be the main causes of landslide on gentle slope in the study site (Yibeltal et al., 2019a).

Nevertheless, factors such as land management practices, low ground cover which affect soil crusting, and high intensity storms may also have a strong effect on gullying (Patton and Schumm, 1975; Vandekerckhove et al., 2000). Moreover, Gutiérrez et al. (2009) report that land uses that increase vegetation cover can increase gully development thresholds, whereas reduced vegetation cover (through increases in cultivated areas, conversion of forests to pasture, and overgrazing) tends to reduce the thresholds and increase the risk of gully erosion. The results indicate that land use type has some impact on gully development among the three sites.

4.6 Conclusion

Gully erosion is the most damaging erosional process in the sub-humid northwestern Ethiopian highlands. So far, limited field study has been carried out to understand the influence of subsurface flow processes in the development of gully erosion in the high rainfall areas. This study was aimed to better understand gully erosion processes and factors in the initiation of gullies in the Upper Blue Nile basin (UBNB), Ethiopia.

The gully head retreat during the 2017 and 2018 rainy season varied from 0.25 to 1.93 m, with mean (± standard deviation) value of 1.07±0.55 m. The gully cross-sectional area varies from 3.77 to 14.72 m^2, with an average of 8.50± 4.41 m^2. The gully headcut volumetric retreat (V_e) values varied from 2.67 to 30.18 m^3, with a mean value of 8.58±7.06 m^3. The soil loss of the individual gullies during 2017 and 2018 ranged from 3.45 to 38.94 t yr^{-1}, with the average soil loss of 11.06±9.11 t yr^{-1}. The water level increased during the rainy season, which decreased the strength and the erosion-resistance of the soil, thereby enhancing gully erosion. The retreat of most of the gullies was affected by gully bank collapse causing widening rather than gully head retreat. The elevated water level appears less to facilitate the slumping of gully walls. In addition, a poor weak relationship between gully headcut retreat and the height of the gully head and the size of the drainage area was found, though in the literature these are commonly regarded as important factors in gully expansion.

In conclusion, best mitigation strategies that increasing the gully bank soil profile strength and protecting the gully heads can play a key role in reducing gully expansion and soil loss will reduce the amount of gully-related sediment loss. In terms of gully erosion control mechanisms, studies need to be designed to evaluate the effects of controlling subsurface water movement, for example by subsurface drainage, on the stability of gully bank.

Chapter 5: General conclusions and recommendations

5.1 General conclusions

This study showed that total gully length and density varied temporally both within watersheds and among the three agro-ecologies in the Upper Blue Nile basin, Ethiopia. In the midland and lowland agro-ecologies, gully density was higher in cultivated lands, whereas in the highland agro-ecology, it was higher in grazing lands. In addition, gully density increased with increase in slope gradients up to 15° and then decreased as the gradients became greater than 15°. Gullies developed mainly in cultivated lands and grazing lands with gentle slope gradients in the three agro-ecologies. Moreover, although gully density showed increasing trends in the three paired watersheds during the study period, in recent years, watersheds with soil and water conservation measures had lower gully densities than those without such measures. This variation suggests that the rate of gully development is greatly influenced by factors including rainfall, land use distribution and change, slope gradient, and the period of the study; hence, site-specific assessment is necessary to precisely determine spatio-temporal changes in gully development.

This study also shows significant and positive correlations between gully morphological parameters (V, L, and A_g). The significant relationship between V and L, the weak relationships between V and TW, and between V and BW confirm that gullying is mainly a longitudinal incision process. This study demonstrated that gully morphological parameters are highly variable across the three agro-ecologies and are mainly related to varying local factors (e.g. land use). This relation can be used whenever it is necessary to make an overview on gullying at regional level and to identify areas more or less prone to gully erosion simply by comparison of aerial photos or satellite images taken at different time interval in a relatively quick and cheap way. This method may find its best application also in remote and difficult to access areas. These results can be used to monitor changes in gully volume and related parameters affected by remedial measures implemented to control and/or reduce gully expansion. This study also demonstrated that the threshold of gully initiation in the highland (Guder site) is among the highest observed worldwide. This is probably due to the high grass cover that increases the soils' resistance to concentrated flow erosion and allows for infiltration. Thus reducing the runoff volume and shear stress and this cause potential subsurficial runoff. The gully initiation threshold is moderate in Aba Gerima (midland) and low in Dibatie (lowland). Based on these topographic thresholds, the dominant gully development process on cultivated lands of the Dibatie and Aba Gerima watersheds is overland flow, whereas subsurface processes affect the Guder watershed. Soil loss is more severe from lowland than from midland and highland gullies. Thus, unexpected result can be account for the highly erodible nature of Vertisols that occur at large in Dibatie. The dominant local factor affecting gully cross-sectional morphology in the three agro-ecologies was land use.

