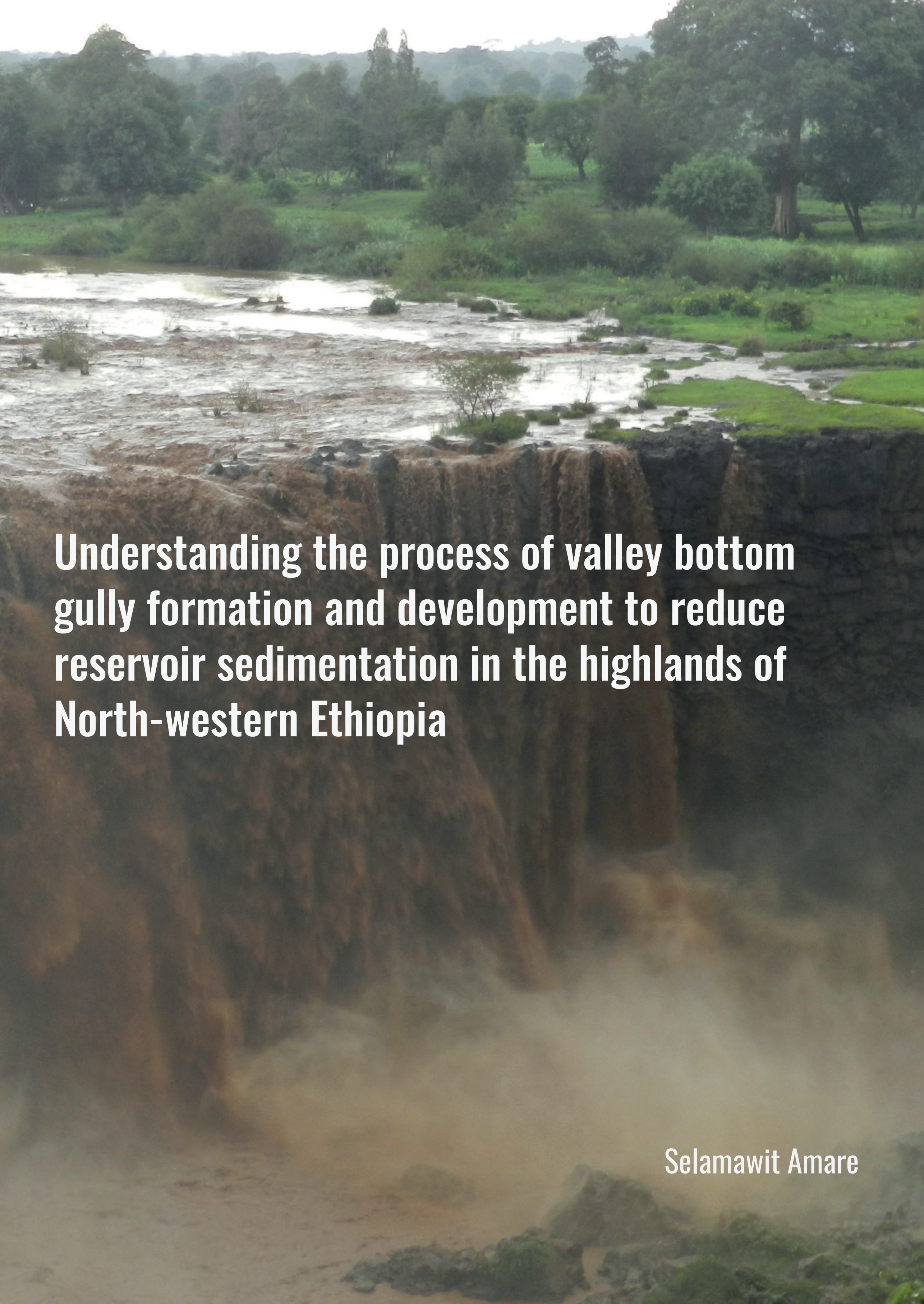

# Understanding the process of valley bottom gully formation and development to reduce reservoir sedimentation in the highlands of North-western Ethiopia

Selamawit Amare

**Propositions**

1. The planning and implementation of gully erosion reclamation measures should consider the integrated gully erosion process at local and landscape scales (this thesis).

2. The design of gully erosion reclamation measures should consider differences in soil hydrology between Nitisols and Vertisols (this thesis).

3. Latest machine learning and statistical methods are robust and cost-effective techniques for mapping areas vulnerable to gully erosion or other land degradation processes.

4. Aside from the severe economic consequences that gullies may have on everyone, they increase the workload on rural girls and women by making mobility difficult and facilitating the drying up of water sources for different use.

5. Field research in developing countries should focus on data storage and repeatability as much as the research itself.

6. International experience is essential for Ph.D. students from developing countries (especially women) to develop into independent researchers of international standards.

Proposition belonging to the thesis, entitled

Understanding the process of valley bottom gully formation and development to reduce reservoir sedimentation in the highlands of North-western Ethiopia.

Selamawit Damtew Amare
Wageningen, 03 June 2022

# Understanding the process of valley bottom gully formation and development to reduce reservoir sedimentation in the highlands of North-western Ethiopia

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This research was conducted under the auspices of the Research School for Production Ecology and Resource Conservation (PE and RC).

# Understanding the process of valley bottom gully formation and development to reduce reservoir sedimentation in the highlands of North-western Ethiopia

**Selamawit Damtew Amare**

**Thesis**
submitted in the fulfilment of the requirements for the degree of doctor
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By the authority of the Rector Magnificus
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# 1. General Introduction

## 1.1 Gully erosion in Ethiopian highland

Gully erosion is severe in Sub-Saharan Africa due to agricultural intensification, population growth, and overgrazing (Frankl et al., 2012). In Ethiopia's highlands, gully erosion is one of the most severe land degradation processes, posing a considerable threat to people and the environment. Gullies induced by unsustainable agricultural land use have been reported for over a century (Guyassa et al., 2018). Gully erosion wreaks havoc on the environment and the economy by interfering with various soil and land functions (Amsalu & de Graaff, 2007). It affects soil hydrology by rapidly lowering the groundwater table (Guzman et al., 2017; Tilahun et al., 2016), which leads to soil desiccation and crop yield reduction (Frankl et al., 2016). Gullies also dissect farmlands, making farming activities difficult, causing damage to crop and grazing plots through sediment deposition, and reducing farmland size (Frankl et al., 2013b; Moges & Holden, 2008; Solomon et al., 2013). Gullies also cause the death of people and animals, a decline in income, displacing people, biodiversity loss, and restricted human and livestock movement (Alemu & Awdenegest, 2014; Hassen & Bantider, 2020; Liuelsegad et al., 2014).

Additionally, gullies enhance landscape connectivity in terms of accelerating water and sediment fluxes by providing an effective link for the transport of runoff, sediment, and other materials from the source to the sink (Poesen et al., 2003; Vanmaercke et al., 2016), resulting in floods and increased sediment load in rivers (Dagnew et al., 2017; Nyssen et al., 2006; Valentin et al., 2005). For instance, gullies serve as a critical sediment channel for other types of erosion (e.g., sheet and rill), increasing the catchment's sediment connectivity (Poesen et al., 2003). Sediment stored in reservoirs leads to a reduction in reservoir capacity, thereby reducing water supply for human consumption, irrigation, hydropower, causing a decline in water quality, increasing the cost of removing sediment, blockage of water navigation pipes, and loss of recreational opportunities (Mekonnen et al., 2015; Wolancho, 2012). As Wolancho (2012) further elaborates, aquatic ecosystems are altered by increased deposition of sediments and adsorbed or dissolved nutrients and chemicals, causing eutrophication, which has a detrimental impact on fish and other organisms.

As gullies in Ethiopia are a significant source of sediment in reservoirs (Valentin et al., 2005), they have become a major concern for current and planned water resource development activities ranging from small-scale irrigation to large hydroelectric dams (Girmay et al., 2012; Haregeweyn et al., 2006; Tamene & Vlek, 2007). Gully erosion studies in the semi-arid region reported as large as 16 t $ha^{-1}$ $y^{-1}$ soil loss (Mukai, 2016b), whereas in the sub-humid region, a soil loss of 530 t $ha^{-1}$ $y^{-1}$ has been reported (Tebebu et al., 2010).

Furthermore, gully erosion caused a 19% annual income loss per person living in a sub-humid catchment (Ayele et al., 2015).

In Ethiopia key bottlenecks of soil erosion management, including gully erosion, are lack of data availability, unreliable data, high heterogeneity of environmental factors, and poor linkage between research and agricultural extension service (Haregeweyn et al., 2015). Haregeweyn et al. (2017) also emphasized lack of adaptable research methods and environmental heterogeneity hampers soil erosion studies in one of the biggest basins in the country, called the Abay basin.

## 1.2 State of the art

Gully erosion in the Ethiopian highlands has been linked to anthropogenic and natural processes that cause concentrated flow and elevated groundwater tables. Concentrated flow contributes to gully erosion by inducing soil detachment, removing collapsed material from the gully channel, and exposing the gully bank for further erosion. Factors that increase surface runoff include vegetation removal, conversion of cultivated land to grazing, road construction, deforestation, culverts, and traditional ditches (Engdayehu et al., 2015; Gebretsadik, 2014; Liuelsegad et al., 2014; Nyssen et al., 2008; Solomon et al., 2013). Shallower groundwater also promotes gully erosion by raising soil pore water pressure and decreasing soil cohesion (Tebebu et al., 2010). Other factors contributing to gully erosion may include soils prone to piping and tunnelling (e.g., Vertisols), intense rainfall, and poorly consolidated soil prone to detachment by water (Frankl et al., 2012; Hassen & Bantider, 2020; Nyssen et al., 2006).

In the Ethiopia sub-humid highlands, raised groundwater levels, gully head height, and drainage area and changing land-use practices such as overgrazing and deforestation have been linked to gully erosion, with groundwater being the most relevant contributor (Tebebu et al., 2010; Zegeye et al., 2016b). In contrast, gullies in the semi-arid Ethiopian highlands are strongly related to drainage areas and are less impacted by head-cut height, slope gradient, land use, and average annual precipitation (Frankl et al., 2012; Nyssen et al., 2002).

Soil and water conservation measures have been more successful in semi-arid areas than in humid ones (Haregeweyn et al., 2015). While measures such as area exclosure (livestock and humans prohibition from freely accessing a degraded land) and check dams help stabilize gullies in semi-arid regions (Frankl et al., 2013a; Nyssen et al., 2008), similar interventions in the sub-humid region have had no positive impact. The lack of effectiveness in gully restoration in the sub-humid area is due to a lack of understanding of the erosion process, resulting in the poor technical quality of soil and water conservation measures and lack of integrated approach (Engdayehu et al., 2015, 2016). Therefore, to implement gully reclamation measures successfully, it is critical to understand the soil and hydrological processes governing gully erosion and identify erosion hotspots.

### 1.3 Motivation

Runoff generation and flow patterns can have significant consequences for erosion and environmental management (Tilahun et al., 2016). According to research conducted in sub-humid Ethiopia, the upper hillslopes were primarily infiltration zones, where infiltrated water became interflow and flowed downhill to valley bottom areas to saturate the soil and produce surface runoff (Bayabil et al., 2010; Engda et al., 2011). Differences in a surface runoff between hillslope and valley bottom sites could result in distinct gully erosion controlling factors which may lead to distinct erosion magnitudes (Ryken et al., 2015). A study of gully and hillslope erosion processes in the Debre Mawi watershed found that erosion from wet valley bottom areas was more significant than erosion from drier hillslope fields (Tebebu et al., 2010; Zegeye et al., 2010). Gullies are a result of both concentrated overland flow and saturated soils. Because water accumulates at the lowest points, the valley bottom soil is mostly saturated and more prone to concentrated flow than the rest of the catchment. As gully incision and expansion is a function of the subsequent removal of collapsed material by overland flow (Zegeye et al., 2016b), concentrated flow at the valley bottom speeds up gully expansion. Furthermore, the drainage line with little soil strength in the saturated valley bottomland is vulnerable to gully formation (Monsieurs et al., 2015a; Monsieurs et al., 2015b; Tebebu et al., 2015). Despite differences in the runoff process and soil response to surface runoff, the same gully management strategy has been implemented at the hillslope and valley bottom of the catchment. For example, brushwood check dams and flood regulators appear to be more successful in controlling gully erosion on hillslopes (Poesen et al., 2003) than in the valley bottom area (Frankl et al., 2012). Gully erosion studies and implementation of rehabilitation measures worldwide, particularly in Ethiopia, are based on lumped investigations and blanket approaches. This explains why little success has been achieved when applying rehabilitation measures without understanding the underlying gully erosion process.

As a result, despite billions of investments in SWC activities in Ethiopia (Adimassu et al., 2018), sediment loads are increasing in water bodies, especially in sub-humid Ethiopian highlands (Zegeye et al., 2018). This is partly due to a considerable sediment load contribution from gullies located at the valley bottom. For example, Tebebu et al. (2010) reported 20 times more soil loss caused by valley bottom gullies than rill and inter-rill erosion at the hillslope. A similar study by Zegeye et al. (2018) also stated that gullies at the valley bottom contributed more than 90% of sediment in rivers. This illustrates that the government's implementation of hillslope SWC practices has not resulted in sediment reduction in rivers as sediments from valley bottom gullies have negated these efforts (Ayele et al., 2018). Despite the massive problems caused by valley bottom gully erosion, there is no spatial prediction (erosion hotspot mapping) of these gullies, and little research has been conducted on the dominant factors controlling gully erosion processes. Gully spatial prediction using various environmental gully controlling factors is a cost-effective mechanism for developing informed gully reclamation strategies. Moreover, in the Ethiopian highlands, creating a model or applying an existing one for gully erosion has not been published. Hence, for the effectiveness of gully management strategies, prior understanding of the valley bottom gully erosion processes is compulsory (Fox et al., 2016; Vanmaercke et al., 2016).

When zooming out, this study also contributes to one of the major concerns (i.e., sedimentation) of the new development of the Grand Ethiopian Renaissance Dam (GERD) and other water resource development activities located in the highland. GERD is the biggest dam in Africa and the 7$^{th}$ biggest in the world. Using this dam, Ethiopia plans to export electricity to neighboring countries, which is expected to be a significant source of export earnings for Ethiopia. To realize this goal and ensure the long-term usage of water in reservoirs, the processes leading to valley bottom gully erosion as one of the most significant sources of sedimentation has to be investigated.

## 1.4 Research questions and thesis outline

This research aims to understand valley bottom gully (VBG) erosion processes using field data and modeling approaches. A systematic representation of the methodological framework is presented in Figure 1.1. A literature review across different agroclimatic conditions supports the identification of parameters for further field investigation.

This research poses the following research questions:

- What factors govern valley bottom gully erosion worldwide, and what are the flaws in current rehabilitation measures?
- How do various hydrological, soil, and morphological factors influence gully head stability in Nitisol and Vertisol as the two main soil types in the Minzir catchment in Ethiopia?
- Which topographic, geological, and hydrologic factors best forecast gully location along the landscape?

- How does a gully head erosion model at a landscape scale responds to changes in groundwater, hydraulic conductivity, drainable porosity, water erodibility, and head-cut height?

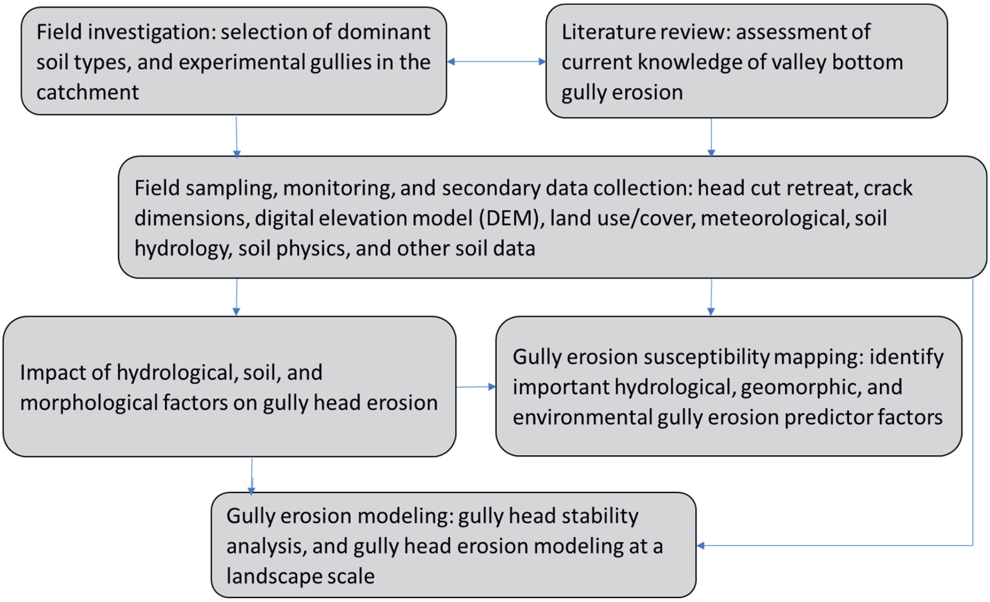


***Figure 1.1 A diagram of the research methodologies***

The following chapters answer the research questions raised here (Chapters 2 to 5). Following the general introduction section, Chapter 2 provides a review of the causes of valley bottom gullies and presents deficiencies in existing rehabilitation measures. For this, peer-reviewed articles were searched in the CAB Abstract and Scopus databases. This chapter gives a discussion on the integral impact of slope gradient, drainage area, precipitation, groundwater, surface runoff, land use, and soil on VBG formation. The chapter also gives an analysis of the role of climatic conditions (e.g., humid and arid) on the performance of VBG rehabilitation measures.

The impact of soil hydrological and morphological characteristics that lead to gully head erosion is discussed in Chapter 3. Two gullies found in the Minzir catchment valley bottomland, one located in a Nitisol and the other in a Vertisol, were studied. This study provides insight into how variations in soil type such as Nitisol and Vertisol lead to variabilities in the soil morphology and hydrology, resulting in variations in gully head retreat rates. The role of soil hydrological, morphological, and geotechnical parameters on the two gully heads' stability was analyzed using the Bank Stability and Toe Erosion Model (BSTEM).

Chapter 4 identifies the most critical gully predictor factors and develops a gully erosion susceptibility map (GESM). The GESM is developed using frequency ratio (FR) and random forest (RF) models. The FR and RF models used hydrological, geomorphic, and environmental gully erosion predictor factors to predict gullies. In addition to GESM, the RF model was used to rank predictor factors based on their importance to gully erosion in the Nitisol and Vertisol soil types. Predictor factors that provide the best gully erosion prediction accuracies were identified.

In Chapter 5, a new numerical model called Gully Erosion by Headcut Migration (GEHM) model is developed. The model accounts for various environmental and climatic factors and models gully head erosion at a landscape scale. The model uses terrainbento and landlab model components in combination with the gully head migration model. The model will save outputs including topographic elevation, aquifer thickness, soil saturation, surface water discharge, sediment transport rate, and gully head location at user-specified time intervals. The sensitivity of the GHEM model to various gully head erosion factors such as groundwater, hydraulic conductivity, drainable porosity, water erodibility, and height-cut height was investigated.

Lastly, Chapter 6 gives a synthesis of the research finding by laying out the added knowledge to gully erosion, catchment hydrology, and catchment management research fields. Besides, this chapter provides recommendations about gully erosion and management options. The chapter finally concludes on future research directions.

### 1.5 Study area

This research was conducted in the Minzir catchment, a sub-catchment of the Koga catchment located in the sub-humid Northwestern part of Ethiopia (Figure 1.2). The catchment receives an average annual rainfall range between 1460 and 1850 mm, most of which (90%) falls between May and October. It covers a drainage area of 18 $km^2$, and its elevation ranges between 2030 and 2265 m a.s.l.

The soil types in Minzir are classified as Nitisols (29.5%), Vertisols (29.2%), Luvisols (14.9%), Leptosols (10%), and Alisols (7.7%). Other soil types such as Cambisols, Fluvisols, and Regosols cover 5% of the catchment. The dominant textural classes include clay (83.7%), clay loam (5.9%), and sandy clay loam (3.5%). Land uses dominantly consist of cultivated land (83%), grassland (13%), and plantation forest (1.6%). The slope in the catchment ranges from 0–34%, with the majority (94%) falling into the 0–10% slope category.

The valley bottom of the Koga watershed is more vulnerable to gully erosion and sedimentation than the hillslope areas (Assefa et al., 2015). Sediment from the catchment becomes a threat to Lake Tana as the basin drains into the lake (Dessie et al., 2015). Because of the sediment it receives from Koga and other upstream catchments, the Abay river is blamed for contributing considerable sediment to the river Nile (Steenhuis et al., 2009). Moreover, the Koga dam (Figure 1.2b) built in the Koga watershed is severely affected by sedimentation problems. Sediment accumulation in the Koga reservoir reduces the irrigable area by 7 ha every year (Asres, 2016). To tackle this problem, the government of Ethiopia made an effort to reduce erosion by implementing different soil and water conservation strategies across the watershed. Still, these strategies seem to exacerbate the rate of gully expansion, mainly at the valley bottom (Ayele et al., 2016; Dagnew et al., 2015). According to Rijkee et al. (2015), reports from the local extension worker confirmed that the rate of gully erosion in the valley bottom of the Koga catchment has increased during the previous five years. Rijkee et al. (2015) went on to say that implementing soil conservation measures on the hillslope might raise the groundwater level in the catchment, leading to an increase in gully incision and expansion. However, this research also said insufficient information on the catchment's groundwater status to determine if higher groundwater levels may have caused the valley bottom gullies. A closer examination of the gully erosion process is required to understand the role of various factors on gully development, including groundwater. Process-based gully erosion studies regarding bank stability and soil characteristics other than simple topographical indicators are also necessary (Fox et al., 2016).

In Minzir catchment, a large percentage (>70%) of gullies were located on a slope gradient of less than 5%. This research looked at two gullies in the Minzir valley bottomland, one situated in a Nitisol and the other in a Vertisol (Figure 1.2d & Figure 1.2e). The gullies investigated are around 1.5 km apart, dissecting communal grazing land. The average gully depths for Nitisol and Vertisol are 5.7 and 2.8 m, respectively, with an average gully width of 13.8 m for both gullies.

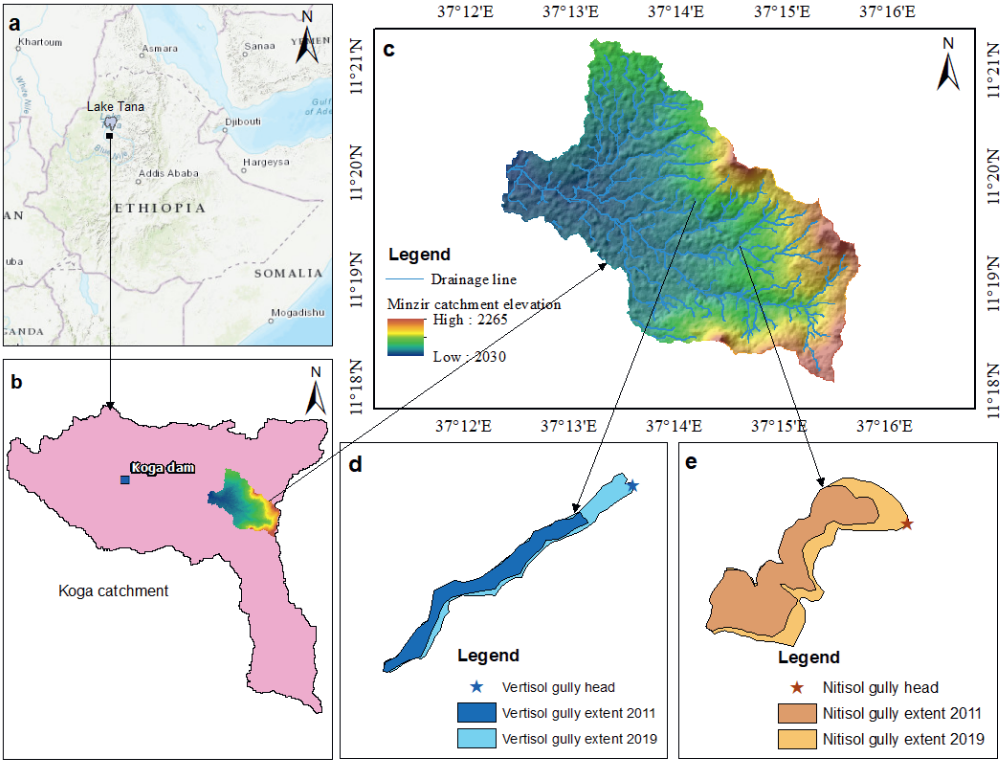


***Figure 1.2*** *(a) location of Ethiopia (b) location of the Koga dam and Minzir catchment in the Koga catchment (c) Elevation of Minzir catchment (d) Vertisol gully and (E) Nitisol gully.*

# 2. Causes and Controlling Factors of Valley Bottom Gullies

This chapter is based on:

Amare, S., Keesstra, S., van der Ploeg, M., Langendoen, E., Steenhuis, T., & Tilahun, S. (2019). Causes and controlling factors of Valley bottom Gullies. Land, 8(9), 141.

## Abstract

Valley bottomland provides diverse agricultural and ecosystem benefits. Due to concentrated flow paths, they are more vulnerable to gully erosion than hillslope areas. The objective of this review was to show what caused valley bottoms gullies and present deficiencies in existing rehabilitation measures. From the literature review, we found the following general trends: watershed characteristics determine the location of valley bottom gullies; an increase in water transported from the watershed initiates the formation of gullies; the rate of change of the valley bottom gullies, once initiated, depends on the amount of rainfall and the soil and bedrock properties. Especially in humid climates, subsurface flow greatly enhances bank slippage and the advancement of gully heads. Valley bottom gully reclamation measures are generally effective in arid and semi-arid areas with limited subsurface flow and deep groundwater tables. For (sub) humid regions, similar remedial actions are not successful as they do not account for the effects of subsurface flows. An integrated landscape approach that accounts for the combined subsurface and surface drainage is needed to implement rehabilitation measures, especially for humid regions, effectively.