This study was aimed to better understand gully erosion processes and factors in the initiation of gullies in the Upper Blue Nile basin (UBNB), Ethiopia. This study found that the gully head retreat during the 2017 and 2018 rainy season varied from 0.25 to 1.93 m, with mean (± standard deviation) value of 1.07±0.55 m. The soil loss of the individual gullies during 2017 and 2018 ranged from 3.45 to 38.94 t yr^{-1}, with the average soil loss of 11.06±9.11 t yr^{-1}. The water level increased during the rainy season, which decreased the strength and the erosion-resistance of the soil, thereby enhancing gully bank collapse. Gullies was affected by gully bank collapse causing widening rather than gully head retreat. The elevated water level appears less to facilitate the slumping of gully walls. By contrast only a poor weak relationship between gully head retreat and the height of the gully head and the size of the drainage area was found, though in the literature these are commonly regarded as important factors in gully expansion.

5.2 Recommendations for future studies

This study revealed that gully distribution and density varies within land use type, topography, agro-ecology, and thus results suggest that careful site-specific identification of factors controlling gully initiation and expansion is crucial for the development of appropriate gully erosion management strategies. This study also found that cultivated lands and grazing lands (gentle slope area) are greatly prone for gully erosion. Hence, careful approach for gully controlling factors analysis should be crucial to develop appropriate gully management strategies within different agro-ecologies.

This study further applied that aerial photographs and high resolution remote sensing images are very important for understanding physical processes in the past and the present. This study provides useful information on the regional importance of gully erosion and draws attention to the need for conservation measures, especially in gully prone areas. Further investigation is therefore necessary to examine the impacts of biophysical factors on gully morphological characteristics and topographic thresholds.

This study suggests that biophysical factors can strongly impact gully morphological characteristics and topographic thresholds in different environmental settings, and thus site-specific investigations are crucial to understanding the major local drivers of gully morphology variability across agro-ecology. In addition, runoff contributing area and slope gradient relation effect analysis also indicated that the threshold for gully development were varied across agro-ecology. This result also need further investigation to delineate runoff contributing area precisely using high resolution images. This will be crucial to accurately estimate the threshold for gully development for different location and land uses, which will be vital to support the planning of appropriate measures to control gully erosion.

This study also revealed that the impact of subsurface water level fluctuation has weak relationship with gully headcut retreat rate. Further study is important to investigate the separate effect of surface runoff and subsurface water level. This will help to understand gully headcut retreat and bank collapse in high rainfall region and proposing best mitigation strategies which focus on increasing the gully bank soil profile strength and protecting the gully heads.

In recent years, in the highland agro-ecology the *Acacia decurrens* plantation covers larger proportion of the watershed area whereas gully density also increases in recent years. This result indicated that the *Acacia decurrens* plantation has less effect on gully development mitigation approach. Also this phenomenon need further investigation for the future. Gully erosion is very important problem in the study three agro-ecologies in all land use types especially cultivated and grazing lands. Further investigation is therefore necessary to develop gully management strategies according to agro-ecologies in the Upper Blue Nile basin, Ethiopia.

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Summary

Gully erosion is a major cause of land degradation in many regions of the world, including Ethiopia, and accounts for a larger portion (10–95%) of the total soil loss at the catchment scales. The Upper Blue Nile basin is highly affected by soil erosion and soil loss from the basin is estimated at 473 Mt yr^{-1}, of which 10–15% is due to gully erosion.