## 2.1 Introduction

Gullies occur worldwide across a wide range of climatic, geomorphological, and pedological conditions (Billi & Dramis, 2003a) and can eventually turn a productive landscape into badlands. When enhanced by human-induced interventions in the landscape, gully erosion is economically detrimental (Ghimire et al., 2006; Ionita et al., 2015a; Muñoz-Robles et al., 2010). Besides, active gullies cause soil losses (Castillo & Gómez, 2016; Kertész & Gergely, 2011; Poesen et al., 2003; Valentin et al., 2005; Vanmaercke et al., 2016) and result in sedimentation in downstream lakes and reservoirs (Ionita et al., 2015a; Kertész & Gergely, 2011; Little et al., 1978; McCloskey et al., 2016). Finally, gullies eliminate any positive effects of upstream soil and water conservation practices to reduce sediment concentrations (Dagnew et al., 2015; Zegeye et al., 2018).

Gullies are defined as incisions in the landscape at least 50 cm deep (SSSA, 2008). Gullies can be actively eroding or have been formed in the past and are either stable or very slowly eroding. Based on the size, gullies are divided as ephemeral and permanent (Poesen, 1993). Ephemeral gullies are the shallowest and can be erased by tillage (Poesen, 1993; SSSA, 2008). Permanent gullies are larger and can be 10 m deep and 30 m or more wide (Vanmaercke et al., 2016). Permanent gullies, in turn, can be further grouped based on topographic location as valley bottom, valley-side, or valley-head gullies (Bradford & Piest, 1980b). Valley bottom gullies, also known in the literature as valley floor gullies, large channels, and downslope gullies (Rădoane & Rădoane, 2017; Vanmaercke et al., 2016), occur in the lowest parts of the landscape where the slope decreases suddenly to less than 3% (Billi & Dramis, 2003b) and the flow from the uplands concentrates. They are often located on deep alluvial and colluvium soils (Descroix et al., 2008; Nogueras et al., 2000; Stavi et al., 2010; Thomas et al., 2009b). A valley bottom gully (VBG) becomes a valley-head gully as its head scarp migrates into the valley head (Bradford & Piest, 1980b). Valley-side gullies occur on the hillside and usually result from flow coming from diverse directions. They are not linked with the valley bottom (Bradford & Piest, 1980b; Rădoane & Rădoane, 2017) and are usually smaller than valley bottom gullies. The severe impact of valley bottom gullies is illustrated by findings in the humid Ethiopian highlands, where watersheds with valley bottom gullies report erosion rates varying from 40 Mg ha$^{-1}$ year$^{-1}$ to over 500 Mg ha$^{-1}$ year$^{-1}$. In comparison, watersheds without valley bottom gullies have soil losses of below 25 Mg ha$^{-1}$ year$^{-1}$ (Addisie et al., 2018). Finally, gullies can be classified according to their shape ranging from U- to V-shaped, with many intermediate types (Rădoane & Rădoane, 2017).

Ample publications in the refereed literature refer to surface runoff as the cause of active gully formation (e.g., (Moges & Holden, 2008; Poesen et al., 2003; Poesen & Valentin, 2003; Rădoane & Rădoane, 2017)). Discharge from surface runoff is assumed as the primary driving force associated with the amount of soil eroded by transforming rills into gullies (Nyssen et al., 2006; SSSA, 2008). While discharge might be the only cause for valley-side gullies, subsurface flow processes play a role in valley bottom gullies by decreasing soil strength due to soil saturation (Moges et al., 2017; Van Den Elsen et al., 2003). Though recent reviews by Castillo & Gómez (2016) and Wilson et al. (2018) attest that the effect of subsurface flow on erosion processes is poorly understood, few publications recognize subsurface flow processes as the main cause in the formation of gullies (Addisie et al., 2017a; Fox et al., 2007; Fox & Wilson, 2010; Tebebu et al., 2010; Wilson et al., 2018; Zegeye et al., 2016a) and pipes (Bernatek-Jakiel & Poesen, 2018; Wilson et al., 2018). Especially seepage faces with high pore pressures are gully initiation points, and once gullies are formed, pore-pressure-induced bank slippage is common (Fox et al., 2007; Okagbue & Uma, 1987; Tebebu et al., 2010; Wilson et al., 2018). These seepage faces are most common in saturated valley bottomlands (Castillo & Gómez, 2016).

Though valley bottom gully erosion contributes significant amounts of sediment, limited information is available on the controlling factors, especially the role of subsurface flow (Wilson et al., 2018). Therefore, our aim was: to review the current knowledge of valley bottom gully erosion; to assess how hydrology, especially subsurface flow, together with topographic factors, determine the vulnerability of valley bottomlands to severe gully erosion; and to identify deficiencies in existing rehabilitation measures.

## 2.2 Materials and Methods

Peer-reviewed articles were searched in the CAB Abstract and Scopus databases. The article search in the CAB Abstract database was executed through advanced search options with the search field "Keyword," whereas, in Scopus, the "TITLE-ABS-KEY" search field was used (Figure 2.1). From these two databases, articles were retrieved with the search criteria: (gull*) AND (erosion) AND (valley* OR downslope OR down-slope OR downhill OR down-hill). Articles written in languages other than English were excluded. Finally, articles that fulfilled the above criteria were exported to the EndNote X7 reference manager. Duplicate articles were removed by using the EndNote tools. Microsoft Excel 2010 was used for data abstraction from reading the full texts.

Articles that were not easily differentiated by their abstract were further probed by reading the study area description. Most papers studied valley bottom gullies as part of a wider set of gullies. We separated information concerning only valley bottom gullies, even from papers with a minor focus on valley bottom gullies. Based on our prior knowledge of the field, we included 69 mainly theoretical manuscripts that were relevant but did not fit the keywords selected. These articles were retrieved from Scopus, Google Scholar, and Research Gate. For this review, 126 articles and one book were used.

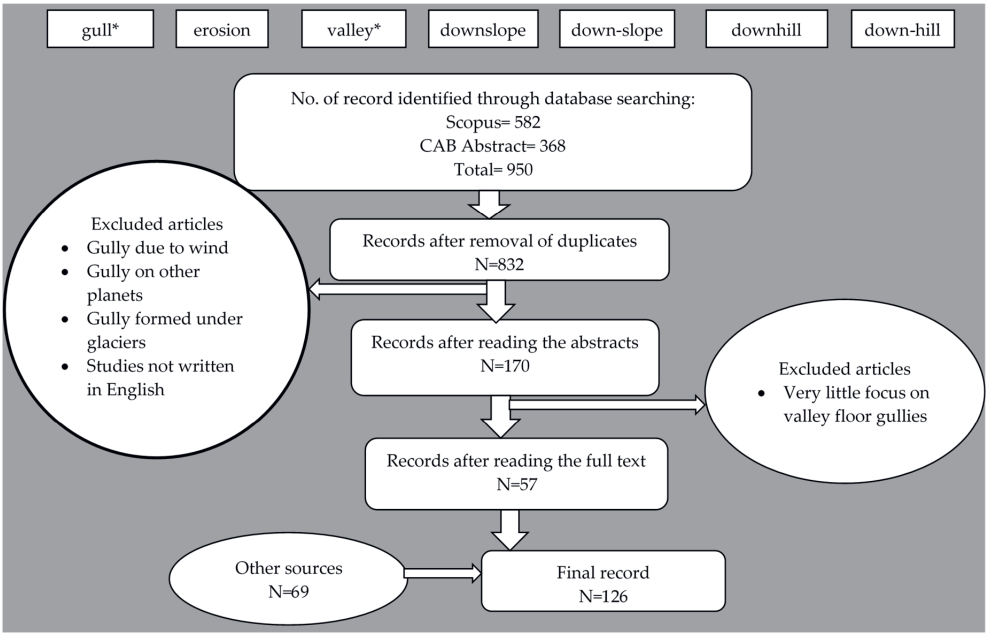


***Figure 2.1*** *A schematic representation of the literature review framework. The rectangular boxes at the top are the list of keywords used to retrieve articles from the CAB and Scopus databases. N represents the number of articles kept after the articles passed a certain screening stage.*

## 2.3 Literature Findings and Discussion

### *2.3.1 Overview*

Valley bottom gullies appear as incisions in the lower periodically saturated part of the landscape where surface and subsurface flow concentrate (Gallant & Dowling, 2003). They become saturated because both the hydraulic gradient is less than in the upper parts, and a large area drains towards it. For the same reasons, valley bottoms are also the most agriculturally productive areas and provide essential ecosystem services (Fagbami & Ajayi, 1990; Keïta et al., 2014; Lidon et al., 1998; Rebelo et al., 2015).

Valley bottom gullies can be stable or active. Stable gullies, such as large rivers in valleys, are in equilibrium with the environment, and erosion is minimal. Active gullies are significant sediment sources and could be caused by short- or long-term climate changes, as illustrated by Carnicelli et al. (2009), who examined gully formation in the Ethiopian Highlands since the late Holocene period. They discovered that gullies developed during periods of excessive precipitation, which later filled up during dry periods. Similarly, Thomas et al. (2004) reported that a reduction in runoff led to a reduction in gully erosion rate.

The findings of the literature review are summarized in Table 2.1 and Table 2.2. Table 2.1 lists each reviewed publication and specifies the geographic location of the VBG, rehabilitation efforts, upland activities, and the causes and controlling factors of VBG erosion. Table 2.2 provides information on catchment characteristics and observed soil losses for each reviewed VBG. Table 2.1 helps us understand what upland environmental conditions generally trigger gully initiation and further development, while Table 2.2 provides the insights. The below sections present various aspects of VBGs reported in the literature. First, a brief overview of gully expansion mechanics aids the discussion of these aspects.

A combination of fluvial and mass wasting erosion mechanisms is responsible for the expansion of gullies at the valley bottoms (Istanbulluoglu et al., 2005; Thorne, 1998; Zegeye et al., 2016a). Mass wasting and fluvial erosion progress through several stages to erode the gully banks (Bradford & Piest, 1980a; Bradford et al., 1973b). (Stage 1) erosion of the bank toe is caused by the applied hydraulic shear stress or collapsibility, which is stress removal from the base and loss of cohesion due to increased pore water pressure. (Stage 2) This leads to steepening or an overhanging gully bank. The steepened or overhanging bank material then collapses (Figure 2.2a). (Stage 3) Fluvial erosion removes the failed bank material. The process (Stages 1–3) repeats itself until either more resistant bank material becomes exposed, or the runoff is unable to erode and transport the collapsed bank material. Fluvial erosion may facilitate gully erosion in two ways: directly by detaching soil particles or gully head-cut retreat (Bradford & Piest, 1980a) and indirectly by triggering gully bank mass wasting through steepening of the gully bank (Kleidon et al., 2013).

Soil saturation, overland runoff, seepage erosion, and crack formation are important factors that control gully bank mass wasting. Infiltrating precipitation and overland runoff increase soil weight and saturation. This added weight destabilizes the gully bank (Kleidon et al., 2013), and soil saturation reduces soil shear strength. For example, in semi-arid Colorado, gully mass wasting is primarily due to bank saturation, causing an 80% increase in soil weight (Rengers & Tucker, 2015). The authors Rengers & Tucker (2015) further suggested plunge pools facilitated gully mass-wasting near the head-cut by reducing bedrock strength. Seepage erosion occurs due to the development of critical hydraulic gradients (Dietrich & Dunne, 1993) that trigger gully mass wasting. Exfiltration of groundwater to the surface (Spence & Sauchyn, 1999) could trigger gully bank mass wasting by washing out soil cementing agents and increasing soil weight (Midgley et al., 2011). Soil pipe collapse due to preferential flow may lead to pipe clogging, increasing soil pore water pressure that may cause mass wasting processes (Fox & Wilson, 2010).

Gullies are the most energy-efficient way to transport excess runoff from the watershed after a landscape disturbance (Addisie et al., 2017a; Zehe et al., 2007). For example, with respect to subsurface drainage, preferential flow paths has been observed in many subsurface flow studies where water flows preferentially through the soils, such as fingered flow and funnel flow (Kung, 1993; Selker et al., 1992). Nieber & Warner (1991) and Nieber

& Sidle (2010) showed pipes and disconnected pipe segments concentrated the flow, thereby further enhancing their dimensions and extent. Gully formation is, therefore, a natural consequence of self-organizing drainage flow paths in the landscape (Poesen et al., 2003; Rodriguez-Iturbe & Rinaldo, 2001), with a change in water flux being the main driving force.

Tension cracks are also important factors for gully bank instability (Oostwoud Wijdenes et al., 1999), as gully mass wasting processes are commonly preceded by the occurrence of tension cracks (Thomas et al., 2009a). On a valley bottom in semi-arid Kenya, tension cracks cause gully mass wasting by allowing more water into the cracks, increasing the soil pore water pressure (Wijdenes & Bryan, 2001). The presence of cracks can also diminish the load-carrying capacity of soil by up to 30%, thereby affecting gully stability (Langendoen & Simon, 2009). Thus, the evolution of valley bottom gullies (unlike hillside gullies) is directly linked to the concentration of the flow paths and the greater moisture contents, leading to periodically saturated soil. Saturation of the soil would destabilize gully banks (Bradford & Piest, 1980a), and fluvial processes carry away the unconsolidated sediment from the failed banks.

**(a)**

**(b)**

***Figure 2.2*** *A picture of a typical valley bottom head-cut (a) and mass wasting phenomenon (b) taken from the Debre Mawi catchment in Ethiopia.*

In the next section, the factors controlling gully formation are presented. We first discussed the topographic factors (slope and drainage area) followed by other factors (precipitation, groundwater depth, land-use, soil type, soil depth, lithology, etc.).

***Table 2.1*** *Rehabilitation measures, upland catchment activities, and causes and controlling factors of valley bottom gully (VBG) obtained from the literature review. LU is the acronym for land-use.*

| Reference | Location (specific place) | Rehabilitation measures | Offsite/ upland activities | Causes and controlling factors |
|---|---|---|---|---|
| Mukai (2016a) | Ethiopia (rift valley) | No rehabilitation measures before 2005 | - | LU change (forest to grazing and cropland), topography, gully morphological variable, rainfall, soil texture, and slope gradient |
| Billi & Dramis (2003a) | Ethiopia (rift valley) | - | - | Overgrazing, deforestation, and soil piping |
| Nyssen et al. (2000); Nyssen et al. (2002); Nyssen et al. (2004b). | Ethiopia (North Ethiopia) | Check dams, unsuccessful diversion and concentration of field runoff | Hillslope vegetati on degradat ion | Road construction, LU change (arable to intensively grazing land), eucalyptus plantation, drought, vegetation degradation, pipe and tunnel erosion, deforestation, concentrated surface runoff, and Vertisol cracking and swelling |
| Hagos et al. (2014) | Ethiopia (Huluk) | No rehabilitation measures | - | Vegetation degradation and intensive cultivation |
| Tebebu et al. (2010); Tilahun et al. (2014); Zegeye et al. (2016a) | Ethiopia (Debre Mawi) | Rehabilitation measures were implemented but were not successful | - | Vegetation degradation, increased surface and sub-surface runoff, and increased gully bank height |
| Addisie et al. (2017a) | Ethiopia (Ene-Chilala) | Riprap integrated with grasses was used effectively to halt shallow (<3 m deep) gully head-cut | Diversio n of runoff from the upslope area to VB land | Presence of shallow groundwater and occurrence of cracks facilitated gullies |

| | | | | |
|---|---|---|---|---|
| Moges & Holden (2008) | Ethiopia (Sidama Umbulo catchment) | No rehabilitation measures | Decline in hillslope vegetation | LU change from tree and shrub to croplands, trail, pipe, and tunnel, and unweathered pumice layers and silt horizon |
| Wijdenes & Bryan (2001) | Kenya | - | - | Drought and LU pressure |
| Olofin, (1984) | Kano, Nigeria | - | - | Hydrological change: dam and reservoir construction |
| Boardman (2014); Boardman et al. (2003a) | South Africa | Erosion control measures halted incision of gullies | - | Vegetation degradation, overgrazing, change in vegetation from grassland to shrubland, periodic drought, wetland drainage, wagon track, climate change, and concentrated water flow, new settlement, trails, and dam construction |
| Rowntree (2013) | South Africa (Karoo) | - | Hillslope vegetation degradation | Deforestation, overgrazing, road and railway construction, intense rainfall, rapid runoff, and increased drainage density |
| Stavi et al. (2010) | Israel (Negev Desert) | - | - | Natural desertification (long-term climate change) |
| Prosser & Slade (1994) | Australia (Murrumbateman Creek catchment) | Swampy meadow helped in halting incision | | Vegetation degradation, LU change, increase in discharge, large drainage area (>10 km$^2$), and climate change |
| Strunk (2003) | Italy | - | - | Overgrazing and cattle trampling, low infiltration caused by VB silt loam sedimentation, presence of silty layer, decrease in the field capacity, residual |

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| | | | | water storage capacity, and infiltration capacity |
| Ionita & Niacsu (2010) | Southern Moldavian Plateau (Pereschivul Mic catchment) | Strip cropping with windbreaks was effective | Vegetation clearance | Up and down farming, inadequate road network |
| Gómez-Gutiérrez et al. (2012) | Southwest Spain | - | - | Antecedent soil moisture, intense rainfall, and long-duration rainfall |
| Gutiérrez et al. (2009a) | Southwest Spain | - | - | Vegetation cover decrease, and cultivation of large areas |
| Nogueras et al. (2000) | Spain (Tabernas Neogene basin) | - | - | Vegetation degradation due to drought and increased runoff coefficient (with high eroding power) |
| Rengers & Tucker (2015) | Eastern Colorado | - | - | Intense rainfall, winter snowmelt, long-duration low-intensity rainfall, and an increase in volumetric water content |
| Mosley (1972) | Northern Colorado (North-northeast of Fort Collins) | - | - | Intense rainfall, vegetation degradation, cattle trampling, and pronounced surface runoff |
| Patton & Schumm (1975) | Northwest Colorado | - | - | Locally oversteepened land |
| Thomas et al. (2004) | Iowa | - | - | Runoff plays an important role |
| Thomas et al. (2009a) | Western Iowa | - | - | Rainfall and snowmelt increase the hydraulic head at the gully bank |
| Marinho et al. (2006) | Brazil (Queixad | Conservation measures are | - | Deforestation, pasture, elevated groundwater, |

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|---|---|---|---|---|
| | a's Brook sub-basin) | not successful (caused the incision of new gullies) | | intense rainfall, a lithological discontinuity that may favor soil piping |
| Descroix et al. (2008) | Mexico (Western Sierra Madre) | - | - | Deforestation, overgrazing and cattle trampling, large cultivation area, large drainage area, high silt content (>20%), and high sand content (>80%) |
| Gellis et al. (2004) | New Mexico (Arroyo Chavez basin) | - | - | Overgrazing, human disturbance (gas pipeline) |

***Table 2.2*** *Catchments characteristics of valley bottomland with corresponding soil losses due to gully erosion.*

| Reference | Location (specific place) | Geology and Lithology | Annual rainfall (mm $y^{-1}$) | Slope † | Soil type | Climate | Hydrology | Land-use | Date of gully initiation | Drain-age area (ha) | Soil loss |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Mukai (2017) | Ethiopia (rift-valley) | Underlain by quaternary lacustrine sediments | 881 | 3–9% and <2% | Vertisols (dominant) | Semi-arid | An increase in drainage area causes an increase in gully expansion | Crop (dominant) and grazing land | Before 1957 | Range between 18 to 611 | 16.2 t $ha^{-1}$ $y^{-1}$ |
| Billi & Dramis (2003a) | Ethiopia (rift valley) | Quaternary volcanic rock and lacustrine deposits | 769 | 4.6–9.3% | - | Semi-arid | - | - | - | - | - |
| Nyssen et al. (2006) | Ethiopia (North Ethiopia) | Quaternary form (alluvium, colluvium, and travertine), Mesozoic limestone and | 750 | 9% | Vertisols | Semi-arid | Surface runoff dominated | Grazing land and eucalyptus plantation | Two gullies that started in 1965 and 1935 in the VB were studied | 108 and 264, respectively | 5 t $ha^{-1}$ $y^{-1}$ and 2.3 t $ha^{-1}$ $y^{-1}$, respectively |

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| | | sandstone, and tertiary basalt flow | | | | | | | | | |
| Hagos et al. (2014) | Ethiopia (Huluk) | - | - | 0.8–5% | Andosol and Nitisol | - | - | Grazing and cultivated land | Before 1973 and after 2000 | - | 0.1 to 8 t $ha^{-1}$ $y^{-1}$ |
| Tebebu et al. (2010) | Ethiopia (Debre Mawi) | Underlain by highly weathered and fractured basalt | 1240 | - | Vertisol dominated | Sub-humid | Subsurface dominated and relatively small surface runoff contribution | Grazing and cropland | 1981 | 17 | 31 to 530 t $ha^{-1}$ $y^{-1}$ |
| Zegeye et al. (2018) | Ethiopia (Debre Mawi) | Underlain by highly weathered and fractured basalt | 1240 | | Vertisol dominated | Sub-humid | Subsurface dominated and relatively small surface runoff contribution | Grazing and cropland | - | 17 | In 2013, 197 t $ha^{-1}$ $y^{-1}$ and, in 2014, 69 t $ha^{-1}$ $y^{-1}$ (the reduced soil loss was due to treated |

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|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | head-cut in 2014) |
| Addisie et al. (2017a) | Ethiopia (Ene-Chilala) | Oligocene to Miocene basaltic shield volcanic origin | 1225 | 5% | Vertisols | Sub-humid | Subsurface dominated and relatively small surface runoff contribution | Grazing land | - | 0.07 to 10.91 ha with an avera ge value of 2.5 | 19.4 $m^3$ $y^{-1}$ per gully head |
| Moges & Holden (2008) | Ethiopia (Sidama Umbulo catchment) | Volcanic lacustrine deposit (tuff, pumice, and ash) | - | - | Mollic Andosol | - | Surface runoff and pipe collapses control gully development | Cultivated land | Between 1974 and 1985 | - | The average rate of soil loss from 11 to 30 t $ha^{-1}$ $y^{-1}$ |
| Wijdenes & Bryan (2001) | Kenya | Alluvio-lacustrine sedimentar y features | - | | Cambisol or Fluvisol | Semi-arid | - | Savannah woodland | - | 0.09 to 1.4 | 6.7 t $ha^{-1}$ $y^{-1}$ to 29.5 t $ha^{-1}$ $y^{-1}$ |
| Olofin (1984) | Nigeria (Kano) | Sandy alluvium deposit old | 800 and 900 | 0.8–1% | - | Tropical dry and wet type | - | - | - | - | - |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | granite and metamorphic rock type | | | | | | | | | |
| Boardman, (2014); Boardman et al. (2003a) | South Africa | Colluvial and fluvial sediment deposits, less resistant Balfour formation mudstone, and shales and sandstone | 346 | <17.6 % | - | Semi-arid | Surface runoff dominated | Grazing and cultivated | Between 1937 and 1960s | | 115 $m^3\ ha^{-2}$ |
| Rowntree (2013) | South Africa (Karoo) | - | 100–400 | - | - | Semi-arid | Both subsurface and surface runoff are important | - | ~1910 | - | - |
| Stavi et al. (2010) | Israel (Negev Desert) | Hard limestone and dolomite, the soil is | 90 | 1–3% | - | Arid | Surface runoff dominated | Grazing land | - | - | - |

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|---|---|---|---|---|---|---|---|---|---|---|---|
| | | alluvial loess with a loamy-sand texture | | | | | | | | | |
| Strunk (2003) | Italy | - | - | Flat | Lithic Borofolists (peat-like organic soil) | - | Hortonian overland flow is reported to be the primary cause of gully erosion | Grazing land | ~1990 | - | - |
| Ionita & Niacsu (2010) | Southern Moldavian Plateau (Pereschivul Mic catchment) | - | 510 | Average slope of 14% | Sandy-clayey chernisoils and luvisol | Temperate continental | Only surface runoff was reported | Crop production | ~1961 | - | 9.8 t $ha^{-1}$ $y^{-1}$ |
| Gómez-Gutiérrez et al. (2012) | Southwest Spain | Alluvial deposit | 518 | 0% | Rigosol | Mediterranean with a pronounced dry summer season | Both surface and subsurface water flow process contribute to | Savannah-like wooded rangelands | ~1790 | - | 0.063 t $ha^{-1}$ $y^{-1}$ |

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|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | gully development | | | | |
| Gutiérrez et al. (2009a) | Southwest Spain | - | 525 | | - | Semi-arid | - | Cultivated land, grass land, and woody vegetation | - | | 2.3 m $y^{-1}$ (head-cut retreat) |
| Nogueras et al. (2000) | Spain (Tabernas Neogene basin) | Colluvial deposit, poorly stratified marls and sandstone beds | 218 | Level | - | Thermo-Mediterranean semi-arid | Surface runoff dominated | Grazing land | - | - | - |
| Rengers & Tucker (2015) | Eastern Colorado | Alluvial deposit, weakly cemented shales, and Sandstone | - | - | - | Semi-arid | - | Grass lined | - | - | 0.34 m $y^{-1}$ (head-cut retreat) |
| Mosley (1972) | Northern Colorado (North-northeast | Alluvial fill shale bedrock | 384 | Gentle | - | Semi-arid | Full saturation of the gully bank and | Grazing land | - | - | - |

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| | of Fort Collins) | | | | | | overland flow control gullies | | | | |
| Patton & Schumm (1975) | Northwest Colorado | Light-brown and grey sandstone interbedded with siltstone and marlstone bed | 317.5 | Overly steepened locally | - | Semi-arid | - | Sagebrush and greasewood are the predominant vegetative cover | - | - | - |
| Thomas et al. (2004) | Iowa | Thick alluvium loess deposits | - | Gentle | - | - | Subsurface dominated | No-till cropland, grasses and shrubs on the lower slopes. | - | - | 320 t $y^{-1}$ |
| Marinho et al. (2006) | Brazil (Queixada's Brook sub-basin) | Covered by alluvial and colluvium deposits, sandstone regolith, | 1600 | <8% | Plinthic, Entisol, Red Oxisol, | Tropical | Both subsurface and surface runoff are important | Pasture and secondary agriculture | Recent (<10 years age) | - | - |

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|---|---|---|---|---|---|---|---|---|---|---|---|
| | | and fine sand soil | | | | | | | | | |
| Descroix et al. (2008) | Mexico (western Sierra Madre) | Thick phaeozems, completed by alluvial fills | 450 (foot slope) and 900 (crest) | Gentle | Phaeozems and Cambisols | Tropical | Surface runoff dominated | Grazing land | - | - | - |
| Gellis et al. (2004) | New Mexico (Arroyo Chavez basin) | Soils derived from underlying sandstones and shales, as well as from eolian silt | 329 | - | - | Semi-arid | Overland flow due to reduced infiltration is reported | Grazing land | - | - | 33.5 t $ha^{-1}$ $y^{-1}$ |

† Both numeric values (in percent) and qualitative descriptors are used. We used qualitative descriptors because the authors did not express slope numerically. According to Food and Agriculture Organization (FAO) slope classification (Jahn et al., 2006), flat, level, and gentle refer to slope classes of 0–0.2%, 0.2–0.5%, and 2–5%, respectively.

### 2.3.2 Factors Related to Valley Bottom Gully Formation

#### 2.3.2.1 Slope Gradient and Drainage Area

Slope gradient and drainage area are important watershed characteristics that affect hydrology (Ali et al., 2014) and thus gully formation (Table 2.2). Valley bottom gullies are found in gently sloping areas (Table 2.1) and not on steep slopes. A negative relationship exists between drainage area and slope (Desmet et al., 1999; Dietrich & Dunne, 1993). As the drainage area increases (it tends to have greater flows), the slope reduces (smaller hydraulic gradients). This, in turn, increases the propensity for soil saturation as the groundwater table rises with greater discharge and smaller hydraulic gradients. Besides, smaller slopes combined with depressions provide more time for surface water to infiltrate into the soil, thereby increasing the soil moisture content (Gallant & Dowling, 2003).

The increasing flux of water associated with increasing drainage area (Mukai, 2016a) not only erodes the gully boundary materials but also aids in the evacuation of soil deposited after gully head and bank collapses, thereby accelerating gully head (Torri & Poesen, 2014) and gully volume (Frankl et al., 2013b) expansion. Similarly, studies undertaken for rivers found that gentler-sloped reaches (<2%) have larger bank height and retreat rates (Macfall et al., 2014). Therefore, valley bottomlands with a small catchment area are relatively stable and do not have gullies (Begin & Schumm, 1979).

#### 2.3.2.2 Topographic Gully Threshold Indices

Because of the strong relationship between hydrology, erosion, and topography, it is no surprise that several studies have reported the importance of topographic controls on incision of gullies or channel incisions in general (Horton, 1945; Moore et al., 1988; Prosser & Abernethy, 1996). Most relationships predict the location of ephemeral gullies (Desmet et al., 1999; Moore et al., 1988; Vandaele et al., 1996) independent of how runoff is generated (Vandaele et al., 1997). For permanent gullies, topographic threshold relationships have a different form for semi-arid regions where overland surface runoff dominates (Torri & Poesen, 2014) and those in humid climates in duplex landscapes with a hardpan with interflow and saturation excess overland flow (Wilson et al., 2018). Existing topographic threshold predictors developed for semi-arid areas are inaccurate or even erroneous for sub-humid and humid regions (Vandekerckhove et al., 2000). Topographic threshold relationships (with drainage area, soil type, and slope as parameters) accurately predict the locations of permanent gullies caused by Hortonian runoff on valley slopes (e.g., in warm sub-humid Swaziland (Morgan & Mngomezulu, 2003)) and valley bottomlands (e.g., in semi-arid Mediterranean Iberian Peninsula (Gutiérrez et al., 2009a) and semi-arid western Colorado (Patton & Schumm, 1975)). In areas with saturation excess runoff, Mhiret et al. (2018) indicated elevated soil wetness is a good predictor of gully location. One of these threshold predictors is the topographic wetness index, defined as the ratio of the amount of water delivered to a point (i.e., contributing area) and the amount transmitted (i.e., a product of slope, conductivity, and soil depth) (Sörensen et al., 2006).

### *2.3.2.3 Precipitation*

Soil loss, in general, is a function of rainfall duration, magnitude, and intensity. Based on the world rainfall erosivity map, high to low rainfall erosivity vary between 7105 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$ for tropical regions, 3729 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$ for temperate regions, 843 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$ for arid regions, and 494 MJ mm $ha^{-1}$ $h^{-1}$ $year^{-1}$ for cold climatic regions (Panagos et al., 2017). Tropical countries, like Ethiopia (specifically the highlands) and Brazil, are among the countries with the highest rainfall erosivity records and, at the same time, are affected by severe valley bottom erosion. In contrast, there is relatively low soil loss (1.1 Mg $ha^{-1}$ $year^{-1}$) recorded for semi-arid Ethiopia, which is in line with the low rainfall erosivity reported for this climatic zone. In general, valley bottom formation becomes more severe for increasing rainfall erosivity.

According to Table 2.2, valley bottom gullies occur across all rainfall regimes in both arid regions, with annual rainfall as low as 90 mm (Stavi et al., 2010), and humid regions, with annual rainfall as high as 1600 mm (Marinho et al., 2006). This indicates it is not the amount of precipitation in itself causing gully formation, but it is the variability in rainfall. For example, Gomez-Gutierrez et al. (2012) found that the impact of increased rainfall due to climate change on valley bottom gully formation was directly through increased surface runoff volume and indirectly through increased soil pore-water pressure (Rengers & Tucker, 2015). Likewise, Bradford & Piest (1980b), Okagbue & Uma (1987), Langendoen (2011a), and Langendoen et al. (2013) found that extended wet periods, coupled with increased runoff volumes, increased the probability of gully widening by bank failures.

Although the initiation of gullies is independent of the amount of precipitation, the rate of gully expansion increases with increasing rainfall amounts. For example, the highest valley bottom gully soil loss (530 t $ha^{-1}$ $year^{-1}$) and head-cut retreat (36 m $year^{-1}$) rates were recorded for sub-humid monsoon-tropical Ethiopian highlands (Table 2.1).

### *2.3.2.4 Groundwater/Surface Runoff*

In most valley bottom gully erosion studies (Table 2.1), the groundwater table was not monitored; hence, the subsurface flow could not be evaluated. For the few studies in which groundwater measurements were conducted, all mentioned elevated groundwater table as an important factor for the genesis of gullies at the valley bottom of a watershed, e.g., in Brazil (Marinho et al., 2006), Ethiopia (Addisie et al., 2017a; Tebebu et al., 2010; Zegeye et al., 2016a), and western Iowa (Thomas et al., 2009a). A study also found that the elevated groundwater level above the gully bottom during the rainy period decreased the soil's strength and erosion resistance along the gully banks and enhanced mass-wasting (Addisie et al., 2017a).

#### *2.3.2.5 Land-use*

Based on the data presented in Table 2.1, Figure 2.3 shows that 36% of the active gullies occurred in grazing land, followed by combined crop and grazing land (20%) and other land-use (20%). Only 12% of the active gullies occurred in cropland. Likewise, in Italy, more gullies have been observed in grazing lands than cropland (Strunk, 2003). Valley bottom gully incision seldom commences in forest lands. Although these results seem to strongly point to a relationship between land-use and active gully development, the underlying reason is again the watershed's hydrology as the grass is grown on soils that are too wet for growing crops (Bayabil et al., 2010). Forest can be found in those parts of the landscape that are usually too dry for good crop yield due to the terrain's steepness or restricted soil depth.

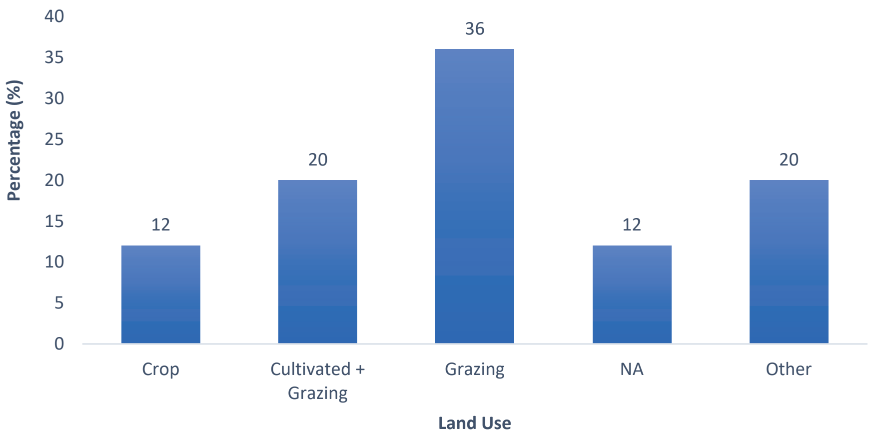


***Figure 2.3*** *The percentage of articles, listed in* ***Table 2.1****, that state the specific land-use type in their VBG (valley bottom gully) studies. 'NA' (not available) denotes articles that do not report the land-use types of the gullied catchment. The 'others' land-use category includes land uses like brush and herbaceous.*

#### *2.3.2.6 Land-Use Change*

Land-use changes were frequently mentioned as the cause of gully initiation and widening in valley bottom areas (Table 2.2). Examples of land-use changes related to gully formation in Ethiopia are eucalyptus plantation, cultivation of previously untilled land, conversion of cropland to pasture, and road construction (Nyssen et al., 2002; Nyssen et al., 2006). The decline in hillslope vegetation and other factors increase the runoff concentration at the valley bottom, resulting in gully erosion (Nyssen et al., 2006). Deforestation leads to persistently increased wetness in valley bottomlands and is followed by gully formation (Tebebu et al., 2010). Mukai (2016b) reported that gully formation was associated with a change in land-use type from forest land to grazing and croplands. Another study reported that, in South Africa, a shift from grassland to shrubland increased the presence of bare soil, which caused a four-fold increment in the runoff amount with a corresponding six-fold rise in the erosion rate at the foot slopes (Boardman et al., 2003a). Besides, Boardman (2014) reported that valley bottom gullies in a semi-arid region were caused by runoff from a degraded area, which was one order of magnitude greater than that from the vegetated areas in the region. Marinho et al. (2006) reported that, in Brazil, land-use changes from forest to pasture increased runoff, resulting in groundwater table rise, increased saturated area, and subsurface flow, leading to gully growth at the valley bottomlands. In Nigeria, Olofin (1984) reported that the cause of valley bottom gully development was associated with hydrological changes due to dam and reservoir construction. Further, a relatively large percentage of the reviewed articles (12%) did not state the land-use type of the gullied catchment (Figure 2.3). This signifies that land-use was not directly related to valley bottom gullies. This is per our hypotheses that change in land-use is responsible for gully formation and not the land-use itself. In summary, in all cases, the unifying principle is that the land-use change caused increased runoff and/or wetness in valley bottoms and enhanced gully development.

#### *2.3.2.7 Soil*

The reviewed publications (Table 2.1) showed that there is not a specific soil type in which gully formation does not occur. What is different among the studies is the size (both width and depth) and the form of the gullies for the various soil types. This is in agreement with our hypothesis that valley bottom gully formation is caused by the changes in hydrology, and thus resilience of rock deposits to erosion and the nature of geomorphic processes determine the shape of the cross-section (Rădoane & Rădoane, 2017). The major soil characteristics that govern mass-wasting after the hydrology has changed are the soil strength, erosion resistance, the type of soils (e.g., loess and vertisols), and the type of soil deposits (alluvium and colluvium).

Of all soil types, loess and vertisols are the dominant types reported in the literature for areas with valley bottom gullies. Both loess soil (Thomas et al., 2009b; Thomas et al., 2004) and vertisol (Mukai, 2016a; Nyssen et al., 2006; Nyssen et al., 2004b; Tilahun et al., 2014) create a favorable condition for valley bottom gully initiation and accelerated growth resulting in large gullies after the hydrology is changed. Vertisols are characterized by deep and wide cracks (Tilahun et al., 2014) that allow preferential water flow into the cracks, which increases soil pore-water pressure and promotes gully formation (Nyssen et al., 2004b). Also, the high swelling and shrinkage nature of vertisols favors the formation of gullies at the valley bottom (Nyssen et al., 2006), complicating the implementation of gully reclamation measures. Loess soils have a large fraction of silt (up to 60%) and low clay and organic matter content (Zhang et al., 2011), and therefore little cohesion. Accordingly, gully banks in silty textured soils are less stable and have lower friction angles (<30º) (Bradford et al., 1973b).

Another principle that most studies have in common, although not stated directly but singled out by Wilson et al. (2018) and noted by Brückner (1986); García-Ruiz (2010); Jin et al. (2012), is that gully formation occurs from duplex soils in the upland where a shallow permeable soil overlays a dense subsoil. As noted by Tebebu et al. (2015) and Zimale et al. (2017), the duplex soils formation, that is enhanced by continuous tillage after clear-cutting, decreases baseflow and increases direct runoff. Tillage results in the loss of organic matter. When the organic matter decreases below 3%, the aggregates break up (Gutiérrez et al., 2009a) and form a fine disperse soil, depending on the parent material, soil structure, high clay disparity, low pH (4.7–6.4), low cation exchange capacity (Vandekerckhove et al., 2000; Vergari et al., 2013), that is easily picked up by raindrop splash and remains in suspension. This then leads to land degradation in the uplands with a slowly permeable layer formed by the fine soil particles carried by the infiltrating rainwater (Strunk, 2003; Tebebu et al., 2015).

Deep percolation in the degraded duplex soils on the hillslopes has decreased, and shallow interflow has increased (Tesemma et al., 2010), which brings about an expansion of the saturated areas (Tebebu et al., 2010; Tilahun et al., 2016) and consequently leads to channel and gully incisions and expansions (Kleidon et al., 2013). Due to the increased erosion vulnerability with increasing saturation (Ma et al., 2016; Wells et al., 2011), large volumes of sediment are transported out of the watershed. The bottomlands in the Debre Mawi watershed, sub-humid Ethiopia, are a good example of gully erosion caused by hillslope land-use changes (Zegeye et al., 2016a).

#### *2.3.2.8 Alluvium and Colluvium*

Alluvium and colluvium are the dominant formations where valley bottom gullies are reported (Table 2.1). The primary soil characteristics associated with alluvium and colluvium deposits in the valley bottoms are greater depth (Mukai, 2016b; Tebebu et al., 2010), e.g., up to 8 m (Boardman et al., 2003a); and low roughness and stoniness (Descroix et al., 2008). However, only a few studies quantitatively stated soil depth. The low roughness and stoniness may ascribe to the valley bottom areas having well-sorted fine-textured alluvial and colluvium formations (Gómez-Gutiérrez et al., 2012; Gutiérrez et al., 2009a; Marinho et al., 2006; Thomas et al., 2009b). In a grazing land valley bottom dominated with thick phaeozems soil type, Descroix et al. (2008) reported gully volume was directly correlated with soil thickness and inversely correlated with surface roughness and stoniness. Because alluvium and colluvium deposited materials near the ground surface are generally unconsolidated and loose, they, coupled with other factors, may create a conducive situation for their erosion by water. Alluvium and colluvium deposits can also exhibit valley bottom lithological discontinuities across the soil profile. Such lithological discontinuities at the valley bottom, in turn, cause pipe occurrence, leading to gully formation and expansion (Ionita et al., 2015b).

### *2.3.3 Soil Loss*

Table 2.2 presents published soil loss from valley bottom gully erosion. The average soil loss for arid and semi-arid region ranged between 0.063 and 33.5 t ha−1 year−1, whereas, for sub-humid regions, the values were in the range between 31 and 530 t ha−1 year−1 (Table 2.2). In humid regions, the soil loss value is about one order of magnitude higher than in arid regions, signifying the severity of VBG erosion in those regions.

It is, however, difficult to compare the soil loss values between studies because the reported studies used different experimental design, study period, and units. Some studies reported combined soil loss from valley bottom gullies and hillslope gullies, which is noted in Table 2.2.

### *2.3.4 Conservation Measures*

Gully development depends on geomorphological (Deng et al., 2015; Pederson et al., 2006) and hydrological (Poesen et al., 2003; Valentin et al., 2005) parameters (Table 2.1). Since these hydrological and geomorphological parameters vary between hillslope and valley bottomlands (Gallant & Dowling, 2003), the type of rehabilitation measures that are likely to be effective will also vary.

Once valley bottom gullies have developed, their reclamation is challenging. Gully reclamation, through vegetation (Sole et al., 1997) and construction of brushwood check dams and flood regulators, is effective at hillslope positions (Nyssen et al., 2006) but fails at the valley bottom (Frankl et al., 2012), where they often exacerbate the rate of gully expansion (Ayele et al., 2016; Dagnew et al., 2015). Valley bottom gully erosion mostly occurs in heavily textured soils (Evans, 1993), where structural reclamation measures fail as a result of soil swelling and shrinkage. Rehabilitation of valley bottom gullies using vegetation is difficult as their growth is dominated by mass-wasting processes that require structural stabilization measures (Valentin et al., 2005). The high economic cost of valley bottom gully rehabilitation is another challenge (Moges & Holden, 2008). There are, however, rare cases where the processes that control valley bottom gully erosion are similar to that of hillslope gullies, and hillslope reclamation practices may work for valley bottom gullies (e.g., semi-arid South Africa (Boardman et al., 2003b)).

A small number of studies (Table 2.1) have been conducted towards the assessment of valley bottom gully reclamation measures. Some successful valley bottom gully reclamation activities in semi-arid regions were reported, whereas, in sub-humid regions, rehabilitation measures have been mostly unsuccessful.

Valley bottom gullies reclamation measures seem effective in arid and semi-arid areas where Hortonian overland flow is the dominant runoff process. For example, in South Africa, the implementation of reclamation measures in the semi-arid climate showed a reduction in gully expansion (Boardman et al., 2003a). On China's Loess Plateau with less than 600 mm annual rainfall, a 60% increase in vegetation cover on the hillslope significantly decreased gullies at valley bottom areas (Li et al., 2015). In semi-arid Ethiopia, an experiment conducted for about two years with vegetative measures at the shoulder, wall, and floor of gullies also proved to be effective in halting gully erosion (Reubens et al., 2009).

On the other hand, in humid areas, where subsurface or saturation-excess-induced erosion is the cause of gullies, stabilizing gullies with existing hillslope gully reclamation measures is challenging. In tropical Brazil, the construction, of terraces to conserve valley bottom gullies, was unsuccessful and created new small gullies at the foot slopes (Marinho et al., 2006). This may be due to terraces only decreasing the impact of surface runoff, but increasing water recharge to the soil, which in turn increases soil pore water pressure that can lead to pipe flow and formation of new gullies (Marinho et al., 2006; Thomas et al., 2009a). In sub-humid Ethiopia, rehabilitation of valley bottom gullies was reported to be unsuccessful but proved to be effective at hillslope locations (Dagnew et al., 2015; Tebebu et al., 2015).

A research effort to better understand gully erosion mechanisms and their controlling factors over a wide range of environmental conditions is fundamental for the identification and adoption of possible conservation strategies (Capra, 2013; Crampton, 1974). Given the factors introduced earlier, valley bottom gully reclamation measures should consider both overland and subsurface flow driven erosion. For example, for gully erosion caused by subsurface flow processes, reclamation measures should focus on reducing the groundwater table elevation and reshaping of tall gully banks to prevent bank and gully head failures (Zegeye et al., 2016a), and covering the valley bottom with wetland plants (Tebebu et al., 2015). Conservation activities that reduce the flow energy near the head-cut have a positive effect on reducing gully erosion rates (Bradford & Piest, 1980a). Reclamation measures, such as facilitating drainage and vegetative measures, play a role in stabilizing gullies by increasing the shear strength of the soil (Langendoen, 2011b; Langendoen et al., 2009). Integration of vegetation and structural engineering measures have also proven to provide better gully erosion control than using a single type of gully conservation measure (Zhang et al., 2015). Vegetation increases the strength of the gully boundary materials and reduces the susceptibility of a gully to external forces, such as surface runoff. Trees can, for instance, provide an additional 15 KPa of cohesive strength for the upper 1.5 m of a stream bank (Konsoer et al., 2016). The effectiveness of vegetation measures has been strongly associated with the distribution rather than the total vegetation (Rey, 2003). Dense vegetative reclamation measures when Hortonian overland flow dominates (Morgan & Mngomezulu, 2003). In comparison, deep-rooted vegetation that enhances evapotranspiration was proposed for gullies caused by seepage and high soil pore-water pressure conditions.

Reclamation activities in upland areas that drain into a gully can be equally crucial as reclamation of the gully channel itself. Even though hillslope conservation measures effectively decrease the amount of sediment and runoff volume, in some cases, they lead to the growth or incision of valley bottom gullies (Dagnew et al., 2015). Adverse effects of hillslope conservation measures are evidenced by infiltration, increasing soil pore-water pressures, or delivery of sediment-starved water to the valley bottom (Keesstra et al., 2005). In summary, reclamation measures should not only be restricted to the valley bottomlands, and it will be most effective when both hillslope and valley bottom rehabilitation activities are integrated within the valley bottom drainage area.

## 2.4 Conclusions

Due to various on- and off-site factors, valley bottomlands are landscape units that are more vulnerable to gully erosion than hillslope areas. Valley bottomlands are also geomorphologically and hydrologically different from hillslope areas. These differences promote contrasting erosion processes and require different rehabilitation measures for valley bottomlands than hillslopes. Nevertheless, research to date has not revealed the need for a different treatment of gullies located at valley bottoms. In this review, we presented parameters that affect the vulnerability of valley bottomland to gully erosion. The presence of thick alluvium and colluvium deposits, loess soils, vertisols, and intensively grazed and cultivated lands are among the factors that make valley bottomland susceptible to gullies. Due to intensive agricultural activities, most valley bottom gullies are reported on grazing and cultivated land-use types. Topographical factors (such as drainage area and slope gradient) and precipitation are among the factors that drive the development of gullies at the valley bottom. The dominant runoff process controlling valley bottom gully erosion in arid and humid regions differs. The dominant runoff process in the arid region is Hortonian overland runoff where as in the humid areas, it is saturation excess runoff. The above-mentioned hydrological and geomorphological factors negatively affect soil stability by lowering soil shear strength and erosion resistance, leading to fluvial and mass-wasting erosion.

Rehabilitation measures of valley bottom gullies are effective for Hortonian overland runoff driven erosion (arid regions), whereas, for saturation excess driven erosion (humid regions), rehabilitation measures are mostly unsuccessful. Similarly, prediction of valley bottom gully using existing topographical threshold predictors has worked well for Hortonian overland-flow controlled gullies. Whereas, for valley bottom gullies controlled by subsurface flow processes, such a threshold predictor might be flawed.

In summary, valley bottomlands are more susceptible to gully erosion than hillslopes, and controlling factors could differ between the two landscape positions. Therefore, valley bottom gullies should be approached differently than the usually grouped characterization with hillslope gullies. Existing gully erosion topographical threshold predictors for humid and sub-humid regions should be re-evaluated to better define the drainage areas into valley bottom gullies and implement effective prevention and rehabilitation measures. However, successful implementation of rehabilitation measures, especially for humid regions, requires an understanding of the erosion process. An integrated landscape approach that, among others, accounts for the combined subsurface and surface drainage into the valley bottomlands should be followed.

# 3. Hydrological and soil controls on valley bottom gully head erosion in the Ethiopian highland, Minzir catchment

This chapter is based on:

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## Abstract

Gully formation in valley bottoms is the primary source of sediment load in many catchments in the Ethiopian highlands. Yet, only a few studies have been conducted to assess the hydrological processes that lead to gully formation. We aimed to understand the impact of soil hydrological and morphological characteristics that leads to gully head erosion. During the 2017 and 2018 Ethiopian rain seasons, two gullies eroding on the valley bottom of the Minzir catchment were studied. One gully was located in a Vertisol, the other in a Nitisol. Data collection included rainfall, groundwater table (GWT), soil moisture content (SMC), soil water potential (SWP), infiltration, geotechnical parameters, gully head cut retreat, and cracks. Gully head stability was analyzed using the Bank Stability and Toe Erosion Model (BSTEM). The average gully head retreat rate (6.75 m $y^{-1}$) in the Vertisol was approximately four times bigger than the Nitisol. The gully bank stability analysis using the BSTEM model showed both a rise in GWT depth and soil crack played a role in reducing gully bank stabilities. Despite reducing the factor of safety (FS) values by the increased water table height, the gully head in both soils remained stable without soil cracks. In contrast, soil cracks in the Vertisol caused an 85% decrease in the FS, which led to an unstable gully head. Hence, the higher gully head retreat rate in the Vertisol is mainly attributed to crack occurrence. In the Nitisol, soil pipes evacuated a significant amount of water from the gully bank to the gully channel. As a result, soil pipes prevented a sizeable saturated zone in the unconsolidated soil and contributed to the smaller gully head erosion rate. This study has given an insight into how variation in soil type (i.e., Nitisol and Vertisol) could lead to variabilities in head cut retreat rates. Management of gully rehabilitation should be tailored to these variations, even though Nitisol and Vertisol's gullies were located within the same landscape and land use.

## 3.1 Introduction

The formation of valley bottom gullies (VBGs) is a primary source of sediment in catchments (Amare et al., 2019; Valentin et al., 2005), causing a myriad of environmental (Nyssen et al., 2002) and socioeconomic problems (Moges & Holden, 2008). Valley bottom gullies often form in periodically saturated lands after the upslope change takes place that reduces evaporation and increases the amount of water transported downhill (Amare et al., 2019), thereby connecting the gullies to their surrounding landscape (Casalí et al., 2009; Poesen et al., 2003; Rowntree, 2013). As a result, the risk of downstream flooding during the rainy season increases (Dessie et al., 2015; Nyssen et al., 2006; Patton & Schumm, 1975; Tebebu et al., 2010), and upland soil conservation efforts are adversely impacted (Zegeye et al., 2018). Moreover, gullies cause enormous environmental problems: lowered water tables (Frankl et al., 2011; Tebebu et al., 2010; Tilahun et al., 2014), soils desiccating, and crop yields are reduced by the land taken out of production (Frankl et al., 2014).