Despite the significant contributions of gully erosion to the overall sediment yield and land degradation in different regions, research efforts for gully erosion are very limited in Ethiopia particularly in the drought prone regions like the Upper Blue Nile basin. Therefore, this study was aimed to investigate the spatio-temporal dynamics, characterization, causes and controlling factors of gully erosion in the Upper Blue Nile basin. The study was conducted in three contrasting agro-ecologies of the basin [i.e., Dibatie (lowland), Aba Gerima (midland), and Guder (highland) watersheds] with three specific objectives: (1) to analyze and quantify the spatio-temporal dynamics of gully lengths and densities; (2) to quantify gully morphological characteristics and gully headcut retreat rates; and (3) to analyze the role of subsurface water on gully headcut and bank retreat. These objectives cover chapters 2–4 of this thesis which includes five chapters summarized as follows:

Chapter 1 explains the introductory section of the study. It presents the study background, problem statement, objectives, and description of the study area based on the existing literatures, field data, and facts. Moreover, it provides summarized descriptions of gully erosion and land degradation, and causing factors and effects of gully erosion on the environment worldwide and in Ethiopia. It then describes the aims of this study and the overall structure of the thesis.

Chapter 2 analyses the spatio-temporal dynamics of gully erosion in three agro-ecologies of the Upper Blue Nile basin of Ethiopia over the last six decades using aerial photographs and satellite images. The aerial photographs were scanned and orthorectified using ENVI 4.3 image analysis software, and gullies were mapped by visual image interpretation in the ArcGIS environment. Rates of increase in gully length in Guder (36.9 m yr^{-1}) and Aba Gerima (33.6 m yr^{-1}) were almost double the rate in Dibatie (17.8 m yr^{-1}) from 1957 to 2016 or 2017, and over the same period, gully density similarly increased by 5.9, 5.4, and 3.7 m ha^{-1} in Guder, Aba Gerima, and Dibatie, respectively. The higher rates in Guder and Aba Gerima reflect the long history of cultivation and human settlement in those sites, whereas agricultural activity became widespread in Dibatie only after implementation of the national resettlement program in the 1980s. Our results indicated that gully erosion was generally higher in the highland (Guder) than in the midland (Aba Gerima) and lowland (Dibatie) agro-ecologies. This result can be attributed to variation in biophysical factors (rainfall characteristics, land use distribution and change, and slope gradient). In addition, gully distribution was linked to land use and landscape position; gully density was higher in cultivated areas and on gentle slope gradients. The results of this study suggest that careful and site-specific identification of factors controlling gully initiation and development is crucial to design appropriate gully management strategies.

Chapter 3 investigates the morphological characteristics and topographic thresholds of gullies, and estimated the gully headcut retreat rates in three agro-ecologies of the Upper Blue Nile basin of Ethiopia. Gully morphological characteristics were analyzed using data measured in the field, whereas the topographic thresholds were estimated using slope and upslope drainage area. Average annual linear (R_l) and volumetric (V_e) headcut retreat rates were estimated by visual interpretation of very high resolution satellite images in a GIS environment. A significant power relationship, fitted between gully volume (V) and length (L) for the three sites, is $V=8.097\ L^{1.032}$ ($R^2=0.902$, n=94). The average annual R_l and V_e were estimated at 0.86 m yr^{-1} and 6.77 $m^3\ yr^{-1}$ in Guder, 2.09 m yr^{-1} and 19.58 $m^3\ yr^{-1}$ in Aba Gerima, and 3.42 m yr^{-1} and 42.16 $m^3\ yr^{-1}$ in Dibatie. The higher gully headcut retreat rate in Dibatie is mainly related to the highly erodible nature of Vertisols. The coefficients of the slope (S)-drainage area (A) relationship $S=aA^{-b}$ were a=0.219 and b=−0.139 in Guder, a=0.133 and b=−0.234 in Aba Gerima, and a=0.113 and b=−0.216 in Dibatie, indicating that topographic thresholds for gully initiation varied among the agro-ecologies. The results of this study can be used to estimate gully erosion rates and identify areas for gully initiation, thereby supporting the planning of appropriate gully control measures in the study sites and other areas with similar environmental settings.

Chapter 4 aims to better understand the impact of subsurface water processes on gully headcut retreat in the tropical humid highlands (Guder) of Ethiopia. The gully headcut retreat during the 2017 and 2018 rainy season varied from 0.25 to 1.93 m, with mean value of 1.07±0.55 m. The gully cross-sectional area varies from 3.77 to 14.72 m^2, with an average of 8.50±4.41 m^2. The gully headcut volumetric retreat (V_e) values varied from 2.67 to 30.18 m^3, with a mean value of 8.58±7.06 m^3. The soil loss of the 16 individual gullies during 2017 and 2018 ranged from 3.45 to 38.94 t yr^{-1}, with the average soil loss of 11.06±9.11 t yr^{-1}. The water level increased during the rainy season, by the time the strength and the erosion-resistance of the soil decreased, thereby enhancing gully bank collapse. The elevated water level after mid-summer appears less to facilitate the slumping of gully walls. In addition, a weak relationship between gully headcut retreat and the height of the gully head. In conclusion, further investigation is important on controlling factors on gully headcut and bank retreat and develop appropriate gully control measures.