Most gullies grow through head cut (HC) expansions and are regulated by region-specific morphological, hydrological, and climatic factors. An increase in rainfall amount (Nan et al., 2014; Valentin et al., 2005) and flow duration (DeLong et al., 2014), which leads to wetting around the HC (Rengers & Tucker, 2015), facilitates gully head erosion through both plunge-pool erosion and gully mass wasting processes. Karimov et al. (2014) reported gully development does not occur during most rainfall events unless the soil is saturated. Yet, the increase in the surface runoff contributing area also leads to an increase in the erosive power of surface runoff (Schnabel & Gomez 1993), which leads to gully head erosion (Marzolff & Ries, 2007; Rengers & Tucker, 2014b; Samani et al., 2010; Vandekerckhove et al., 2001a; Vanmaercke et al., 2016; Wijdenes & Bryan, 1994). Gully head erosion can also occur in soils with low soil moisture content when bulk density and cementing agents are small (Bennett et al., 2000; Xia et al., 2018). In addition, gully head failure is also likely for soils with low moisture content and soils with high unsaturated strength when gully walls are under-cut and tension cracks are present (Collison, 2001b). Gully HC height is also an essential factor for gully head erosion (Vandekerckhove et al., 2001b).

Significant HC retreats have been observed in areas with large HC heights or gentle slopes (Flores-Cervantes et al., 2006). An increase in the HC retreat rates with increasing HC height (Zhang et al., 2018) is attributed to increased potential energy, shear stress, and plunge pools (Zhang et al., 2016). As a result, gullies with smaller HC heights are more stable than gullies with larger HC heights (Zegeye et al., 2016b). Gully head retreat on terrain with gentler slopes is more pronounced due to concentrated surface runoff (Mukai, 2016b) and elevated groundwater table (GWT) (Ayele et al., 2018). Both factors contributed to soil detachment and increased soil pore water pressures that promote gully mass wasting. Soil piping and cracking also contribute to gully development (Wijdenes & Bryan, 1991). For example, Frankl et al. (2012) found that larger gully head retreats were observed for a Vertisol with evidence of soil pipe collapse. The formation of cracks hastened gully head erosion (Robinson et al., 2000; Whitlow, 1994) through wet and dry mass wasting processes (DeLong et al., 2014).

Valley bottom gullies are a primary sediment source in catchments (Amare et al., 2019), with soil losses several times higher than other hillslope erosion forms (Zegeye et al., 2018). Huge investments are being made to restore degraded lands, including valley bottom gullies, across the Ethiopian highlands, but their benefits have been inconclusive (Tebebu et al., 2015). Upland soil conservation efforts are negated by sediment generated from valley bottom gullies (Zegeye et al., 2018). Construction of a check dam in gullies formed on valley bottom Vertisol did not successfully halt the problem (Nyssen et al., 2004c). Unsuccessful gully reclamation measure was associated with insufficient knowledge about the dominant hydrological processes controlling local gully erosion (Dagnew et al., 2015). Other reasons for the lack of success of the conservation measures include the use of imported methods and blanket approaches (Bekele-Tesemma, 1997; Reij, 1991) and a lack of general understanding of the problem (Mitiku et al., 2006).

Therefore, the presented research objective is to develop knowledge of the hydrological processes controlling gully head erosion in the sub-humid, northern Ethiopian highlands. The study was carried out in the Minzir catchment in the upper Blue Nile Basin. Two valley bottom gullies that developed in Nitisols and Vertisols were studied. So far, there have been no attempts to investigate the effect of soil type on gully erosion. Therefore, our specific aim was to 1) understand the impact of hydrological processes that lead to gully head erosion in lowland valley bottoms, 2) analyze gully head stability using Bank Stability and Toe Erosion Model (BSTEM). BSTEM is one of the most robust, extensively studied, and widely used process-based models for predicting streambank erosion and failure (Klavon et al., 2017).

## 3.2 Material and Methods

### *3.2.1 Study site description*

The study was conducted in the Minzir catchment (18 km$^2$), a sub-catchment of the Koga catchment that drains into Lake Tana (Figure 3.1). The Minzir catchment is located in the cool, semi-humid northwestern highlands of Ethiopia and receives an average annual rainfall of 1480 mm. Due to population pressure, land use has changed significantly from 1950 to 2010. The land covered by woody vegetation has decreased from 5576 ha to 3012 ha (Yeshaneh et al., 2013), and livestock density has increased. The valley bottoms land in the Koga catchment, with a slope of less than 5%, are the most sensitive to gully formation (Mhiret et al., 2018; Rijkee et al., 2015) and account for about 75% of the erosion hotspots (Assefa et al., 2015).

The dominant soil types in the valley bottom of Minzir catchment are Vertisol (36%), Nitisol (32%), Alisol (9.4%), Luvisol (8%), Ferralsol (5.5%), and Leptosol (5.5%). The valley bottom's remaining (~4%) consists of Fluvisol, Cambisol, and Regosols. The soil texture consists of clay

(84%), clay loam (6%), and loam (3%). The geology is composed of quaternary basalts (Williams, 2016).

We focused our investigation on gullies formed in Nitisols and Vertisols since they are the dominant soil types within the Minzir catchment. The gullies investigated are around 1.5 km apart dissecting communal grazing land. As a brief comparison of the two soil types: Nitisols are well-drained soils with high porosity (between 50 and 60%), well-developed soil aggregates, and strongly weathered soils (Bridges, 1998; Driessen et al., 2001), while Vertisols are characterized by high bulk density (1.5-1.8 Mg $m^{-3}$), high plasticity, and discontinuous and non-permanent soil pores (Ahmad, 1983; Bouma & Loveday, 1988; Bridges, 1998; Driessen et al., 2001). Good soil structural stability found in Nitisols is due to higher free iron-oxides from kaolinite and halloysite, the dominant clay minerals in this soil (Chen et al., 2018; Dorel et al., 2000; Van Zijl et al., 2014). Vertisols have smectites or montmorillonites characterized by low electrolyte concentration and a low level of sodicity (up to 5% ESP) that can impair soil hydraulic conductivity and internal drainage (Balpande et al., 1996). These facilitate soil dispersion and pipe formation (Crouch et al., 1986), promoting gully head erosion (Nachtergaele, 2001).

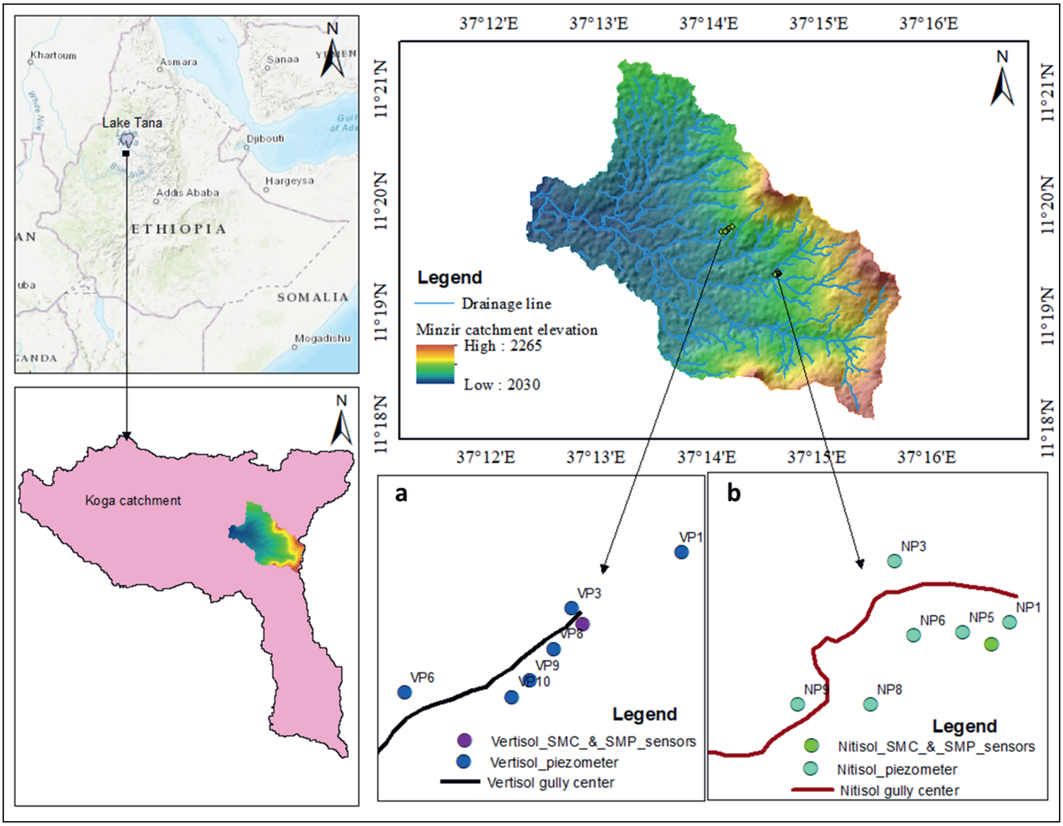


***Figure 3.1*** *Location of the Minzir catchment in Ethiopia (left panels), topography (upper right panel) and measurement locations for groundwater, soil moisture content (SMC) and soil water potential (SWP), and gully-centreline for Nitisol (lower middle panel (a)) and Vertisol study sites (lower right panel (b)).*

### *3.2.2 Field observation and measurements*

Field observations and data collection were carried out during the rainy seasons of 2017 and 2018. Two gullies found in the Minzir valley bottomland, one located in a Nitisol and the other in a Vertisol, were studied (Figure 3.2). The gullies' morphological characteristics and data on the hydrology of each gully's surrounding area were obtained. Daily gully head cut retreats were measured by installing erosion pins with a known distance from the gully edges. A seven-meter-long measuring tape measured the distance from a gully edge to the pins. Besides, the total gully head retreat rate from 2011 to 2019 was obtained from Google Earth (Figure 3.2). A sixteen-meter-long measuring rope was used to set perpendicular and parallel transects to the head cut. Crack depth, width, and length were then monitored using a measuring tape and thin metal rope. Given the orientation and location of cracks, three transects were aligned perpendicular to the head cut, and one transect was aligned parallel to the head cut.

Table 3.1 presents the characteristics of the two gullies. The Nitisol gully is eroding down to the bedrock to 6.2 m depth, whereas Vertisol's incision did not reach the bedrock and had a shallower depth (3 m). In the Nitisol, at the bottom 1.5 m depth of the gully bank, percolation from the rain hits a dense layer and then flows laterally, eroding the soil and forming the soil pipes.

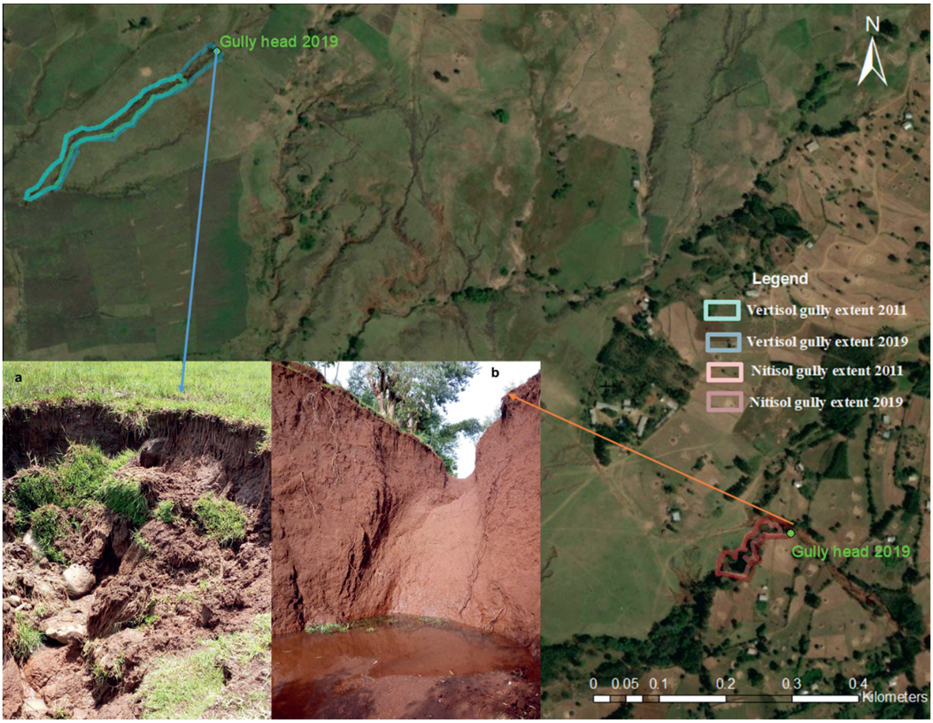


***Figure 3.2*** *Vertisol (a) and Nitisol (b) gully heads and their extents in 2011 and 2019.*

***Table 3.1*** *Descriptions of the studied Nitisols and Vertisol gullies*

| **Parameters** | **Vertisol gully** | **Nitisol gully** |
|---|---|---|
| Drainage area (ha) | 17 | 34 |
| Presence of cracks | A network of cracks | Very few cracks |
| Gully network | Gullies have a large width-to-depth ratio | Gullies have a small width-to-depth ratio |
| Occurrence of pipes | Evidence of soil pipes in the gully surrounding (Figure 7.1d, Appendix) | Evidence of soil pipes in the gully bank that discharges water to the channel (Figure 7.2, Appendix) |
| Average angle of internal friction (m $m^{-1}$) | 0.4 | 0.48 |
| Soil depth (m) | >11 | ~6 |
| Average gully depth (m) | 2.8 | 5.7 (eroded down to the bedrock) |
| Average gully width (m) | 13.8 | 13.8 |
| Soil surface slope above the head-cut (m $m^{-1}$) | 0.07 | 0.05 |

Besides crack and head-cut retreat measurements, data collected for this study include: meteorological (rainfall and flow depths), soil hydrology (groundwater table, soil moisture content, soil water potential, and infiltration rate), and soil physics (cohesion and friction angle). Each measurement is described further below:

*Rainfall and flow depth*

We used manual and automatic rain gauges (tipping bucket) to measure daily rainfall depth and rainfall intensities at a 5-minute interval. Daily rainfall was measured for the 2017 and 2018 rainy seasons, whereas rainfall intensity was measured only for 2018. Flow depths were measured using a staff gauge from a rectangular weir constructed in both gullies.

*Groundwater table depth*

Groundwater depth was measured by installing piezometers to a depth of about 4 m. 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 45 cm and screened with fabric to avoid silt and sand intrusion. Both ends of the piezometers were capped. We measured groundwater table depth daily using measuring tape. The larger number of piezometers in the Vertisol was due to the longer gully-channel length for this soil. Another 28 piezometers were installed farther away from the gully reaches to see groundwater flow direction with respect to gully locations. The 28 piezometers were installed following four transect lines from uphill to the downslope area (where the two experimental gullies were located). The spacing within transects ranged between 50 and 300 meters. Some piezometers were installed closer to each other when the elevation changed abruptly. Data collection was started in mid-July as the soil was too dry to allow manual installation before that time.

*Soil moisture content (SMC) and soil water potential (SWP)*

Soil moisture content and soil water potential were monitored using GS1 Soil moisture and MPS-6 Water Potential sensors, and the data were stored in EM50 data loggers manufactured by Decagon.

The data loggers were installed approximately 3 m away from the gully bank to avoid the impact of a retreating head cut. Each of the two EM-50 data loggers was connected to four moisture content sensors and one water potential sensor. The four soil moisture sensors were installed at 20, 45, 75, and 130 cm depth from the soil surface, whereas the water potential sensors were installed at 30 cm depth from the soil surface. Instruments in the Nitisol area were damaged in 2018; thus, analysis of these data is limited to the 2017 monitoring period.

Both moisture content and water potential were sampled at 5-minute intervals. For analysis purposes, daily averages were calculated as variations during the day were minimal. Soil samples (four samples per soil type) were collected using a soil core cutter from different depths across the soil profile to determine the error in soil moisture readings. The samples were shipped to the lab and oven-dried to calculate the actual moisture content and the bulk densities. Then the readings of the instruments were calibrated with the observed values.

The soil characteristic curves were obtained by plotting the calibrated daily moisture contents against the daily suction measurements with potentiometers. Saturated moisture contents were obtained by using the bulk densities, assuming that the specific weight of the soil was 2.65 Mg $m^{-3}$.

*Infiltration rate*

We measured the steady-state infiltration rates in October 2017 at 20 locations near both the Nitisol and Vertisol gully using a double-ring infiltrometer manufactured by Eijkelkamp. The smaller ring had a height of 27.5 and a diameter of 30 cm, while the larger ring was 25 high and 57 cm wide. The measurements were conducted away from visible fractures and cracks. The water depths were measured with a float and measuring rod.

*Shear strength parameters*

The friction angle and soil cohesion were determined by collecting undisturbed and unsaturated soil samples, four for Nitisol and three for Vertisol. A 50 cm by 30 cm soil cutter was used to sample undisturbed soil from the field. Samples were then transported to Bahir Dar Soil and Construction Material Testing Laboratory for analysis. In the laboratory, a shear strength test was conducted using the direct shear box method (Krishna, 2002) by applying 22, 43, and 87 kPa normal stresses on a 10 cm by 10 cm shear box.

### *3.2.3 Data Analysis*

*Catchment hydrology*

The groundwater table surface was derived in the ArcGIS setting using the inverse distance weighting (IDW) interpolation technique for the date (15 August 2018) when the groundwater was stable and peak or the highest for most piezometers. The groundwater contour was then generated from the interpolated groundwater surface.

*Gully head stability*

Gully head stability was analyzed using the Bank Stability and Toe Erosion Model (BSTEM). BSTEM is a deterministic spreadsheet tool that has been successfully used to simulate bank stability conditions and the design of streambank stabilization (Simon et al., 2011). BSTEM consists of three sub-models: bank toe erosion, bank stability, and root-reinforcement. The bank toe erosion model simulates bank toe and surface hydraulic erosion. The bank stability model predicts geotechnical mass failure, whereas the root-Reinforcement sub-model predicts vegetation's reinforcing effect (Simon et al., 2011). This study employed the bank stability sub-model to examine the Nitisol and Vertisol's gully head stability. Bank stability in BSTEM is assessed by computing the factor of safety (FS), defined as the ratio of driving forces to resisting forces for a given failure plane (Klavon et al., 2017). If the FS value is greater than 1.3, the bank is considered stable, whereas when the FS value is less than 1, the bank is unstable. FS value between 1 and 1.3 is conditionally stable, indicating uncertainties and variabilities in the soil property and failure geometries (Langendoen et al., 2014). The bank stability sub-model combines three limited equilibrium methods: horizontal layers (Simon et al., 2000), vertical slices for failure with a tension crack, and cantilever failures (Langendoen & Simon, 2008). The input variables for BSTEM are soil shear strength properties (Table 3.2), gully head cut height, groundwater level, bank slope, flow depth, and soil crack depth (Table 3.3).

***Table 3.2*** *Soil shear strength properties near the gully head-cut*

| Soil type | Gully bank layers | Cohesion (kPa) | Friction angle (°) |
|---|---|---|---|
| Vertisol | Layer 1 | 7.9 | 23.2 |
| | Layer 2 | 6.6 | 23.3 |
| | Layer 3 | 10.3 | 19.4 |
| Nitisol | Layer 1 | 9.2 | 30.4 |
| | Layer 2 | 5.3 | 25.7 |
| | Layer 3 | 9.2 | 20.1 |
| | Layer 4 | 17.9 | 25.9 |

The Vertisol gully head's stability, using the BSTEM model, was tested in the presence and absence of soil cracks by varying the groundwater depths (3, 2, 1.5, 1, 0.5, and 0.1 m). The effect of crack on the Vertisol gully head stability was evaluated using the measured average crack depth (0.92 m) near the gully head cut. The Nitisol gully head stability was tested by varying GWT depths (4, 3, 2, 1.5, 1, and 0.5 m) in the absence of crack, as cracks were not observed in Nitisols.

***Table 3.3*** *Bank geometry, channel, and flow parameters*

| Soil type | Head cut height (m) | Bank angle (°) | Bank toe length (m) | Bank toe angle (°) | Channel length (m) | Channel slope (m $m^{-1}$) | Elevation of flow | Flow duration (hrs) |
|---|---|---|---|---|---|---|---|---|
| Vertisol | 1 | 85 | 0.3 | 45 | 315 | 0.09 | 0.15 | 24 |
| Nitisol | 2.8 | 80 | 0.5 | 55 | 200 | 0.11 | 0.25 | 24 |

## 3.3 Results

This section is organized into two parts: Part 3.3.1 presents basic observations used for further analysis and part 3.3.2 analyses gully head stability.

### *3.3.1 Phenomenology*

#### *3.3.1.1 Gully head retreat and soil surface cracks*

*Gully head retreat*

The total gully head retreat from 2011 to 2019 was 14 m and 54 m for Nitisol and Vertisol gullies (Figure 3.2). The head retreat for the Vertisol gully during the measurement period was 6 m in 2017 and 4 m in 2018, compared to 0.3 m in 2017 and 1.35 m in 2018 for the Nitisol gully. The 0.3 m gully head retreat in Nitisol in 2017 resulted from gully head failure triggered by a previous undercutting by plunge pool scour. Thus the gully head retreat rate in Vertisol is approximately four times bigger than in Nitisol. The observed head cut retreat rate for the Vertisol was of the same order as the median retreat rate of 3.6 m $y^{-1}$ observed for a similar sub-humid Ethiopian climate (Addisie et al., 2018).

This shows that despite the shallow gully head and smaller drainage area for the gully in the Vertisol (17 halves 34 ha), gully head and sidewall collapse were more prominent for the Vertisol than for Nitisol.

*Soil surface cracks and pipes*

Although both Vertisol and Nitisol gullies were eroding in grazing lands, tension cracks and swelling and shrinkage cracks were only observed in the Vertisol catchment (Figure 7.1, Appendix). Soil pipes were present in both soils; however, their location with respect to the gully was different. In Vertisol, they were located in areas surrounding the gully channel, whereas, in Nitisol, they are located along the gully bottom cross-section.

In the Vertisol, soil pipes were frequently observed in the center of the soil cracks, indicating the pipes were eroding the soil. The pipe's diameter was up to 90 cm. Their depths ranged from 0.2 to 1 m and were about 0.4 m deep on average. More cracks were oriented in the same direction as the channel below the head cut than perpendicular (Table 3.4). The crack shape was mainly straight and discontinuous. Most of the swelling and shrinkage cracks were closed after the rainfall began, while the soil pipes and larger cracks became smaller but stayed open throughout the rain phase. As a result, water flowed through the opening during most of the rain phase.

In the Nitisol, soil pipes were located until about 1.5 m depth above the gully bottom. From the end of July to the end of November, these pipes drained a significant volume of water from the gully bank to the gully channel. The estimated discharge through the pipes was approximately 1.1 l $s^{-1}$ per 30 m length of the gully. However, there was no evidence of pipes on the Nitisol gully's catchment.

***Table 3.4** Crack depth, width, distance from the head cut, the distance between cracks, and crack lengths measured for three gully heads in the Vertisol area*

| Crack orientation with respect to the HC | Crack parameter | Mean | Max. | Min. | Standard deviation |
|---|---|---|---|---|---|
| Parallel (number of cracks captured is 52) | Depth (m) | 0.92 | 1.86 | 0.095 | 0.33 |
| | Width (m) | 0.14 | 0.53 | 0.03 | 0.06 |
| | Distance between cracks (m) | 2.06 | 5.1 | 0.048 | 1 |
| | Crack length (m) | 4.63 | 96.02 | 0.34 | 16.2 |
| Perpendicular (number of cracks captured is 9) | Depth (m) | 0.68 | 0.85 | 0.5 | 0.1 |
| | Width (m) | 0.15 | 0.17 | 0.13 | 0.02 |
| | Distance between cracks (m) | 3.7 | 10.8 | 1.72 | 3.16 |
| | Crack length (m) | 6.34 | 40 | 1.03 | 12.7 |

#### *3.3.1.2 Soil hydrological characteristics*

*Perched groundwater*

Figure 3.3 plots the piezometer's water levels with respect to the height above the gully bottom (left) and the soil surface (right side) in the Nitisol and Vertisol. Groundwater depth measured in 2017 and 2018 was shallower in the Vertisol (1.85 m) than in the Nitisol (2.75 m). The water table in the 2018 rain phase in the Nitisol gradually rose from mid-July to mid-August and progressively decreased (Figure 3.3a). The GWT reading in NP3 was the shallowest (Figure 3.3a) and, at the same time, the closest to the gully bed (Figure 3.3a). That is because more water flows to this piezometer as it was installed at a lower elevation near the gully bed. In contrast, piezometers in Vertisol didn't show uniform patterns except that they all showed a gradual decline starting from mid-September towards the end of the rainy phase (Figure 3.3b).

Piezometer VP1 was located about 70 m upstream of the head cut with no soil pipes and had shown slight short-term fluctuations. Piezometer VP3 installed at the head cut had the shallowest groundwater reading. VP8 and VP10 installed on the gully's left side, where soil cracks and pipe holes were more pronounced, showed slightly bigger short-term GWT fluctuations than VP6 installed on the right side with no evidence of soil pipe. Although VP9 was located at a lower elevation inside the gully bank, the groundwater in this piezometer was the deepest.

Figure 3.3a and Figure 3.3b show that, in most rainy phases, the groundwater table depths were above the gully floor depths (i.e., 5.7 for Nitsol and 2.8 for Vertisol). Furthermore, for NP1 and VP3 installed at Nitisol and Vertisol gully heads, the GWT was above the gully floor for 54% and 81% of the time. Studies reported that the water table above the gully bottom usually indicates gully instability (Bradford et al., 1973a; Tebebu et al., 2010). In section 3.2 below, we will explore the impact of the measured GWT depths on gully head stabilities (factor of safety) using the BSTEM model.

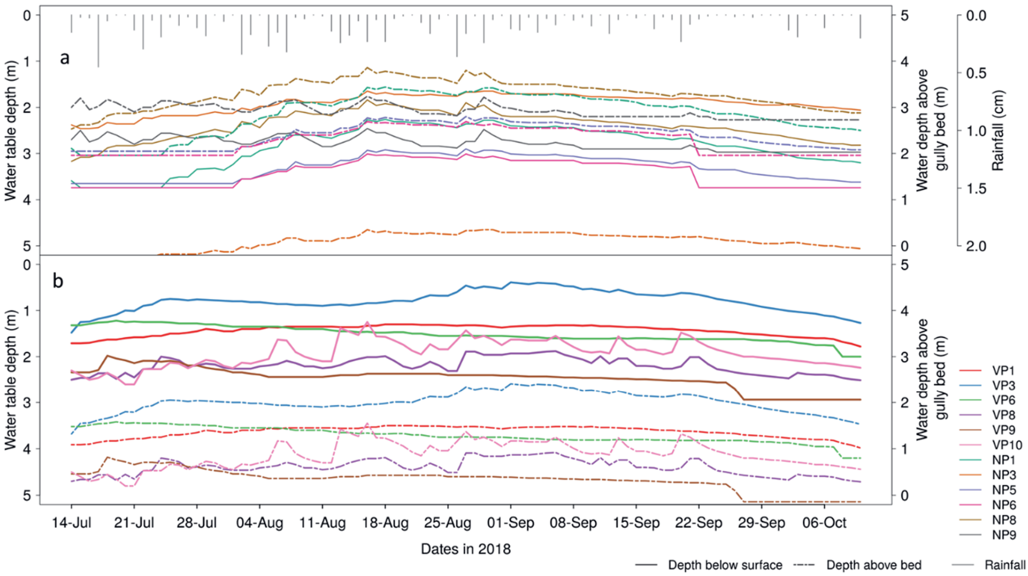


***Figure 3.3*** *Water table depth with respect to the gully bottom and the soil surface, Nitisol (a) and Vertisol (b). NP and VP represent piezometer ID installed close to the Nitisol and Vertisol gullies. The locations of the piezometers are given in* ***Figure 3.1****.*

The perched groundwater contour generated from 50 piezometer readings is presented in Figure 3.4. The groundwater flow direction is towards the location of the Nitisol and Vertisol gullies. This presumably explains the elevated groundwater above the gully beds of the two soils (Figure 3.3).

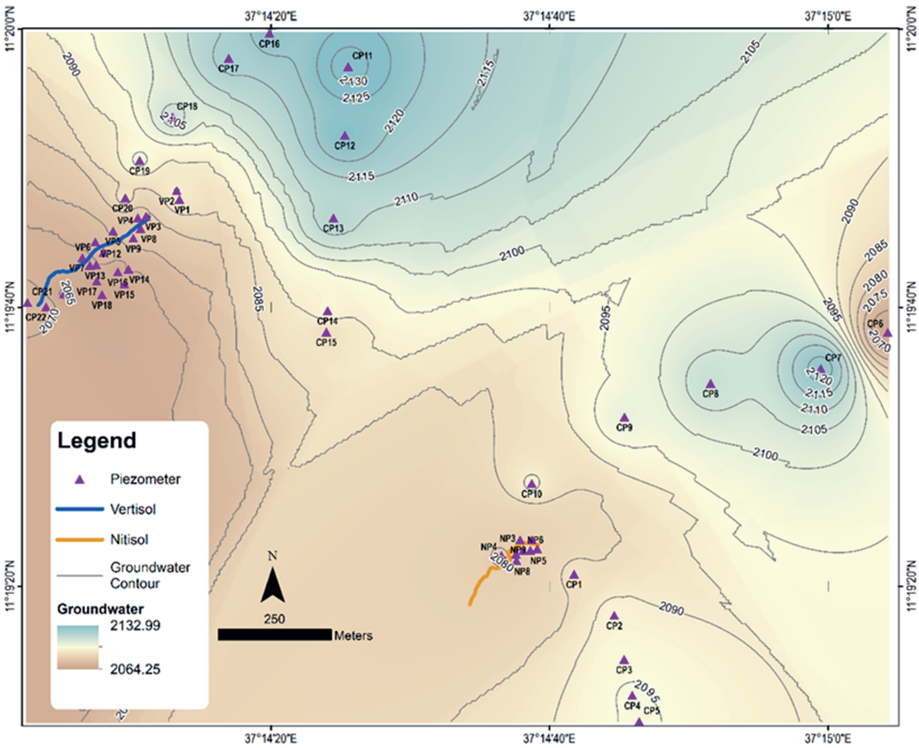


***Figure 3.4*** *Interpolated groundwater level (in m a.s.l.) in the Minzir catchment.*

*Soil moisture content and soil water potential*

Figure 3.5 presents the 2017 rainy-season moisture content at depths of 20, 45, 75, and 130 cm from the soil surface and water potential measured at a depth of 30 cm. The sensors are located near the piezometer VP3 in the Vertisol and NP1 in the Nitisol (Figure 3.1).

The water table depth in VP3 is around 1 m below the soil surface. The tensiometer's matric potential at location VP3 is around -7 Kpa, which is equivalent to -70 cm suction head. With a suction head equal to the distance to the water table where the suction head is 0 cm by definition, the water in the unsaturated zone is thus in static equilibrium (i.e., hydraulic potential constant). This means the moisture content above the groundwater can be found from the soil characteristic curve by equating the height above the groundwater with the soil characteristic curve's matric potential. Therefore, for the Vertisol, Figure 3.6 presents the soil moisture characteristics curve obtained from the moisture sensors and the water table.

For the Nitisol, the groundwater in NP1 starts at 3.8 m and rises to a 2 m depth, and falls again. The matric potential in this soil is independent of the groundwater table height. Hence, the matric potential is limited by the soil's conductivity to transport the water down from the surface to the groundwater table. For the Nitisol, Figure 3.6 presents the soil moisture characteristics curve obtained from the moisture sensors and the bulk density measurement (i.e., at soil saturation). Figure 3.6 clearly indicates that the soil is unsaturated at 30 cm depth (20% less than saturation).

As shown in Figure 3.5a, the Nitisol SWP showed a sharp decline towards a more negative water potential at the end of the rain period. In contrast, the Vertisol water potential remains stable despite significant decreases in rainfall at the end of the rain period. For Vertisol, the ranges in SWP (-6.95 to -7.85 kPa) were smaller than those for Nitisol, with SWP ranging from -7.65 to -10.8 kPa.

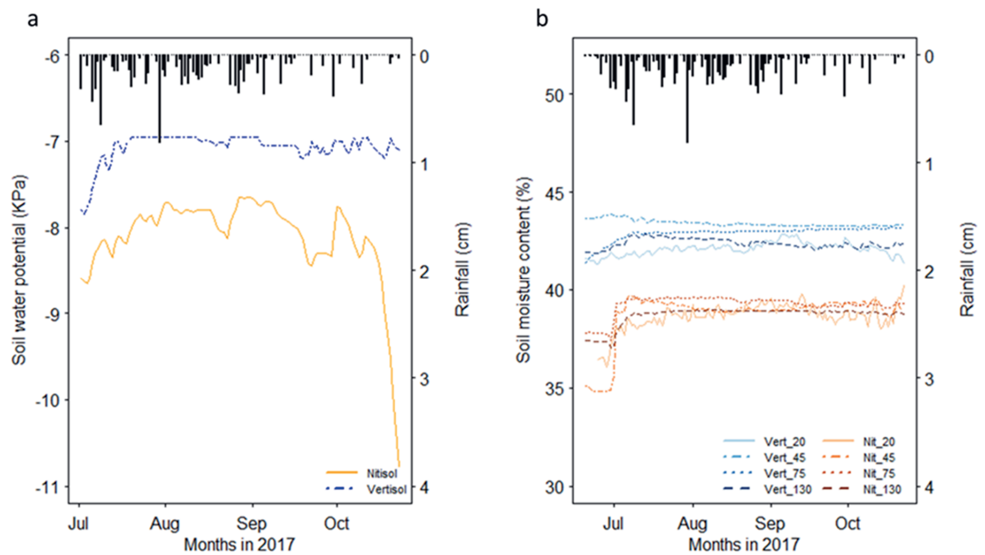


***Figure 3.5*** *(a) Comparison of Nitisol and Vertisol soil water potential and (b) comparison of Nitisol and Vertisol soil moisture content at various depths.*

In general, for all depths, the moisture content for the Vertisol is greater than for the Nitisol (Figure 3.5b). The minimum, maximum, and standard deviation soil moisture values for Nitisol are 35%, 40%, and 1%, respectively, whereas Vertisol values are 41%, 44%, and 0.5%, respectively. Most variation in SMC with rainfall for the two soils occurred during the first two weeks when the soil was wetting up. After that, the variations were similar.

Moisture sensors installed at a depth of 20 cm quickly reacted to rainfall events and showed a rapid decline when there was no rain (Figure 3.5b). For the Vertisol, moisture content decreased with increasing depth below depths of ~40 cm. The SMC at 45 and 75 cm depths was fairly constant over time, whereas it steadily decreased at 130 cm. For the Nitisol, the soil moisture below the depth of ~40 cm was fairly stable over the rainy season after the soil had wetted up, with the moisture content at a depth of 75 cm, on average, slightly larger than at depths of 45 and 130 cm. The temporal pattern in SMC below depths of 40 cm suggests the deeper soils are hardly affected by rapidly infiltrating water or fluctuating shallow groundwater.

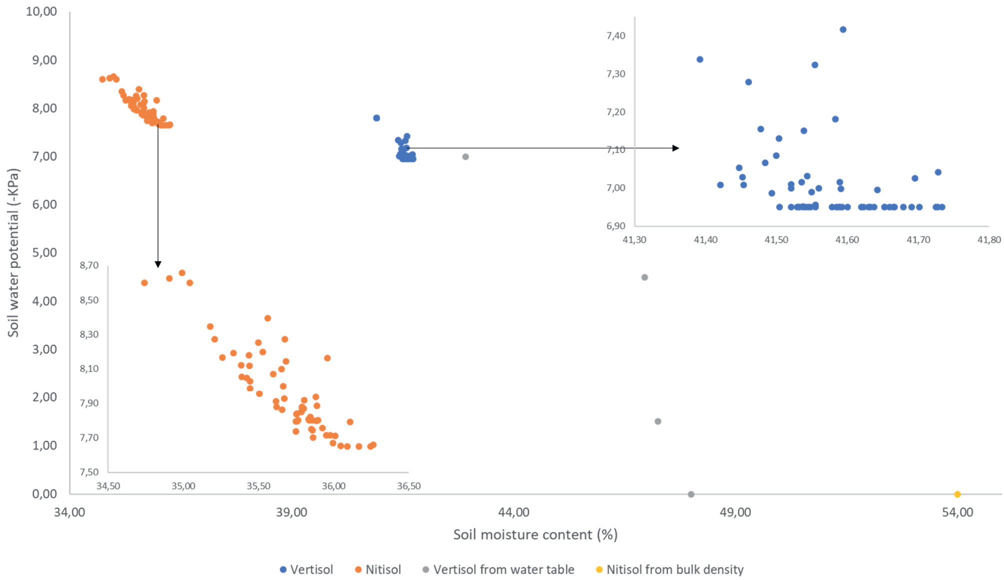


***Figure 3.6*** *Soil water retention curves using sensors observed values and calculated values from the groundwater for Vertisol and bulk density for Nitisol.*

Table 3.5 presents the volumetric saturated soil moisture content obtained from the measured bulk densities. For the Vertisol, it is between 45 and 51%, and for the Nitisol, between 50 and 60%. Thus, the soil moisture contents in the Vertisol (Figure 3.5b) are close to saturation. At 130 cm depth in the Vertisol, the soil is saturated, but the sensors' moisture content indicates that it is not, which might be because sensors at this depth may not provide an accurate measurement. The other moisture contents decrease with height, which is what one would expect because there is static equilibrium.

***Table 3.5*** *Volumetric saturated soil moisture content obtained from bulk density measurement*

| Soil depth below the soil surface (m) | Vertisol | | Nitisol | |
|---|---|---|---|---|
| | Bulk density (Mg $m^{-3}$) | Saturated moisture content (%) | Bulk density (Mg $m^{-3}$) | Saturated moisture content (%) |
| 0.2 | 1.28 | 50 | 1.25 | 51 |
| 0.45 | 1.44 | 46 | 1.17 | 56 |
| 0.75 | 1.47 | 45 | 1.07 | 60 |
| 1.3 | 1.3 | 51 | 1.35 | 49 |

*Infiltration capacity*

The average infiltration capacity for Nitisol (88 mm $hr^{-1}$) is approximately twice as large as for Vertisol (43 mm $hr^{-1}$). These values are comparable with the combined Nitisol and Vertisol average infiltration rate of 70 mm $hr^{-1}$ in a similar sub-humid Ethiopian catchment (Tilahun et al., 2015). The hourly rainfall intensities were calculated for 510 rainfall events. Rainfall intensities were mostly less than the median and minimum infiltration rate for both soil types (Figure 3.7). The hourly rainfall intensities never exceeded the 67 mm $hr^{-1}$ median infiltration rate for Nitisol. The minimum infiltration rate (17 mm $hr^{-1}$) for Nitisol was only exceeded 2% of the time. For Vertisol, the hourly rainfall intensity exceeded the median (20.5 mm $hr^{-1}$) and minimum (4 mm $hr^{-1}$) infiltration rates 1% and 15% of the time, respectively.

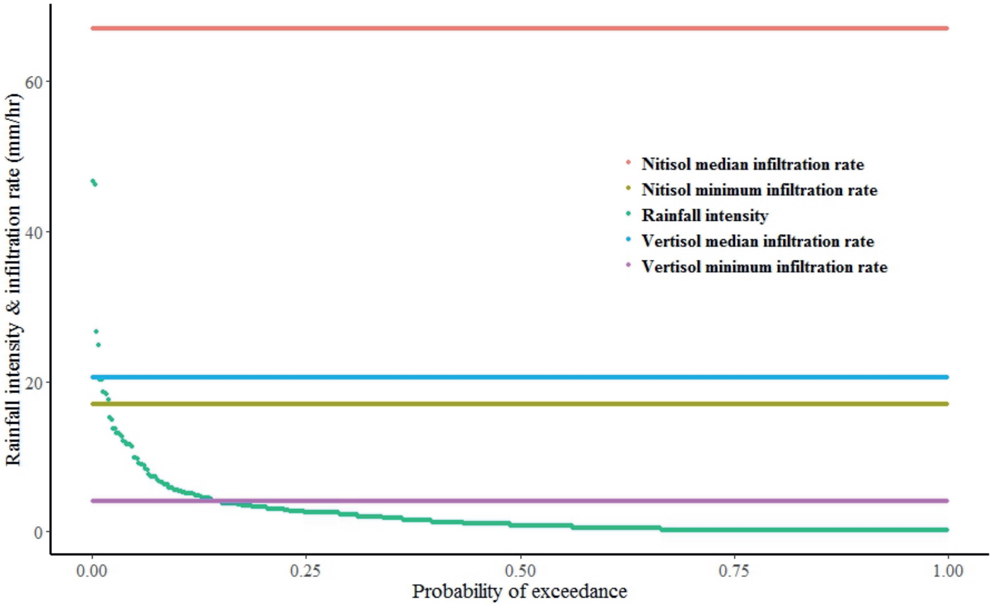


***Figure 3.7** Comparison between exceedance probability of hourly rainfall intensity and median and minimum infiltration rates.*

### *3.3.2 Gully bank stability*

Table 3.6 presents the FS values obtained for Nitisol and Vertisol gully heads using the BSTEM model. To run the BSTEM model, we had used input parameters given in Table 3.2 and Table 3.3. There is no considerable difference in the input parameter for both soils except for the larger head cut height in the Nitisol and the soil crack in the Vertisol. Without tension crack for all groundwater depths, Vertisol gully head was much more stable (FS between 3.9 and 8.9) than the Nitisol gully head (FS between 2.1 and 4.3). In the presence of tension crack, the Vertisol gully head was unstable (FS < 1.3) during all the rainy phases except when the GWT was 3 m deep. However, the groundwater near the Vertisol gully head was shallower than 3 m for the entire rainy phase. Despite the larger gully head height in the Nitisol, the gully head remained stable (FS > 1.3) at all groundwater depths. However, it is essential to note that an increase in groundwater from the deep layer to the soil surface in the Nitisol reduced the FS values, but not to the degree that the gully bank is unstable.

***Table 3.6*** *The factor of safety values at varying water table depth for both soils and in the presence of soil crack for Vertisols*

| Vertisol | | | | | Nitisol | | |
|---|---|---|---|---|---|---|---|
| GWT | FS with 0.92 m deep crack | Stability condition | FS no crack | Stability condition | GWT | FS | Stability condition |
| 3 | 1.32 | Stable | 8.93 | Stable | 4 | 4.29 | Stable |
| 2 | 1.04 | Conditionally stable | 6.93 | Stable | 3 | 3.52 | Stable |
| 1.5 | 0.9 | unstable | 6.01 | Stable | 2 | 2.84 | Stable |
| 1 | 0.77 | unstable | 5.15 | Stable | 1.5 | 2.51 | Stable |
| 0.5 | 0.59 | unstable | 4.37 | Stable | 1 | 2.28 | Stable |
| 0.1 | 0.54 | unstable | 3.9 | Stable | 0.5 | 2.09 | Stable |

### 3.4 Discussion

The gully head retreat rate in Vertisol was approximately four times larger than in Nitisol. The following sections will discuss the underlying soil hydrological and morphological differences that caused variations in the HC retreat rate in the two soil types (Figure 3.8).

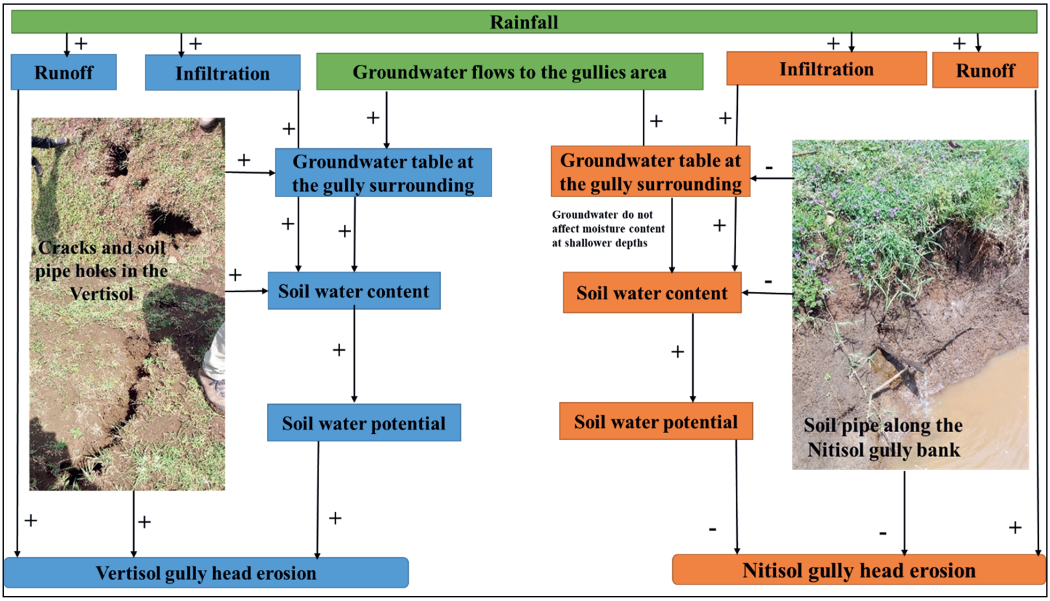


***Figure 3.8*** *Process of gully erosion whereby soil hydrological characteristics control gully head erosion. The + and – sign shows when one factor causes the other factor to increase and decrease in quantity, respectively. The orange and blue boxes demonstrate soil hydrological characteristics for Nitisol and Vertisol, respectively.*

### *3.4.1 Impact of morphological features on the rate of head cut retreat: role of crack and soil pipes*

In the Nitisol, soil pipes' impact was through evacuating excess water from the gully bank to the gully channel. Evacuation of water through the soil pipes explains the deeper groundwater table observed for the Nitisol. This also explains why we had smaller SMC and a more negative SWP in Nitisol than Vertisol.

Although studies have associated the occurrence of soil pipes with unstable gully banks (Chaplot, 2013; Collison, 2001a; Deng et al., 2015; Wilson, 2009), we found that for the Nitisol gully, the drainage provided by soil pipes prevented gully wall collapse. Furthermore, the water leaving the pipes was sediment-free, indicating no internal erosion of the soil pipe that could destabilize the gully walls. Soil pipes, therefore, prevented the occurrence of a sizeable saturated zone in the unconsolidated soil and contributed to the smaller gully head erosion rate in the Nitisol.

In the Vertisol, soil pipes and cracks impact was the opposite of what was observed for the Nitisol (i.e., through promoting water recharge into the soil). At the beginning of the rainy period, cracks occupied 4% of the soil volume, and then a 1 mm rainfall event would lead to apparent groundwater level variations of 25 mm. This agrees with Drumm et al. (1997) and

Collison (2001b), who reported that cracks facilitate preferential water flow and increase flow velocity through the gully wall by order of magnitude. Besides, more cracks were oriented in the same direction as the channel below the head cut than perpendicular (Table 3.4). The large number of cracks parallel to the HC may have facilitated gully expansion as the concentrated flow enters the crack to weaken the soil against erosion, thereby hasten the frequency of gully bank collapse. Moreover, the crack's discontinuous nature may promote pressure build-up that can cause gully slumping. Studies conducted in a similar region on Vertisol also reported cracks would cause both increase in positive pore water pressure (Tebebu et al., 2010) and an enhanced groundwater level (Addisie et al., 2017b) that eventually promote gully bank collapses. Thus, it is possible that soil cracks and pipes weakened the Vertisol to fluvial erosion and mass wasting through increased preferential water flow and elevated groundwater table.

### *3.4.2 Role of soil hydrology in head cut retreat*

The average SMC in Vertisol is 3.3% higher than the Nitisol. Yang et al. (2011) reported that capillary rise is enhanced when GWT is shallower than 2.5 m depth. The relatively smaller SMC in Nitisol is related to the deep GWT minimizing the impact of capillary rise. Additionally, the infiltration capacity of Nitisol is larger, allowing more water to drain from the surface layers to deeper layers. At the end of the rain season, the SWP for Nitisol responded relatively quickly and attained a larger negative value in response to consecutive dry days (Figure 3.5a). In contrast, Vertisol SWP responds quite slowly, suggesting that shallow groundwater maintained higher SMC that keeps the SMP stable. In agro-climatic conditions similar to our study area, Karuku et al. (2012) observed a high infiltration rate for a Nitisol with a large amount of clay. They explained the high infiltration rate with the presence of a well-aggregated soil matrix and large macropores.

Furthermore, as depicted in Figure 3.3b, the GWT in piezometer VP3 near the actively eroding Vertisol gully head is shallower, suggesting the soil near the gully head contains more water. Duiker et al. (2001) found soil erodibility of a wet Vertisol is two times higher than when it is dry. Rengers and Tucker (2015) also emphasized gully head retreat is highly enhanced by high SMC around the gully head. Moreover, Zhang et al. (2020) and Osman and Barakbah (2006) remarked that a high soil moisture content destabilizes slopes by reducing frictional shear strength and apparent soil cohesion. Lin et al. (2015), who experimented with clay loam soil, reported an increase in SMC beyond 25% could cause a corresponding five KPa reduction in the soil cohesion and a decline in the internal angle of friction from 38° to 25°.

### 3.4.3 Gully head stability

#### 3.4.3.1 Impact of groundwater and soil crack on gully head stability estimated from BSTEM

The result of gully bank stability analysis using the BSTEM model showed both a rise in GWT depth and soil crack played a role in reducing gully bank stabilities (Table 3.4). An increase in GWT from 3 to 0.1 m depth in Vertisol caused a 41% and 44% drop in FS values in the presence and absence of cracks. Similarly, in Nitisol, GWT rise from 4 to 0.5 m depth caused a 49% decrease in the FS values. Despite the reduction in the FS values by the increased water table height, the gully head in both soils remained stable without soil cracks. The presence of soil crack in the Vertisol caused an 85% decrease in the FS compared with the results obtained without cracking, leaving the gully head unstable. Both groundwater and soil cracks were found to affect gully head stabilities; however, the impact of tension crack compared to GWT on gully head stability is substantial. As a result, cracks justify the observed higher head cut retreat in the Vertisol than the Nitisol. Our finding agrees with Langendoen et al. (2014) and Zegeye et al. (2020), who stated that gully bank stability is greatly affected by tension crack and groundwater table depths. Moreover, Klavon et al. (2017) also reported that crack weakens bank materials and exposes them to fluvial erosion and geotechnical failures.

#### 3.4.3.2 Other stability factors at the head-cuts

Gully bed slope in both Nitisol (0.11 m $m^{-1}$) and Vertisol (0.09 m $m^{-1}$) were larger than a corresponding 0.05 m $m^{-1}$ and 0.07 m $m^{-1}$ average soil surface slope above the head-cut. This suggests that the land slope is not the cause of gully head retreat (Oostwoud Wijdenes & Bryan, 2001). Furthermore, the average angle of internal friction 25.5$^{\circ}$ (0.5 m $m^{-1}$) for Nitisol and 22$^{\circ}$ (0.4 m $m^{-1}$) for Vertisol was larger than the drainage area slope above the head-cut. Therefore, in both soils, erosion of the gully head due to slope instability is less likely.

## 3.5 Conclusion

We studied two valley bottom gullies in the Minzir catchment located in the sub-humid Northwestern Ethiopian highlands. These gullies had developed in Vertisol and Nitisol grazing lands. Despite the larger drainage area and steeper and taller gully walls for Nitisol, Nitisol gully was relatively stable than the Vertisol gully, which had shallower and less steep sidewalls. The gully bank stability analysis using the Bank Stability and Toe Erosion Model (BSTEM) model showed that groundwater and soil cracks were found to affect gully head stabilities. However, the impact of tension crack compared to GWT on gully head stability was substantial. Therefore, cracks in the Vertisol would justify the observed higher head cut retreat in the Vertisol than the Nitisol. Although studies have associated the occurrence of soil pipes with unstable gully banks, we found that for the Nitisol gully, the drainage provided by soil pipes prevented a sizeable saturated zone in the unconsolidated soil and contributed to the smaller gully head erosion rate.