Chapter 5 provides the general synthesis of the whole thesis based on the key findings from Chapters 2–4. The findings of Chapter 2 indicate that gully lengths and densities clearly varied over space and time. Thus, careful site-specific identification of factors controlling gully initiation and development is crucial to develop appropriate management strategies. Chapter 3 demonstrates gully morphological characteristics and gully headcut retreat rates in three different agro-ecologies, and Chapter 4 investigates subsurface water impact on gully headcut and bank retreat in the tropical humid highland of Ethiopia. The results provide useful information to estimate gully headcut retreat rates, identify areas for gully initiation, and to support the planning of appropriate gully control measures in the Upper Blue Nile basin of Ethiopia and other areas with similar environmental settings.

学位論文概要

ガリー侵食は、エチオピアを含む世界の多くの地域の土地劣化の主な原因であり、小流域スケールでの総土壌損失の大部分（10〜95%）を占めている。青ナイル川上流域は土壌侵食の影響を強く受けており、流域からの土壌損失は473 Mt yr^{-1}と推定され、その10〜15%はガリー侵食によるものである。

ガリー侵食はさまざまな地域の土砂生産と土地の劣化に大きく寄与しているが、エチオピア、特に青ナイル川上流域のような干ばつが起こりやすい地域でのガリー侵食の既往研究は非常に限られている。したがって、本研究は、青ナイル川上流域におけるガリー侵食の時空間分布、特性、原因、および要因を解析することを目的とする。本研究は、三つの対照的な農業生態系（Dibatie（低地、Aba Gerima（中間地、Guder（高地）における小流域）で、具体的には以下の3点について実施されまた。（1）ガリーの長さと密度の動態に関する時空間的分析と定量化。（2）ガリーの形態的特徴とガリーヘッドカット（ガリー頭部）の後退速度の定量化。（3）ガリーヘッドカット後退における地下水の役割の分析。上記3点は、本論文の2〜4章に対応している。

本論文第1章では、本研究の背景と目的について説明します。既往文献、フィールドデータ、および事実に基づいて、研究の背景、問題の説明、目的、および研究領域を説明する。さらに、ガリー侵食と土地劣化の概要およびガリー侵食が世界およびエチオピアの環境に及ぼす要因と影響を説明する。次に、この研究の目的と論文の全体構造について説明する。

第2章では、航空写真と衛星画像を使用して、過去60年にわたるエチオピアの青ナイル川上流域の3つの農業生態系におけるガリー侵食の時空間動態を解析する。航空写真は、ENVI 4.3画像解析ソフトウェアを使用してスキャンおよびオルソ補正され、ガリーはArcGIS環境での視覚画像解釈によってマッピングされた。Guder（36.9 m yr^{-1}）およびAba Gerima（33.6 m yr^{-1}）のガリー長の増加速度は、1957年から2016年または2017年まで、Dibatie（17.8 m yr^{-1}）のほぼ2倍の速度であった。この期間、ガリー密度は、Guder、Aba Gerima、Dibatieで、それぞ

れ5.9、5.4、3.7 m ha^{-1}増加した。 GuderとAba Gerimaの高い増加速度は、それらのサイトでの長い耕作と人間の定住の歴史を反映しているが、農業活動は1980年代に国の再定住プログラムが実施されて初めてDibatieで広まった。本研究結果は、ガリー侵食は一般に中間地（Aba Gerima）および低地（Dibatie）の農業生態系よりも高地（Guder）で高いことを示した。この結果は、生物物理学的要因（降雨特性、土地利用の分布と変化、および斜面勾配）の変動に起因する可能性がある。さらに、ガリーの分布は土地利用と景観の位置と関連していた。ガリー密度は、耕作地と緩やかな勾配傾斜地でより高かった。この研究の結果は、適切なガリー管理戦略を設計するために、ガリーの開始と発達を制御する因子の慎重かつサイト固有の識別が重要であることを示唆している。