This study provided insight into how variations in soil type such as Nitisol and Vertisol lead to variabilities in the soil morphology and hydrology, resulting in variations in gully head retreat rates. Planning for gully rehabilitation should be tailored to these variations, even though Nitisol and Vertisol's gullies have located on the same landscape and land use. For Vertisol, besides structurally stabilizing the gully head and sidewalls, rehabilitation measures should safely remove the excess water from both the catchment and the gully bank to reduce bank collapses. For Nitisol, reducing upslope runoff and stabilizing the gully head and sidewalls could suffice. The exact trade-offs between drainage area, surface runoff, and infiltration capacity for these soil types would merit further investigation.

# 4. Susceptibility to Gully Erosion: Applying Random Forest (RF) and Frequency Ratio (FR) Approaches to a Small Catchment in Ethiopia

This chapter is based on:

Amare, S., Langendoen, E., Keesstra, S., Ploeg, M. V. D., Gelagay, H., Lemma, H., & van der Zee, S. E. (2021). Susceptibility to Gully Erosion: Applying Random Forest (RF) and Frequency Ratio (FR) Approaches to a Small Catchment in Ethiopia. Water, 13(2), 216.

## Abstract

Soil erosion by gullies in Ethiopia is causing environmental and socioeconomic problems. A sound soil and water management plan requires accurately predicted gully erosion hotspot areas. Hence, this study develops a gully erosion susceptibility map (GESM) using frequency ratio (FR) and random forest (RF) algorithms. A total of 56 gullies were surveyed, and their extents were derived by digitizing Google Earth imagery. A literature review and a multicollinearity test resulted in 14 environmental variables for the final analysis. Model prediction potential was evaluated using the area under the curve (AUC) method. Results showed that the best prediction accuracy using the FR and RF models was obtained using the top four most important gully predictor factors: drainage density, elevation, land use, and groundwater table. The notion that the groundwater table is one of the most important gully predictor factors in Ethiopia is a novel and significant quantifiable finding and is critical to the design of effective watershed management plans. Results from separate variable importance analyses showed land cover for Nitisols and drainage density for Vertisols as leading factors determining gully locations. Factors such as texture, stream power index, convergence index, slope length, and plan and profile curvatures were found to have little significance for gully formation in the studied catchment.

### 4.1 Introduction

Although gullies occupy, on average, a small portion of a catchment (<5%), land degradation due to gully erosion causes severe environmental and socioeconomic problems by affecting soil and land functions (Ionita et al., 2015b; Ryken et al., 2015). Gully erosion lowers the groundwater table (Tilahun et al., 2016) and increases the susceptibility of soils to drought, causing crop yield reduction (Frankl et al., 2016). Gullies also increase landscape connectivity by providing efficient paths for the transport of water, sediment, and other materials from the source to the sink (Casalí et al., 2009; Poesen et al., 2003). This affects flooding and reservoir siltation (Nyssen et al., 2006). Soil erosion studies worldwide have shown that sediment in rivers mainly originates from gully erosion (Valentin et al., 2005). In Ethiopia, severe gully erosion has been a major concern for current and planned water management developments, ranging from small-scale irrigation to large-scale hydroelectric dams (Girmay et al., 2012; Haregeweyn et al., 2006; Tamene & Vlek, 2007). Gully erosion in the Ethiopian highlands accounts for 28% of the soil loss in semiarid regions (Nyssen et al., 2008). In contrast, in the subhumid areas, it accounts for two orders of magnitude more soil loss than rill and inter-rill erosions (Tebebu et al., 2010).

In Ethiopia, the dominant causes of gully erosion have been investigated with regard to anthropogenic, morphologic, hydrologic, soil, and environmental aspects of a catchment. Land degradation by gullies has been associated with stagnation of agricultural technology and lack of agricultural intensification (Nyssen et al., 2004a), increased traditional drainage ditches (Monsieurs et al., 2015a), and elevated groundwater levels (Addisie et al., 2017b; Zegeye et al., 2016b). Furthermore, road construction can facilitate gully development by increasing its drainage area (Nyssen et al., 2002) and can cause up to one order of magnitude increase in gully head retreats (Frankl et al., 2012). Soil cracks and pipes also aggravate gully erosion by allowing preferential water flow in the soil and increasing soil pore water pressure (Frankl et al., 2012; Tebebu et al., 2010).

Previous studies of gully erosion in Ethiopian highlands have been based on field monitoring (Ayele et al., 2018; Billi & Dramis, 2003b; Frankl et al., 2016; Zegeye et al., 2018) and combined field monitoring and interviews (Nyssen et al., 2006; Tebebu et al., 2010). However, large-scale field monitoring of gullies throughout a catchment is costly and labor-demanding. As a result, only a few parameters to understand the gully dynamics are often measured, omitting other environmental factors that affect gully development.

In regions with developing economies, where resources are particularly limited to undertaking extensive field surveys, the use of prediction models can be effective for identifying areas susceptible to gully erosion and determining the most important drivers of gully erosion (Arabameri et al., 2020). Prediction of gully-susceptible areas is essential for appropriately planning sustainable soil and water conservation measures (Arabameri et al., 2020; Kariminejad et al., 2019). Nowadays, statistical and machine-learning models have been successfully used to predict a variety of environmental properties across different fields, e.g., groundwater zoning (Sameen et al., 2019), landslide hazard mapping (Park & Kim, 2019; Sevgen et al., 2019; Yusri et al., 2019), flood risk assessment (Chen et al., 2020a), and gully-head susceptibility mapping (Hosseinalizadeh et al., 2019). Various techniques have been used to map gullies, such as entropy information value (Zhao & Cheng, 2019), multivariate adaptive regression splines (Javidan et al., 2019), certainty factor and maximum entropy (Azareh et al., 2019), frequency ratio (Arabameri et al., 2019a; Rahmati et al., 2016a) and random forest (Arabameri et al., 2019b; Rahmati et al., 2017b).

Few studies in Ethiopia have predicted gully erosion by using topographical threshold factors such as the topographic wetness index (TWI) and the stream power index (SPI) (Assefa et al., 2015; Mhiret et al., 2018). These thresholds are flawed mainly because streams and saturated-bottom lands are preferentially considered most vulnerable to gullies. This is particularly problematic when gullies are predominantly controlled by other factors (e.g., land use, soil type, and elevation). Since gully erosion is a function of various hydrological, geomorphic, and environmental factors (Valentin et al., 2005), using more gully erosion factors in modeling would improve prediction accuracy.

Recently, FR and RF models were tested in several countries and gave very good gully prediction accuracies (Gayen et al., 2019; Zabihi et al., 2018). A recent field campaign in the Minzir catchment in the upper Blue Nile river basin (Ethiopia) provides the necessary extra gully erosion factors for a more accurate gully-erosion susceptibility map (GESM) (Selamawit Amare et al., 2020). Therefore, the objective of this study is to develop this GESM using frequency ratio (FR) and random forest (RF) models for the Minzir catchment, Upper Blue Nile River Basin (Ethiopia). In addition to GESM, the RF model was also used to rank predictor factors based on their importance to gully erosion. Among the 16 selected factors, soil type and groundwater table (GWT) are new variables introduced to the models that were not used in previous studies. Gully erosion predictor factors for the Nitisol- and Vertisol-dominated sub-catchment were ranked separately. This distinction is based on the fact that the rate of gully erosion in Nitisol and Vertisol has been reported to be different (Selamawit Amare et al., 2020), which inspired this study to hypothesize that the most important factors controlling gully erosion might also be different.

## 4.2 Materials and Methods

### *4.2.1 Study Area*

The Minzir catchment is in the subhumid part of the upper Blue Nile River basin (Ethiopia) and covers a drainage area of 18 km$^2$ (Figure 4.1). Its altitude ranges from 2030–2265 m a.s.l. with an average of 2095 m a.s.l. The catchment receives an average annual rainfall of 1480 mm, of which more than 90% falls between May and October. The mean maximum monthly temperature is 30.0 °C in March to 23.1 °C in August, whereas the mean minimum monthly temperature is 5.4 °C in December, with up to 13.1 °C in May and June.

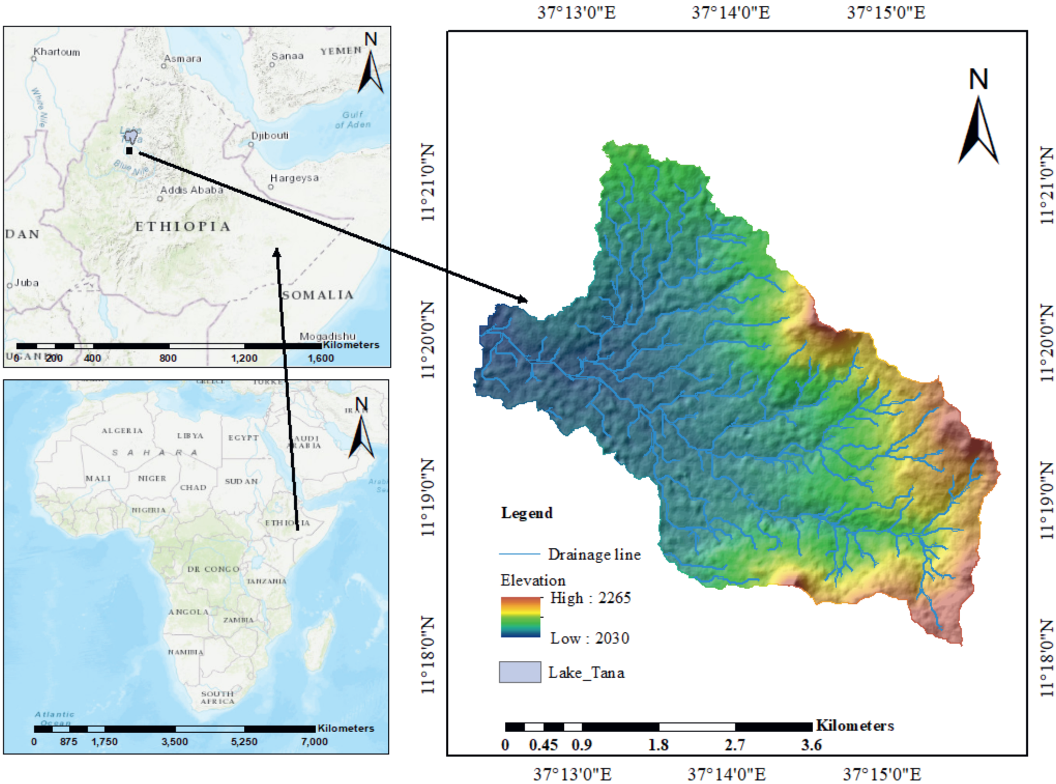


***Figure 4.1*** *Study area map and elevation range of the Minzir catchment.*

The geology is dominated by Quaternary basalts (Williams, 2016), with soil types dominantly being Nitisols (29.5%), Vertisols (29.2%), Luvisols (14.9%), Leptosols (10%), and Alisols (7.7%). Cambisols, Fluvisols, and Regosols cover the remaining 5% of the catchment. The soil texture is dominantly clay (83.7%), clay loam (5.9%), sandy clay loam (3.5%), and loam (3.1%). The major land cover in the study area is cultivated land (83%), grassland (12.8%), and plantation forest (1.6%). Woodland, bushland, villages, and water bodies comprise less than 3% of the catchment.

Different biological, agronomic, and physical soil and water conservation measures (e.g., bunds and check dams) were introduced in the catchment area (Jemberu et al., 2018). Despite this effort, the amount of sediment reaching the Koga reservoir, located downstream of Minzir, is still significant and amounts to 25 Mg ha$^{-1}$ y$^{-1}$ (Mekonnen et al., 2017; Yeshaneh et al., 2017). Moreover, soil and water conservation efforts in the last 15 years resulted in only a 35% reduction in soil erosion (Dagnew et al., 2015; Molla & Sisheber, 2017). An increase in cultivated land and a decrease in woody vegetation has contributed to the increased sediment yield in the catchment (Yeshaneh et al., 2017).

The same study further stated that poorly planned and poorly constructed soil and water conservation measures are among the main causes of soil erosion in the catchment. A similar study from an adjacent catchment revealed that due to the lack of integrated approaches and the lack of maintenance, rehabilitation measures have not been able to reduce sediment in rivers (Dagnew et al., 2015). This and an increase in cultivated land and a decrease in woody vegetation have contributed to the increased sediment yield in the catchment (Yeshaneh et al., 2017) despite the construction of rehabilitation measures.

### *4.2.2 Data Collection and Preparation*

This research is organized as follows (see Figure 4.2): (1) data organization, including gully erosion inventory and selection of gully predictor factors; (2) multicollinearity test of gully predictor factors; (3) gully-erosion susceptibility mapping (GESM); (4) ranking gully predictor factors; (5) model validation.

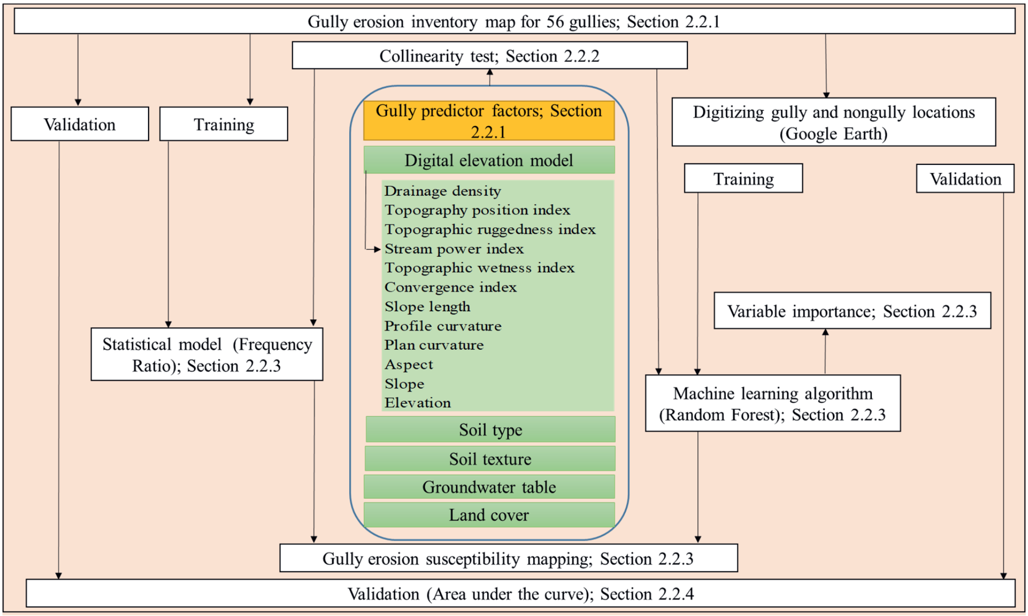


***Figure 4.2*** *Research methodology flowchart.*

#### *4.2.2.1 Data Organization*

- Gully erosion inventory

Gully erosion inventory data were prepared by combining field surveys with Google Earth™ imagery analysis. Fifty-six gullies were surveyed in the field. Gully morphology including width, depth, length, and locations was monitored. Then, the areal extent of each gully was derived by digitizing Google Earth imagery.

- Gully erosion predictor factors

From a literature review, 18 predictor factors that control gully erosion were selected. These factors were obtained from four data sets: digital elevation model (DEM), groundwater table, soil, and land cover (Table 4.1). We omitted those that do not vary throughout the catchment and do not have explanatory values in our modeling (e.g., geology and rainfall depth). Therefore, 16 gully predictor factors, which have been subjected to the multicollinearity test (elaborated in Table 4.2), will be used.

***Table 4.1*** *Data sources.*

| Data used | Description | Resolution | Source |
|---|---|---|---|
| Digital elevation model (DEM) | DEM to delineate the catchment boundary and river networks and characterize the landscape. Topography plays a vital role in runoff processes and helps us to understand the physical processes of disaggregation, transport, and soil deposition (Oliveira et al., 2013) | 12.5 m | Advanced Land Observing Satellite (*ALOS)* |
| Land use/cover | Land use/cover are used to quantify the hydrological processes and soil erosion in a catchment (Arnold et al., 2012) | 12.5 m | Song et al. (Watson & Philip, 1985) |
| Soil data | This data set includes soil type and texture data for the Minzir study catchment. | 1:50,000 | Amhara Design and Supervision Works Enterprise, Ethiopia |
| Groundwater level | In this study, we used groundwater table (GWT) readings from 50 piezometers, reported for 2018. GWT was measured from the soil surface to the location of the GWT. GWT surface was generated using inverse distance weighting (IDW) interpolation of the observations using ArcGIS (Watson & Philip, 1985). | 50 piezometers distributed across the catchment | (Selamawit Amare et al., 2020) |

Note: vector maps of land use/cover and soil were reprocessed into 12.5-m rasters to match the DEM resolution.

ArcGIS 10.5 was used to rasterize the gully inventory and predictor factors map to the same pixel size of 12.5 m to ascertain compatibility during modeling. To extract different gully-erosion factors from the DEM, SAGA GIS 7.5 was used (Conrad et al., 2015). The first 12 factors presented in Table 4.2 were derived from DEM data.

The 1:50,000 scale soil data (soil type and soil texture) has an equivalent resolution of 25 m. The nearest resampling technique (GISGeography) was used to match the soil data resolution with the DEM resolution. This resampling technique will not change the value of the cell. The maximum spatial error of applying the nearest resampling technique is one-half of the size of the cell.

The GWT surface generated using the IDW technique was resampled using the bilinear resampling technique. This method determines the new value of a cell based on a weighted distance average of the four nearest input cell centers (GISGeography). This method is used for continuous data and will cause some smoothening of data.

***Table 4.2*** *Description of gully predictor variables.*

| Variable | Description | Classes/Class Range |
|---|---|---|
| Elevation | Determines vegetation distribution and rainfall patterns (Jin et al., 2008; Joseph et al., 2012), which indirectly affect gully distribution (Arabameri et al., 2020). | 2030–2265 |
| Slope | Determines both the kinetic energy and the volume of surface runoff (Valentin et al., 2005), which, in turn, affects drainage density, discharge, and soil erosion (Arabameri et al., 2020). | 0–34 |
| Aspect | Variation in aspect influences the distribution of vegetation by influencing the rate of recharge, soil moisture content, and evaporation that, in turn, control gully development (Patton & Schumm, 1975; Wang et al., 2011). | Flat, North, Northeast, East, Southeast, South, Southwest, West, Northwest and North |
| Plan curvature | Plan curvature, also known as contour curvature (Peckham, 2011), is defined as “the rate of change of aspect along a contour” (Wilson & Gallant, 2000). Plan curvature can have positive, negative, and zero values representing convexity, concavity, and flatness, respectively (Conforti et al., 2011). Flow diverges on a convex slope and converges on a concave slope. | Concave, flat, and convex |
| Profile curvature | Profile curvature is defined as “the rate of change of slope down a flow line” (Wilson & Gallant, 2000), and its values can be positive, negative, and zero. Profile curvature with positive values is concaved upward, with slopes decreasing downhill and flows being accelerated. Profile curvature with negative values is upwardly convexed, with slopes increasing downhill and flows being decelerated. Zero values are flat surfaces. | −2.69–2.01 |

| | | |
|---|---|---|
| Convergence index (CI) | CI estimates the divergence (when CI is negative) and convergence (positive) of flow in a given area; it is calculated based on aspect information (Thommeret et al., 2009). | −100–99.2 |
| Topographic ruggedness index (TRI) | TRI is a measure of topographic heterogeneity and is calculated based on relief and drainage (Shankar & Dharanirajan, 2014). The TRI value for flat areas is zero, while the value for mountain areas with steep ridges is positive (Amatulli et al., 2018). | 0.35–19.6 |
| Topography position index (TPI) | TPI is derived from DEM by comparing a given cell elevation to the average of its surroundings (Jenness, 2006). The TPI value can be positive (when the elevation of a location greater than the average of its neighborhood), negative (when less than the surrounding areas), and zero (for flat or constant slope) (Weiss, 2001). | −7.90–22.8 |
| Slope length (LS) | LS is defined as the distance between the start of overland flow to a point where the slope gradient decreases sufficiently to cause depositions (Gayen & Saha, 2017). LS influences soil erodibility and critical shear stress (Zhang et al., 2017). | 0–772 |
| Drainage density (DD) | Drainage density is a measure of stream length per unit of catchment area (Brandt et al., 2005) and is used as a predictor of gully erosion in many studies. The soil drainage characteristics affect soil water retention capacity, which, in turn, determines the rate of soil erosion (Lowery et al., 1995). | 0–2.2 |
| Topographic wetness index (TWI) | TWI quantifies the effect of local topography on the hydrological process and assesses the spatial distribution of soil moisture and surface saturation (Qin et al., 2011). In areas where saturation excess runoff is the dominant process of gullies, TWI predicts saturated areas susceptible to gullies (Gómez-Gutiérrez et al., 2015). | 2.89–17.6 |
| Stream power index (SPI) | SPI estimates the erosive power of surface runoff due to the relationship between discharge and catchment area (Shit et al., 2015). Similarly, it predicts the potential of streams to modify the geomorphology of a catchment by gully erosion (Vijith & Dodge-Wan, 2019). | 0–5965 |
| Groundwater table depth (GWT) | Research conducted in humid and subhumid regions has shown that elevated groundwater is one of the most important causes of gully erosion (Addisie et al., 2017b; Marinho et al., 2006; Thomas et al., 2009b). Nevertheless, we do not see this critical factor incorporated in gully erosion prediction models. | 0.01–4.05 (m) |
| Soil type | Although gullies can evolve on any soil type, the soil type determines the size and shape of the gullies (Amare et al., 2019). | Alisols, Cambisols, Ferralsols, Fluvisols, |

| | | |
|---|---|---|
| | Therefore, integrating soil type into gully modeling increases prediction accuracy. | Leptosols, Luvisols, Nitisols, Regosols, and Vertisols. |
| Soil texture | Soil texture determines the rate of infiltration (Mamedov et al., 2001) and erosion resistance, which determines the volume of gully erosion (Dunaway et al., 1994; Shahrivar & Christopher, 2012) | Clay, clay loam, loam, sandy clay, sandy clay loam, silty clay, and silty clay loam. |
| Land cover | Land cover and gullies are closely linked (Gutiérrez et al., 2009b), as a land cover is one of the factors that set the threshold for gully initiation (Gutiérrez et al., 2009b) | cultivated land, bushland, plantation forest, village, waterbody, woodland, and grassland |

#### *4.2.2.2 Multicollinearity Test*

In this study, multicollinearity was tested by combining results from the variance inflation factor (VIF) and tolerance (TOL), which are commonly used in different fields, including forest fire and gully erosion (Gayen et al., 2019; Gigović et al., 2019), with a correlation matrix of all predictor factors. The correlation method used in this study is the Pearson correlation coefficient. A correlation with a corresponding *p*-value of >0.01 is considered insignificant. The corrplot package, implemented in R statistical software, has been used to present the correlation matrix and the confidence interval graphically (Wei & Simko, 2017). Tolerance is the reciprocal of VIF. Collinearity among predictor factors reduces model prediction accuracy (Arabameri et al., 2019c). Therefore, input factors with evidence of collinearity will be discarded before the GESM is developed.

#### *4.2.2.3 Gully Erosion Susceptibility Map (GESM) and Variable Importance*

The frequency ratio (FR) and random forest (RF) models discussed below were used to build the GESM. The GESM was finally classified as “low,” “moderate,” “high,” and “very high” using the natural break method or the Jenks method in ArcGIS (Jenks & Caspall, 1971). This classification method was selected as it reduces variance within a class. The RF model was also used to rank gully predictor factors based on their importance to gully erosion.

- Frequency ratio (*FR*) model

As depicted in Equation (1), *FR* is the ratio of gully erosion probability of occurrence to nonoccurrence within a gully predictor factor class (Gayen et al., 2019; Park & Kim, 2019). This method is one of the simplest statistical bivariate techniques used in various fields, such as landslide susceptibility mapping (Kornejady et al., 2019). Moreover, studies have shown that the FR model predicts gully susceptible areas very well (Arabameri et al., 2018; Rahmati et al., 2016a). The modeling was executed by randomly dividing the gullies into a training set (n = 39 or 70%) and a validation set (n = 17 or 30%). ArcGIS 10.5 was used to develop the GESM using the FR model.

$$FR = (A/B)/(C/D) \tag{1}$$

where *A* is the number of gully erosion pixels for each class of predictor factors, *B* is the total number of gully erosion pixels in the study area, *C* is the number of pixels in each class of gully predictor factor, and *D* is the number of total pixels in the study area.

The FR values obtained using Equation (1) were normalized using Equation (2).

$$Y_{NFR} = (X_{FR} - MIN_{FR})/(MAX_{FR} - MIN_{FR}) \tag{2}$$

where $Y_{NFR}$ is the normalized frequency ratio, $X_{FR}$ is the frequency ratio of the class within a predictor factor, $MIN_{FR}$ is the minimum of all frequency ratios within a predictor factor, and $MAX_{FR}$ is the maximum of all the frequency ratios within a predictor factor.

Finally, the gully erosion susceptibility map is developed by summing up the normalized frequency ratio values for each predictor factors class.

- Random forest (RF) model

After conducting the multicollinearity test, gully erosion variable importance is computed using the RF model. The RF is known for effectively predicting variable importance in different disciplines, including land subsidence (Mohammady et al., 2019), invasive plant (Lawrence et al., 2006), groundwater (Rahmati et al., 2016b), gully head susceptibility (Hosseinalizadeh et al., 2019), and forest fire susceptibility (Gigović et al., 2019). The RF model is a multivariate nonparametric machine learning technique developed by Breiman (2001). The RF is a powerful decision tree classifier that predicts well when there is missing data, avoids over-fitting problems, produces more stable results, and is less sensitive to multicollinearity than other machine learning algorithms (e.g., support vector machine (SVM) and classification and regression tree (CART)) (Chen et al., 2020a; Fang et al., 2020; Lai & Tsai, 2019; Mohammady et al., 2019). It is also known for predicting gully erosion well compared to other machine learning algorithms (Gayen et al., 2019).

The RF model was implemented in R statistical software (Liaw, 2018). As the analysis in the RF model was cell-based, a total of 2963 and 6560 gridded cells (12.5 by 12.5 m) were extracted from the gully and non-gully irregularly shaped sample spatial polygons, respectively.

The RF model works by growing many decorrelated decision trees as a base learner using a fraction of randomly selected gully observation and gully predictor factors, with replacement.

Every tree was trained using 2/3 of the randomly selected training samples, while the remaining 1/3 training samples, named out-of-bag (OOB) samples, were used to validate the prediction result. Finally, the majority vote or mode rule was used to allocate a pixel to a class (Ghimire et al., 2012). The mean decrease in the Gini index (or Gini impurity) was used as an indicator for variable importance of the evaluated gully-erosion predictors (Han et al., 2016). The mean decrease in Gini is the mean of the total decrease in node impurity of the variable (i.e., gully predictor factors), weighted by the proportion of samples reaching that node in each decision tree in the RF. A higher mean decrease in Gini indicates higher variable importance.

Determination of variable importance using the RF model was executed for three scenarios with different combinations of gully predictor factors: (1) keeping all 15 non-soil type gully predictor factors for Nitisol soils only (i.e., excluding other soil types); (2) keeping all 15 factors for Vertisol soils only (i.e., excluding other soil types), and (3) using all 16 variables (i.e., including all soil types in the analysis).

#### *4.2.2.4 Model Validation*

In this study, model performances were evaluated using the area under the ROC curve (AUC). A ROC curve is the plot of sensitivity versus 1-specificity for different threshold values. The area under the ROC curve (AUC) is a commonly used parameter for quantifying the quality of a classificator because it is a threshold-independent performance measure (Bradley, 1997). It is a valuable technique for visualizing and measuring the accuracy of the models (Sameen et al., 2019), and its value ranges between 0.5 and 1, with the highest accuracy at 1 (Park & Kim, 2019). This method has been successfully used in gully erosion prediction research (Arabameri et al., 2020; Hosseinalizadeh et al., 2019; Kariminejad et al., 2019).

## 4.3 Results

### *4.3.1 Multicollinearity Test*

The multicollinearity test showed the VIF ranges from 1.04 to 7.8, while TOL (the reciprocal of VIF) varies from 0.13 to 0.96 (Table 4.3). VIF values greater than 5, with corresponding TOL values less than 0.2, indicate serious multicollinearity among predictor factors (O’brien, 2007). VIF values for TRI and slope are greater than 5, suggesting multicollinearity (Table 4.3).

***Table 4.3*** *Multicollinearity test statistics of gully predictor variables.*

| **Gully Predictor Variables** | **Collinearity Statistics** | |
|---|---|---|
| | **Tolerance (TOL)** | **Variance Inflation Factors (VIF)** |
| Land cover | 0.88 | 1.13 |
| Plan curvature | 0.49 | 2.04 |
| Profile curvature | 0.56 | 1.79 |
| Texture | 0.79 | 1.27 |
| Aspect | 0.96 | 1.04 |
| Convergence index | 0.68 | 1.46 |
| Drainage density | 0.78 | 1.28 |
| Groundwater | 0.81 | 1.23 |
| Elevation | 0.36 | 2.75 |
| Slope length | 0.59 | 1.68 |
| Stream power index | 0.77 | 1.29 |
| Topographic position index | 0.65 | 1.54 |
| Terrain ruggedness index | 0.13 | 7.8 |
| Topographic wetness index | 0.42 | 2.39 |
| Slope | 0.13 | 7.4 |
| Soil type | 0.5 | 1.99 |

In addition to the multicollinearity test using the VIF method, the results of the correlation matrix (Figure 4.3) suggest that TRI and slope are strongly correlated (0.9), with a corresponding *p*-value of 0 (Figure 7.3, Appendix), indicating that the correlation is significant. Guided by the results obtained using the correlation matrix and VIF, we removed TRI and slope from the entire analysis. Besides, model prediction performance was evaluated by varying the number of gully predictor factors, depending on their importance as presented in Figure 4.4c.

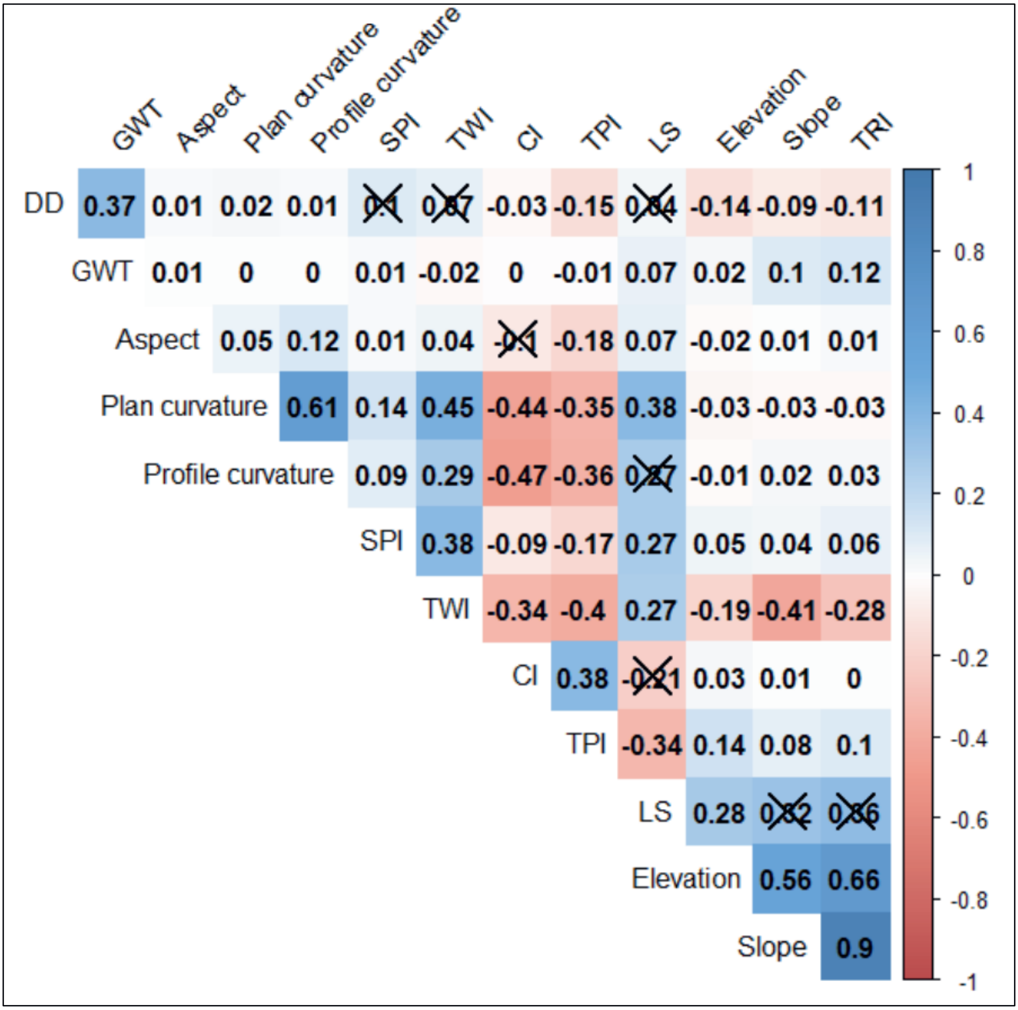


***Figure 4.3*** *Correlation matrix for the 13 quantitative gully-erosion predictor factors. Crosses are added for correlations having p-values >0.01 or when the correlation is insignificant.*

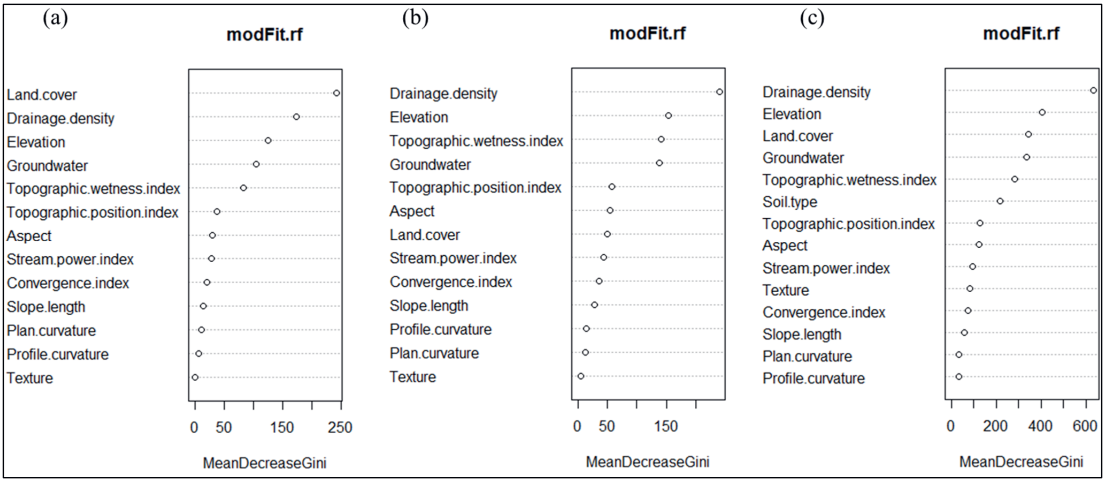


***Figure 4.4** Variable importance plot of gully-erosion predictor factors for (a) Nitisol soil type only, (b) Vertisol soil type only, and (c) all soil types.*

### *4.3.2 Gully Characteristics and Spatial Distribution*

The average width, depth, and length of the 56 gullies were 6, 1.6, and 227 m, respectively (Table 4.4). Gullies in the study watershed occupy 16.8 hectares of land. On the basis of the average land-holding size (~0.7 ha) in the Ethiopian highlands (Yitbarek et al., 2012), the land taken over by the gullies would have been able to support 24 households. Furthermore, the gullies in the study catchment are primarily located on cultivated land (57.45%) and grasslands (41.3%), indicating that they are eroding economically important land and threatening the food security of the rural community.

***Table 4.4** Statistical summary of the 56 surveyed gullies.*

| Parameter | Minimum | Maximum | Average | Median |
|---|---|---|---|---|
| Width (m) | 2.06 | 15 | 6.08 | 5.13 |
| Depth (m) | 0.47 | 8.18 | 1.65 | 1.44 |
| Length (m) | 22.8 | 1463 | 227 | 134 |
| Area (ha) | 0.004 | 5.16 | 0.3 | 0.08 |

Many of the gullies were found on valley bottoms compared to hillslope areas. A larger percentage (>70%) of gullies were located on slope gradients less than 5%, and for areas with flat (48.1%) plan curvatures rather than concave and convex plan curvatures. Compared to high elevation classes, many gully pixels were also found at lower elevations (2030–2070 m a.s.l. and 2070–2104 m a.s.l). Furthermore, though the flat aspect class occupied a relatively small area, many gullies were found on lands with a flat aspect.

### 4.3.3 Gully Erosion Susceptibility Mapping and Variable Importance

#### 4.3.3.1 FR Model

The frequency ratio values listed in Table 4.5 provide a spatial relationship between gully locations and predictor factors (see Figure 7.4 to Figure 7.17, Appendix). When FR values are greater than 1 in a given gully-erosion predictor class, the class may be considered susceptible to gullies (Arabameri et al., 2018). Here, we will present the FR values of the top 4 gully-erosion predictor classes that provide the best FR model accuracy. However, this does not mean that the other gully predictor factors do not play a role in gully erosion, but only that the top four important predictor factors well illustrated the effects of these factors.

Though large areas (40%) were covered by the DD class between 0 and 0.2 km $km^{-2}$, they had the smallest FR (0.34) and were less vulnerable to gully erosion. Drainage density (0.2–0.5 and 0.5–0.9 km $km^{-2}$), with FR 1.67 and 1.48, respectively, were the most susceptible areas for gully formation. Drainage density of 0.9–1.4 and 1.4–2.2 km $km^{-2}$ covers a small portion of the catchment, has relatively smaller FR values, and is less susceptible to gully erosion.

Based on FR values, the vulnerability to gully erosion increases with a decline in elevation. Low elevations (2030–2070 and 2070–2104 m a.s.l), with FR 1.21 and 1.27, were the most susceptible areas for gully formation, while higher elevation areas showed little to no susceptibility to gully erosion.

Grassland (for grazing) with an FR value of 3.22 was the most susceptible area to gully-erosion. Though large areas were cultivated (82.7%), they had smaller FR (0.68) and were less prone to gully erosion. Other land uses, such as bushland, woodland, and plantation forests were less correlated with gully erosion.

The FR values showed that gullies are positively correlated with shallower GWT zones. GWT depths (1.03–1.51 and 1.51–1.95 m) were found to have a higher FR (1.34) value, indicating that they are strongly correlated with gully erosion. Conversely, areas with deeper GWT had lower FR values, reflecting lower susceptibility to gully erosion. Areas with GWT depths between 0 and 1.03 occupy a small percentage of the catchment (2%) and are less prone to gully erosion (FR = 0.04).

***Table 4.5*** *(1) Areal coverage of gully predictor factors and training gully pixels and (2) the frequency ratio (FR) and normalized frequency ratio (NFR) calculated for the training data set.*

| Factors | Class | Pixels in Domain | % of Pixels in Domain | Training Gully Pixels in Domain | % of Gully Training Pixels in Domain | FR | NFR |
|---|---|---|---|---|---|---|---|
| CI | −100–−42.75 | 12,282 | 10.8 | 320 | 14.5 | 1.34 | 1 |
| | −42.7–−10.6 | 22,765 | 19.9 | 509 | 23 | 1.15 | 0.65 |
| | −10.6–9 | 44,119 | 38.7 | 805 | 36.4 | 0.94 | 0.27 |
| | 9–39.6 | 22,656 | 19.8 | 391 | 17.7 | 0.89 | 0.18 |
| | 39.6–99.2 | 12,274 | 10.7 | 188 | 8.49 | 0.79 | 0 |
| Elevation | 2030–2070 | 42,552 | 37.3 | 836 | 37.8 | 1.01 | 0.66 |
| | 2070–2104 | 33,214 | 29.1 | 984 | 44.5 | 1.53 | 1 |
| | 2104–2141 | 18,891 | 16.6 | 360 | 16.3 | 0.98 | 0.64 |
| | 2141–2186 | 14,494 | 12.7 | 33 | 1.49 | 0.12 | 0.08 |
| | 2186–2265 | 4945 | 4.33 | 0 | 0 | 0 | 0 |
| Plan curvature | Concave | 31,069 | 27.2 | 502 | 22.7 | 0.83 | 0 |
| | Flat | 52,826 | 46.3 | 1076 | 48.6 | 1.05 | 0.86 |
| | Convex | 30,201 | 26.5 | 635 | 28.7 | 1.08 | 1 |
| Profile curvature | −2.69–−0.75 | 4566 | 4 | 72 | 3.25 | 0.81 | 0 |
| | −0.75–−0.31 | 27,155 | 23.8 | 446 | 20.1 | 0.85 | 0.07 |
| | −0.31–0.30 | 50,120 | 43.9 | 1017 | 45.9 | 1.05 | 0.50 |
| | 0.30–0.75 | 27,292 | 23.9 | 555 | 25.1 | 1.05 | 0.50 |
| | 0.75–2.01 | 4963 | 4.35 | 123 | 5.56 | 1.28 | 1 |
| LS (m) | 0–25 | 79,752 | 69.9 | 1463 | 66.1 | 0.94 | 0 |
| | 25–78 | 23,282 | 20.4 | 468 | 21.1 | 1.04 | 0.12 |
| | 78–163 | 7754 | 6.79 | 207 | 9.35 | 1.38 | 0.59 |
| | 163–315 | 2601 | 2.28 | 52 | 2.35 | 1.03 | 0.12 |
| | 315–772 | 707 | 0.62 | 23 | 1.04 | 1.68 | 1 |
| TPI | −7.90 to −1.61 | 14,649 | 12.8 | 618 | 27.9 | 2.17 | 1 |
| | −1.61 to −0.17 | 37,952 | 33.3 | 838 | 37.9 | 1.14 | 0.47 |
| | −0.17–1.19 | 40,363 | 35.4 | 575 | 30 | 0.73 | 0.27 |
| | 1.19–3.67 | 19,316 | 16.9 | 175 | 7.91 | 0.47 | 0.13 |
| | 3.67–22.8 | 1816 | 1.59 | 7 | 0.32 | 0.2 | 0 |
| SPI | 0–128 | 110,406 | 96.8 | 1999 | 90.3 | 0.93 | 0 |
| | 128–507 | 2643 | 2.32 | 106 | 4.79 | 2.07 | 0.24 |
| | 507–1170 | 743 | 0.65 | 80 | 3.61 | 5.55 | 1 |
| | 1170–2365 | 238 | 0.21 | 21 | 0.95 | 4.55 | 0.78 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2365–5965 | 66 | 0.06 | 7 | 0.32 | 5.47 | 0.98 |
| TWI | 2.89–5.86 | 42,422 | 37.2 | 665 | 30 | 0.81 | 0 |
| | 5.86–7.15 | 35,986 | 31.5 | 612 | 27.7 | 0.88 | 0.03 |
| | 7.15–8.67 | 19,052 | 16.7 | 385 | 17.4 | 1.04 | 0.12 |
| | 8.67–10.7 | 12,163 | 10.7 | 314 | 14.2 | 1.33 | 0.27 |
| | 10.7–17.6 | 4473 | 3.92 | 237 | 10.7 | 2.73 | 1 |
| DD (km $km^{-2}$) | 0–0.2 | 45,742 | 40.1 | 300 | 13.5 | 0.34 | 0 |
| | 0.2–0.5 | 30,765 | 26.9 | 998 | 45.1 | 1.67 | 1 |
| | 0.5–0.9 | 21,601 | 18.9 | 619 | 28 | 1.48 | 0.85 |
| | 0.9–1.4 | 12,484 | 10.9 | 231 | 10.4 | 0.95 | 0.46 |
| | 1.4–2.2 | 3504 | 3.07 | 65 | 2.94 | 0.96 | 0.46 |
| land cover | Cultivated land | 94,296 | 82.6 | 1243 | 56.2 | 0.68 | 0.21 |
| | Bushland | 951 | 0.83 | 11 | 0.5 | 0.6 | 0.18 |
| | Plantation forest | 2173 | 1.90 | 0 | 0 | 0 | 0 |
| | Village | 431 | 0.38 | 0 | 0 | 0 | 0 |
| | Waterbody | 62 | 0.05 | 0 | 0 | 0 | 0 |
| | Woodland | 1153 | 1.01 | 21 | 0.95 | 0.94 | 0.29 |
| | Grassland | 15,030 | 13.2 | 938 | 42.4 | 3.22 | 1 |
| Soil type | Alisols | 8800 | 7.71 | 102 | 4.61 | 0.6 | 0.17 |
| | Cambisols | 2743 | 2.40 | 163 | 7.36 | 3.06 | 0.89 |
| | Ferralsols | 4262 | 3.73 | 0 | 0 | 0 | 0 |
| | Fluvisols | 1782 | 1.56 | 119 | 5.38 | 3.44 | 1 |
| | Leptosols | 11,390 | 9.98 | 46 | 2.08 | 0.21 | 0.06 |
| | Luvisols | 16,893 | 14.8 | 168 | 7.59 | 0.51 | 0.15 |
| | Nitosols | 33,675 | 29.5 | 615 | 27.8 | 0.94 | 0.27 |
| | Regosols | 1284 | 1.12 | 0 | 0 | 0 | 0 |
| | Vertisols | 33,267 | 29.1 | 1000 | 45.2 | 1.55 | 0.45 |
| Texture | Clay | 95,486 | 83.7 | 2149 | 97.1 | 1.16 | 0.47 |
| | Clay loam | 6676 | 5.85 | 44 | 1.99 | 0.34 | 0.14 |
| | Loam | 3503 | 3.07 | 0 | 0 | 0 | 0 |
| | Sandy clay | 373 | 0.33 | 18 | 0.81 | 2.49 | 1 |
| | Sandy clay loam | 3960 | 3.47 | 0 | 0 | 0 | 0 |
| | Silty clay | 1423 | 1.25 | 2 | 0.09 | 0.07 | 0.03 |
| | Silty clay loam | 2675 | 2.34 | 0 | 0 | 0 | 0 |
| GWT (m) | 0–1.03 | 2514 | 2.20 | 2 | 0.09 | 0.04 | 0 |
| | 1.03–1.51 | 8718 | 7.64 | 227 | 10.2 | 1.34 | 1 |
| | 1.51–1.95 | 38,198 | 33.5 | 994 | 44.9 | 1.34 | 0.99 |
| | 1.95–2.42 | 36,005 | 31.5 | 622 | 28.1 | 0.89 | 0.65 |
| | 2.42–4.05 | 28,661 | 25.1 | 368 | 16.6 | 0.66 | 0.48 |
| Aspect | Flat | 4915 | 4.31 | 85 | 3.84 | 0.89 | 0.43 |
| | North | 12,441 | 10.9 | 85 | 3.84 | 0.35 | 0.04 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Northeast | 7781 | 6.82 | 44 | 1.99 | 0.29 | 0 |
| East | 4312 | 3.78 | 34 | 1.54 | 0.41 | 0.08 |
| Southeast | 8028 | 7.04 | 151 | 6.82 | 0.97 | 0.48 |
| South | 13,624 | 11.9 | 448 | 20.2 | 1.694 | 1 |
| Southwest | 23,504 | 20.6 | 675 | 30.5 | 1.484 | 0.85 |
| West | 20,385 | 17.9 | 410 | 18.5 | 1.04 | 0.53 |
| Northwest | 19,106 | 16.7 | 281 | 12.7 | 0.76 | 0.33 |

Figure 4.5a presents the GESM obtained using the FR model. Susceptibility is classified as "low," "moderate," "high," and "very high." The classifications were made using the natural break method or the Jenks method in ArcGIS (Jenks & Caspall, 1971): 13.9%, 23.8%, 45.5%, and 16.8% for "low," "moderate," "high," and "very high" classes, respectively.

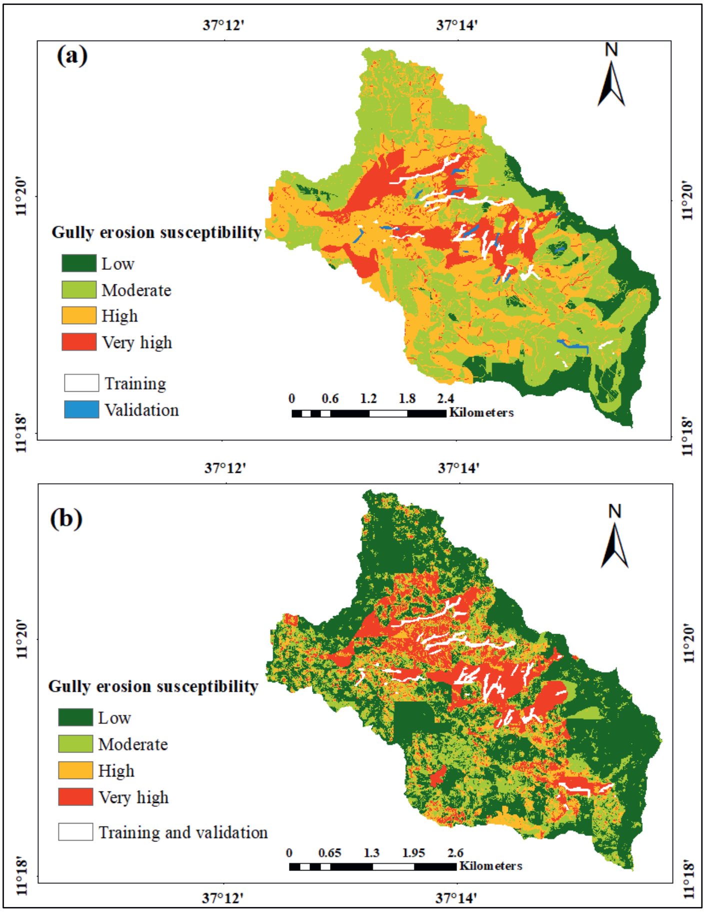


***Figure 4.5*** *Gully erosion susceptibility map using (a) frequency ratio and (b) random forest models: for this model, the training and validation gully polygon takes the same white color as the model that classifies the training and validation data internally.*

### 4.3.3.2 RF Model

The magnitude and rate of gully expansion differ between Nitisols and Vertisols (Selamawit Amare et al., 2020); therefore, the most important gully predictor factors were examined separately for these soils (Figure 4.4a and Figure 4.4b) in addition to all the soil types (Figure 4.4c).

Based on the mean decrease in Gini index values for the Nitisol soil type (Figure 4.4), the five most important gully-erosion predictor factors were land use (242.4), DD (173.8), elevation (124.9), GWT (105.3), and TWI (83.4), respectively. For the Vertisol soil type (Figure 4.4b), the five most important gully-erosion predictor factors were DD (240.4), elevation (153.5), TWI (141.4), GWT (140.0), and TPI (57.3). With soil type included as a gully-erosion predictor factor, the most important variables were DD (625.9), elevation (416.6), land cover (331.3), GWT (330.7), TWI (293.5), and soil type (225.7) (Figure 4.4c). In general, factors such as texture, CI, LS, and profile and plan curvature had little importance to explain gully erosion in the study area. Despite the degree of importance of each factor, all the 14 factors were identified as important except texture with no significance for gully development in Nitisol.

The RF-model-derived GESM is presented in Figure 4.5b. The Jenks algorithm in ArcGIS (Jenks & Caspall, 1971) was used to determine the “low,” “moderate,” “high,” and “very high” susceptibility classes at the class break of 46.7%, 20.8%, 13%, and 19%, respectively.