第3章では、ガリーの形態的特徴と地形的閾値を解析し、エチオピアの青ナイル川上流域の3つの農業生態系におけるガリーヘッドカット後退速度を推定した。地形の閾値は斜面と上り斜面の排水面積を使用して推定された。ガリーの形態的特性は、フィールドで測定されたデータを使用して分析された。ヘッドカットの後退速度に関する平均年間長さ変化（R_l）および体積変化（Ve）を、GIS環境での超高解像度衛星画像の目視判読によって推定した。 3つのサイトのガリー量（V）と長さ（L）の間で得られた有意な相関関係は、$V = 8.097\ L^{1.032}$（R^2 = 0.902、n = 94）である。平均年間R_1およびVeは、Guderで0.86 m yr^{-1}および6.77 m^3 yr^{-1}、Aba Gerimaで2.09 m yr^{-1}および19.58 m3 yr^{-1}、Dibatieで3.42 m yr^{-1}および42.16 m^3 yr^{-1}と推定された。Dibatieのガリーヘッドカット後退速度が高いのは、主にVertisolの侵食性が高いためである。勾配（S）−排水面積（A）の関係$S = aA^{-b}$の係数は、Guderでa = 0.219とb = -0.139、Aba Gerimaでa = 0.133とb = -0.234、Dibatieでa = 0.113とb= - 0.216であった。これは、ガリー開始の地形的閾値が農業生態学間で異なることを示している。この研究の結果を使用して、ガリー侵食速度を推定し、ガリー開始領域を特定することができる。これにより、本研究対象地や同様の環境条件を持つ他の地域での適切なガリー制御対策の計画を支援することができる。

第4章は、エチオピアの半湿潤な高地（Guder）におけるガリーヘッドカット後退に対する地下水プロセスの影響を理解することを目的としている。 2017年と2018年の雨季のガリーヘッドカット後退は、0.25から1.93mまで変化し、平均値は1.07±0.55 mでした。溝の断面積は3.77から14.72 m^2で、平均は8.50±4.41 m^2である。ガリーヘッドカットの体積後退（Ve）値は2.67から30.18 m^3まで変化し、平均値は8.58±7.06 m^3であった。2017年および2018年の16の個々のガリーの土壌損失は、3.45から38.94 t yr^{-1}の範囲で、平均土壌損失は11.06±9.11 t yr^{-1}であった。雨季には水位が上昇し、土壌の強度と耐侵食性が低下するまでに、ガリーバンクの崩壊が促進された。真夏以降の水位の上昇は、ガリー壁の崩壊を促進しにくいようだ。適切なガリー対策を開発するためには、ガリヘッドカット後退の制御要因に関するさらなる調査・分析が求められる。

第5章では、第2章から第4章の主要な研究結果に基づいて、論文全体の総合的な結論を示す。第2章の結果は、ガリーの長さと密度が空間と時間によって明らかに変化したことを示している。したがって、適切なガリー管理戦略を開発するには、ガリーの発生と発達を制御する要因をサイトごとに慎重に特定することが重要である。第3章では、三つの異なる農業生態系におけるガリーの形態的特徴とガリーヘッドカットの後退速度を示し、第4章では、エチオピアの熱帯湿潤高地におけるガリーヘッドカットの後退に対する地下水の影響を分析した。本研究の結果は、ガリーのヘッドカット後退速度を推定し、ガリの開始領域を特定し、エチオピア青ナイル川上流域および同様の環境条件を持つ他の地域での適切なガリー対策戦略の策定を支援するために役立つ情報を提供する。

List of Publications

1. Yibeltal, M., Tsunekawa, A., Haregeweyn, N., Adgo, E., Meshesha, D.T., Aklog, D., Masunaga, T., Tsubo, M., Billi, P., Vanmaercke, M., Ebabu, K., Dessie, M, Sultan, D., and Liyew, M. (2019). Analysis of long-term gully dynamics in different agro-ecology settings. Catena 179: 160–174 (Published, DOI: org/10.1016/j.catena.2019.04.013, this article covers **Chapter 2** in the thesis).

2. Yibeltal, M., Tsunekawa, A., Haregeweyn, N., Adgo, E., Meshesha, D.T., Masunaga, T., Tsubo, M., Billi, P., Ebabu, K., Fenta, A.A., and Berihun, M. L. (2019). Morphological characteristics and topographic thresholds of gullies in different agro-ecological environments. Geomorphology 341: 15–27 (Published, DOI: org/10.1016/j.geomorph.2019.05.012, this article covers **Chapter 3** in the thesis).