The percentage of gully erosion susceptibility class for Vertisols and Nitisols is presented in Figure 4.6. Class breaks of the low, moderate, high, and very high susceptibility classes in Nitisol are 47.9%, 18.8%, 19.8%, and 13.5%, whereas in the Vertisol, class breaks are 33.7%, 23.7%, 17.2%, and 25%, respectively. One can see that the areas with a low susceptibility class are higher for Nitisols than Vertisols. In contrast, the most susceptible area in Vertisols is approximately two times higher than in Nitisols. Similar predictions have been obtained for both soils for the moderate and high susceptible classes.

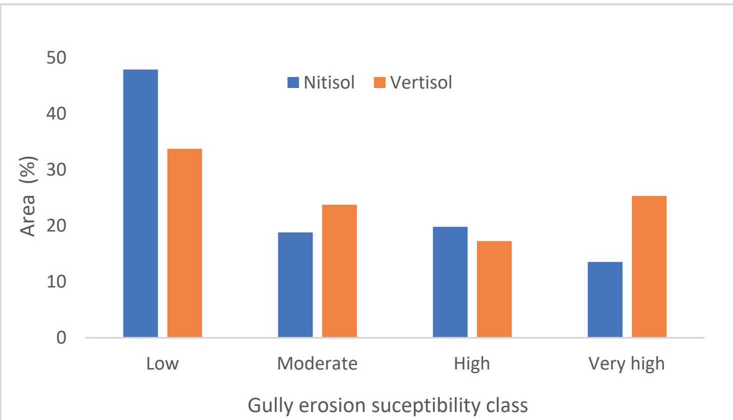


***Figure 4.6*** *Gully erosion susceptibility in Nitisol and Vertisol soils.*

### *4.3.4 Model Validation*

Model performance for the FR and RF models was evaluated for five scenarios (Figure 4.7). The first case involved all predictor factors (i.e., using the 14 gully-predictor factors, excluding TRI and slope), called “All” hereafter. The second case used the top six factors obtained from Figure 4.4c, called “Top6” hereafter. The third case used all the top six gully-predictor factors but excluded soil type, called “exclSoil” hereafter. The fourth case involved all the top six gully-predictor factors but excluded GWT, called “exclGWT” hereafter. The third and fourth cases were evaluated to see the predictive potential of the newly introduced parameters (i.e., soil type and GWT) for gully prediction. In the fifth scenario, the top four factors obtained from Figure 4.4c were used; this scenario is called “Top4” hereafter.

The prediction accuracy of models using AUC is categorized as poor (0.5–0.6), average (0.6–0.7), good (0.7–0.8), very good (0.8–0.9), and excellent (0.9–1) (Meliho et al., 2018). In the case of RF, all five scenarios demonstrated excellent model prediction accuracy. The Top4 and Top6 model scenarios provided the best AUC values (99.9%). A higher AUC value (99.8%) was also obtained for the All model scenario in the RF model. Prediction accuracy after excluding soil type (exclSoil) and GWT (exclGWT) from the top six factors was 97.9% and 99.3%, respectively.

Prediction accuracy using the FR model ranged from average to good. Similar to the RF model, the highest prediction accuracy (AUC = 71.6%) was obtained for the Top4 FR model. The AUC values for the exclSoil and Top6 models were 70.8% and 70.7%, respectively. Lower AUC values were obtained for the All model (AUC = 63.3%) and the exclGWT model (AUC = 63.1%). Excluding the GWT reduced the FR model prediction accuracy by about 7%, whereas excluding the soil type did not affect the FR model’s performance.

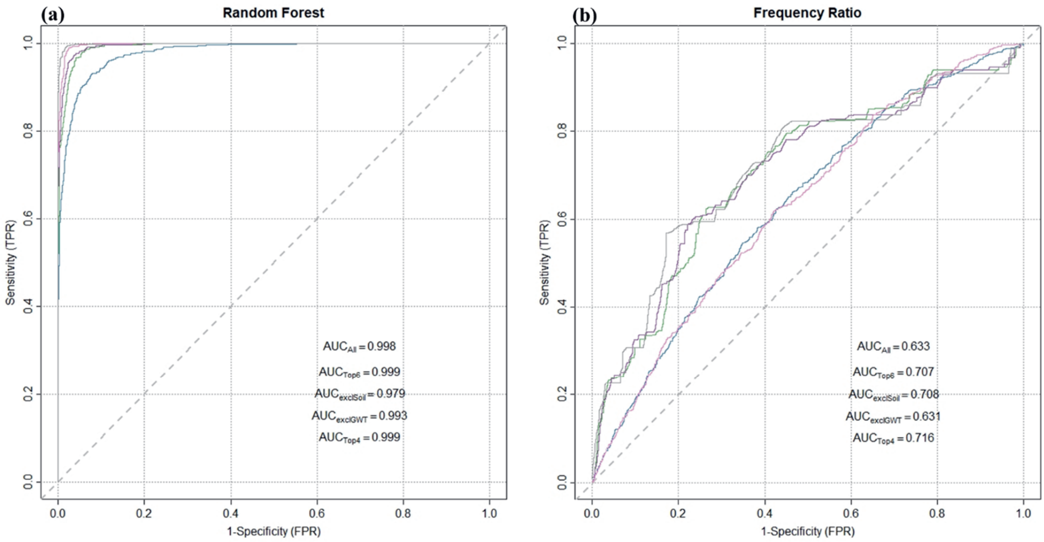


***Figure 4.7*** *Receiver operating characteristic (ROC) curves for the random forest (a) and frequency ratio (b) models. Model performance was evaluated for five different cases: (1) All: using all predictor factors; (2) Top6: using the top six factors, as presented in* ***Figure 4.4****c; (3) exclSoil: using all top six gully-predictor factors except soil type; (4) exclGWT: using all top six gully-predictor factors except GWT; and (5) Top4: using the top four factors, as presented in* ***Figure 4.4****c.*

## 4.4 Discussion

### *4.4.1 Spatial Distribution of Gullies and Gully-Erosion Predictor Variable Importance*

All 14 gully-erosion predictor factors were important for gully the development in the Minzir catchment at different levels of importance. However, gully erosion prediction using the FR and RF models showed that the best prediction accuracy was obtained using the top four most important gully-predictor factors (DD, elevation, land use, and GWT). This suggests that the impact of the other factors on gully erosion is well illustrated by DD, elevation, land use, and GWT.

DD was found to be the most important factor that determines gully location in the study catchment. Studies have shown that gully erosion susceptibility increases with increasing DD (Akgün & Türk, 2011; Javidan et al., 2019; Rahmati et al., 2017a). The FR values obtained in this study are the highest for the middle DD classes, and smaller values were obtained for the two highest classes. As described above, gully erosion is dominantly a function of the four major factors. Therefore, lower FR values for the two highest DD classes may be attributed to little contribution from the other three gully predictor factors. For example, the GWT in this area was the deepest, indicating little susceptibility to gully erosion.

Elevation was found to be the second most important gully-erosion predictor factor. The two lower elevation classes (2030–2070 and 2070–2104 m a.s.l.) had the largest gullied area, which was revealed by high FR values obtained for these classes (Table 4.5). This finding is consistent with studies in subhumid Iran, which found low elevation areas are vulnerable to gullies due to concentrated flow (Zabihi et al., 2018).

The third most important gully-erosion predictor factor was land use/cover. This is consistent with studies that found land cover as one of the most important factors determining gully locations (Arabameri et al., 2019b; Conforti et al., 2011; Hosseinalizadeh et al., 2019). While in the Minzir catchment, the area of grazing land (13.2%) is smaller than that of cultivated land (82.7%), it has the largest proportion of gullies, which was revealed by a high FR value (Table 4.5). Studies have stated that grazing lands are more susceptible to gully-erosion than other land-use groups (Amare et al., 2019; Kariminejad et al., 2019; Zabihi et al., 2018). Moreover, Bewket (2002); Gábris et al. (2003) reported that the conversion of forest land to cultivated and grazing land had resulted in increased gully erosion. Land-use change affects gully erosion by altering soil's hydrological and physicochemical properties. For instance, in tropical Brazil, grazing has increased the amount of surface runoff that, in turn, increased saturated area and subsurface flow in valley bottoms, which has led to gully development (Marinho et al., 2006). Forest plantations have resulted in a double increase in organic carbon and steady-state infiltration, improving aggregate stability (Jha et al., 2010). It was found that uncultivated land had twice as much soil organic carbon as 50-year-old cultivated land, which enhances soil aggregate stability and, therefore, increases soil resistance to erosion (Liu et al., 2010).

The relationship between the spatial distribution of gullies and the elevation of the terrain and slope suggested that gullies are mainly located at the valley bottom. This finding agrees with Arabameri et al. (2020); Javidan et al. (2019), who reported that valley bottoms are more vulnerable to gullies due to concentrated flow. Field observations have also shown that intensified agricultural activities in the valley bottom expose the catchment to all forms of land degradation.

The fourth most important factor that determines gully erosion is GWT. Gullies have been observed in all classes of GWT, but FR values have shown that areas with GWT depths shallower than 2 m are the most susceptible to gullies (Table 4.5). This is consistent with most studies in subhumid Ethiopia, where elevated groundwater increases soil pore water pressure and enhances gully erosion rate (Ayele et al., 2018; Tebebu et al., 2010). This is also in agreement with the findings of (Selamawit Amare et al., 2020), who have reported a higher gully head retreat rate (about four times) for gullies with shallower GWT than areas with deeper GWT.

### 4.4.2 Gully Susceptibility in Vertisols and Nitisols

Both Nitisols and Vertisols, the dominant soils in the study catchment, were vulnerable to gully erosion (Table 4.5). However, both the GESM and the FR value showed that Vertisols are more prone to gully erosion than Nitisols. The RF-model-derived GESM showed that “low” susceptible classes in Nitisols (47.9%) were larger than Vertisols (33.7%), whereas “very high” susceptible classes were larger in the Vertisols (25%) than the Nitisols (13.7%). This is in line with the finding by Selamawit Amare et al. (2020) that higher moisture retention capacity, poor drainage, and elevated GWT lead to increased pore water pressure, which results in higher rates of gully erosion in Vertisols than in Nitisols that have lower water retention capacity and deeper GWT. In addition, Nitisols are a well-drained soil type (Spaargaren, 2001) that reduces gully erosion due to both concentrated flow and soil saturation. Additionally, Nyssen et al. (2000) found that Vertisols' high swelling and shrinkage nature makes them more sensitive to gully erosion. The FR values also show that Fluvisols and Cambisols, which occupy a very small percentage of the catchment, are susceptible to gullies.

The results of separate variable importance analyses for Nitisols and Vertisols showed land cover and drainage densities as the number-one factor determining the location of the gully in each soil, respectively. Land cover for Vertisols was ranked number nine, suggesting it has little significance for gully-erosion in this soil. The other important gully-erosion factors (i.e., elevation, TWI, and GWT) are similar for both soils. Further research is needed on the fact that land cover is the most important gully-erosion factor for Nitisols.

### 4.4.3 Model Performance and Comparison

The performance of the FR models ranged from average to good, whereas, for the RF model, excellent prediction accuracy was obtained. Excellent model performance was achieved for all five models in the RF model. FR model performance was average for the exclGWT and All models, whereas Top4, Top6, and exclSoil models performed good. The Top4 model performed better in both RF and FR cases than the other four models. This suggests that despite the importance of all predictor factors for gully erosion, gully erosion can successfully be predicted using only DD, elevation, land cover, and GWT.

The impact of excluding GWT and soil type as gully erosion predictor factors had a smaller impact on the RF model performance, whereas excluding GWT from the top six parameters caused a 7% reduction in the AUC value of the FR model. This shows the high explanatory power of the GWT parameter on the FR model. Moreover, GWT is among the top four most important parameters determining gully locations. Therefore, accounting for this parameter in future gully erosion prediction research can improve accuracy, especially in subhumid areas. Excluding soil type from the FR model did not affect the model performance. Despite this, soil type being the sixth most important factor determining gully development suggests its significance for gully erosion.

The excellent model performance in all five RF model scenarios may attribute to the ensemble learning algorithm in the RF model that works on majority voting principles by growing a large collection of decorrelated decision trees (or models) as a base learner. As a result, a single classifier error in the RF model is outweighed by the majority (Wang et al., 2020), whereas FR is a single model. Furthermore, RF can handle high dimensionality (high numbers of attributes) and large datasets better than FR.

The excellent prediction accuracy achieved by the RF model is in agreement with Arabameri et al. (2019b) and Hosseinalizadeh et al. (2019), who have successfully mapped gully erosion and gully head susceptible areas. The FR model employed in this study predicts gully areas better than other statistical models such as weight of evidence and index of entropy (Rahmati et al., 2016a; Zabihi et al., 2018).

Current approaches toward gully erosion susceptibility mapping in the Ethiopian highland are based on topographical threshold factors such as topographic wetness index (TWI) and stream power index (SPI) (Assefa et al., 2015; Mhiret et al., 2018). The application of these thresholds is flawed, primarily because streams and saturated-bottom lands are preferentially considered most vulnerable to gullies. However, our findings have shown that TWI and SPI's importance on gully erosion is limited compared to the top four factors presented in this study, which have provided the best model prediction accuracy. Therefore, the finding of this research can be used for the successful planning and design of gully reclamation measures in a catchment.

## 4.5 Conclusions

There is no single factor responsible for the formation of gullies in the study area; all 14 factors we examined were important for the development of gullies in the Minzir catchment. However, gully erosion prediction using the FR and RF models showed that the best prediction accuracy was obtained using the top four most important gully-predictor factors: drainage density, elevation, land use, and groundwater. This suggests that the impact of other gully-erosion parameters is well illustrated by the top four important gully-erosion predictor factors. The separate variable importance analysis for Nitisols and Vertisols showed land cover and drainage densities, respectively, as the most important factors that determine gully locations. The other most important factors for both soils were more or less similar. The fact that land cover is the most important factor for the development of gullies in Nitisols requires further investigation. This study suggests that future planning and implementation of conservation measures in subhumid regions of Ethiopia should target areas with higher drainage density, low-lying areas, grazing land, and shallower groundwater table, which are vulnerable to gully erosion.

Frequency ratio (FR) and random forest (RF) models have been identified as useful techniques for mapping vulnerable areas and identifying the most important gully erosion predictor factor. The performance of the FR models ranged from average to good, whereas for the RF model, excellent prediction accuracy was obtained. The gully erosion susceptibility map developed in this study can be used to plan informed gully erosion rehabilitation and prevention measures in the Minzir catchment. As sediment from gullies threatens the entire upper Blue Nile basin, a water source for many water resource development activities, we recommend similar studies in different agroecology and geomorphic settings within the degraded Ethiopian highlands.

# 5. Landscape Evolution by Combined Hillslope Erosion and Gully Head Migration

This chapter is based on:

Amare, S., Langendoen, E., Keesstra, S., Ploeg, M. V. D. & van der Zee, S. E.. Landscape Evolution by Combined Hillslope Erosion and Gully Head Migration. Earth Surface Processes and Landforms (to be submitted).

## Abstract

Gullies expand primarily through gully head-cut retreat and, to a lesser extent, through the expansion of gully wall retreat. Most gully head-cut retreat equations developed for various agro-ecology have local importance. There is a lack of models for predicting the effects of environmental factors on gully head erosion at different temporal and spatial scales. This study developed a new model called Gully Erosion by Headcut Migration (GEHM), which accounts for various environmental and climatic factors, and models gully head erosion at a landscape scale. GEHM is a new Python package that enables gully head erosion to be modeled along with other earth surface processes at a landscape scale over a period spanning tens of years or less. The model uses various terrainbento and landlab model components in combination with the gully head migration model. The sensitivity analysis for selected gully erosion parameters showed that the model is sensitive to changes in groundwater level, hydraulic conductivity, drainable porosity, water erodibility, and head-cut height. Model outputs such as gully head retreat, cumulative soil erosion, aquifer thickness, and groundwater storage showed similar trends as existing studies for a given change in the input parameter. In addition to modeling gully head evolution at the landscape scale, the GHEM can model changes in groundwater storage due to soil losses from gully head and hillslope erosion, which can be used as input in the design and planning of land and water resource management.

## 5.1 Introduction

Gully formation causes significant onsite and offsite problems. On-site, it reduces soil quality significantly due to high soil losses of up to 10–100 t $ha^{-1}$ $y^{-1}$ (Poesen et al., 2002). They also cause a reduction in the groundwater table, root zone soil moisture, and transpiration (Chen et al., 2020b), leading to significant crop yield reductions through enhanced drainage and soil desiccation. Furthermore, gullies reduce land trafficability, resulting in an additional economic cost for farmers and residents (Poesen et al., 2011). Offsite impacts include transportation of pollutants from agricultural land to water bodies (Mircea et al., 2007) and reservoir sedimentation (Ionita et al., 2015a).

Gully erosion is defined as the erosion process in which runoff water accumulates and frequently recurs in narrow channels, removing soil from these narrow areas to great depths over short periods (Poesen et al., 2002). They are also defined by (SSSA, 2008) as too deep channels to be easily remedied with regular farm tillage equipment, depth typically ranging from 0.5 m to 30 m. Gullies form when a geomorphic threshold is exceeded due to decreased material resistance, increased runoff erosivity, or both (Patton & Schumm, 1975). The threshold may be related to factors external to the gully (e.g., climate and anthropogenic) or related to the gully itself (e.g., bank height) (Schumm, 1979). However, little progress has been made in connecting factors external to the gully to factors related to the gully itself and model gully erosion at a landscape scale.

Furthermore, mathematical models for gully erosion are far less developed than sheet erosion and rills (Mircea et al., 2015). Once initiated, gullies expand primarily through gully headcut retreat and, to a lesser extent, by gully wall retreat. However, most head retreat equations developed for different agro-ecology are of local importance (Poesen et al., 2011). Only a few studies have attempted to model gully head evolution at a landscape scale (Flores-Cervantes et al., 2006; Leyland & Darby, 2009). However, to our knowledge, there are no studies that attempted to model gully head erosion due to a combination of gully morphology, soil saturation, discharge, groundwater table, and gully height both at shorter time and landscape scales. Models that integrate gully channels with the hillslope process are also lacking.

The interactions between gully erosion and hydrological and other soil erosion processes must be better understood to improve predictions of hydrological response and land degradation rates under various environmental conditions. This improved understanding serves as the foundation for taking appropriate and effective soil erosion control measures (Poesen et al., 2011).

Therefore, in this study, a new model called Gully Erosion by Headcut Migration (GEHM) is developed, which accounts for various environmental and climatic factors, and models gully head erosion at a landscape scale. GEHM is a new python package that enables gully head erosion to be modeled along with other earth surface processes. The model uses terrainbento and landlab model components in combination with the gully head migration model. We will test the model's sensitivity to various hydrological and soil parameters that have been confirmed to impact gully head erosion.

## 5.2 Materials and methods

Gully erosion has been linked to hydrologic, soil, morphologic, and climatic factors of a given place (Valentin et al., 2005). Different studies have emphasized the need for a landscape gully erosion model that takes these factors into account. As a result, in this study, we developed a new model called Gully Erosion by Headcut Migration (GEHM), which accounts for various environmental and climatic factors, and models gully head erosion at a landscape scale. The model will save outputs including topographic elevation, aquifer thickness, soil saturation, surface water discharge, sediment transport rate, and gully head location at user-specified time intervals.

### *5.2.1 Numerical model*

In this section, we will demonstrate the usage of a new model called the GEHM (Gully Erosion by Head-cut Migration) model, which combines features of various terrainbento (see Barnhart et al. (2019) and (Barnhart et al., 2020; Hobley et al., 2017) landlab model components with the gully head migration model of Rengers and Tucker (2014a). GEHM uses the groundwater percolator landlab component of Litwin et al. (2020) to calculate runoff. Landscape evolution is based on terrainbento's two lithology erosion model with sediment transport and channel erosion simulated using the SPACE landlab component of Shobe et al. (2017) and soil creeps simulated with the Taylor nonlinear diffuser landlab component.

This model is aimed to study gully erosion processes over a period spanning tens of years or less. Therefore, we will neglect bedrock incision and soil creep that are included to simulate landslides when a hillslope exceeds a threshold value. In the following section, we presented a summary of gully head erosion model (section 2.1.1) and its incorporation into GEHM model (section 2.1.2), as well as the procedures followed to implement the GEHM using the python programing language (section 2.1.3).

#### *5.2.1.1 Gully head erosion model*

The sediment derived from head-cut wall retreat and downstream sediment depositional patterns were calculated using the Rengers and Tucker (2014b) method. The depositional pattern of sediment generated by the head cut is expressed using an exponential pattern that decays downstream from the head-cut face (equation 1).

$$d_{hc}(l) = \frac{RHc}{l*} e^{-l/l*} \tag{1}$$

where $d_{hc}$ (L$^2$ T$^{-1}$) is the deposition rate due to wall collapse downstream of the head cut, $R$ (L T$^{-1}$) is the head-cut retreat rate, $Hc$ (L) is the height of the head-cut, $l$ (L) is the distance downstream of the head-cut, and $l*$ (L) is a characteristic length scale for wall collapse.

In this study we employed and tested four gully head retreat methods ($R$), namely 1) "constant", 2) "discharge", 3) "saturation", and 4) "q_sat". The constant and discharge retreat rate methods are described in detail by Rengers and Tucker (2014b). The "saturation" and "q_sat" are new headcut retreat methods introduced in this study. The "saturation" retreat method calculates retreat rate as a function of the soil saturation at the gully head, whereas "q_sat" is a linear combination of the discharge and saturation retreat methods.

#### *5.2.1.2 Gully Erosion by Head-cut Migration, GEHM*

GEHM is a new python package that enables gully head erosion to be modeled along with other earth surface processes at a landscape scale. As described above, the model uses terrainbento and landlab model components in combination with the gully head migration model. Terrainbento allows multi-model comparison, sensitivity analysis, and calibration of earth's surface process models. It also offered a set of model programs that incorporate alternative transport laws related to four processes: hillslope processes, surface-water hydrology, erosion by flowing water, and material properties (Barnhart et al., 2019). Landlab is a python-language that provides tools and process components that can be used to construct earth-surface dynamics models over various temporal and spatial scales (Adams et al., 2017).

Landscape evolution by GEHM takes an equation of the form described in equation (2). The terms I-III on the right-hand side of the equation concern I channel erosion, II head-cut migration, and III soil creep or hillslope soil volume flux.

$$\frac{\partial \eta}{\partial t} = \underbrace{\frac{D_s - E_s}{1-\phi}}_{I} + \underbrace{\frac{RH_c}{l_*} e^{-l/l_*}}_{II} - \underbrace{\nabla q_h}_{III} \tag{2}$$

where $\eta$ (L) is topographic elevation, $t$ (T) is time, $E_s$ (L T$^{-1}$) and $D_s$ (L T$^{-1}$) is entrainment and deposition sediment flux, respectively, $\phi$ (–) is soil porosity, $R$ (L T$^{-1}$) is gully head retreat rate, $H_c$ (L) is head-cut height, $l$ (L) is distance downstream of the head-cut, $l_*$ (L) is a characteristic length scale for gully-head collapse deposits, and $q_h$ (L$^2$ T$^{-1}$) is hillslope sediment flux.

$$D_s = V_s Q_s$$

$$E_s = (1-\phi)[\omega - \omega_c(1-e^{-\omega/\omega_c})](1-e^{-H/H_*})$$

$$q_h = -DS\left[1 + \left(\frac{S}{S_c}\right)^2 + \left(\frac{S}{S_c}\right)^4 + \cdots \left(\frac{S}{S_c}\right)^{2(N-1)}\right]$$

where $V_s$ (L T$^{-1}$) is settling velocity, $Q_s = \int_0^A (E_s - D_s)dA$ (L$^3$ T$^{-1}$) is sediment flux, $A$ (L$^2$) is the local upstream drainage area, $\omega = K(\eta, \eta_C)QS$ (L T$^{-1}$) is stream power, $Q$ (L$^3$ T$^{-1}$) is discharge, $S$ (–) is the local slope, $\omega_c(\eta, \eta_C) = w\omega_{c1} + (1-w)\omega_{c2}$ (L T$^{-1}$) is threshold stream power for erosion, $K(\eta, \eta_C) = wK_1 + (1-w)K_2$ (L$^{-1/2}$ T$^{-1/2}$), $K1$ (L$^{-1/2}$ T$^{-1/2}$) and $K2$ (L$^{-1/2}$ T$^{-1/2}$) are the erodibilities of the upper and lower soil layers, $\omega c1$ (L T$^{-1}$) and $\omega c2$ (L T$^{-1}$) are the threshold stream power values of the upper and lower soil layers, $w = \frac{1}{1+e^{-(\eta-\eta_C)/W_C}}$ (–) is a weight used to calculate the effective erodibility and threshold stream power based on the depth to the contact zone, $\eta_C$ (L) and the width of the contact zone, $W_c$ (L) of the two soil layers, $H = \eta - \eta_b$ (L) is soil thickness, $\eta_b$ (L) is bedrock surface elevation, $H_*$ (L) is bedrock roughness length scale, $D$ (L$^2$ T$^{-1}$) is the regolith transport parameter, and $Sc$ (–) and $N$ (–) are critical slope and number of terms in the nonlinear hillslope diffusion model.

#### *5.2.1.3 Model implementation*

*Preparing the topography*

We created the Gully Erosion model in Terrainbento using Landlab features to generate a 2D hillslope topography having an S-shaped hillslope profile that mimics a natural hillslope profile. The topography developed consists of a 2D raster hillslope with a width of 1000 m and a height of 600 m (see Figure 5.1). The hillslope profile is generated based on toe, mid, and top hillslope segments. The S-shaped profile comprised a 250 m long bottom segment at 3% slope, a 250 m long middle segment at 10% slope, and a 100 m long top segment at 5% slope. These segments are connected by curved sections whose radius of curvature is 2500 m. The raster cell size is 5 m x 5 m. A random, uniformly distributed roughness with a vertical extent of 0.3 m is superimposed on the hillslope topography. The base elevation is 10 m, and the initial soil depth across the entire hillslope is 3 m. The soil comprises two units of 1.5 m in height each.

The generated hillslope raster is used to construct a LandlabRasterModelGrid named mg. The grid's left, top, and right boundaries are closed, whereas the bottom boundary is open (i.e., water and sediment can leave the hillslope through its bottom boundary).

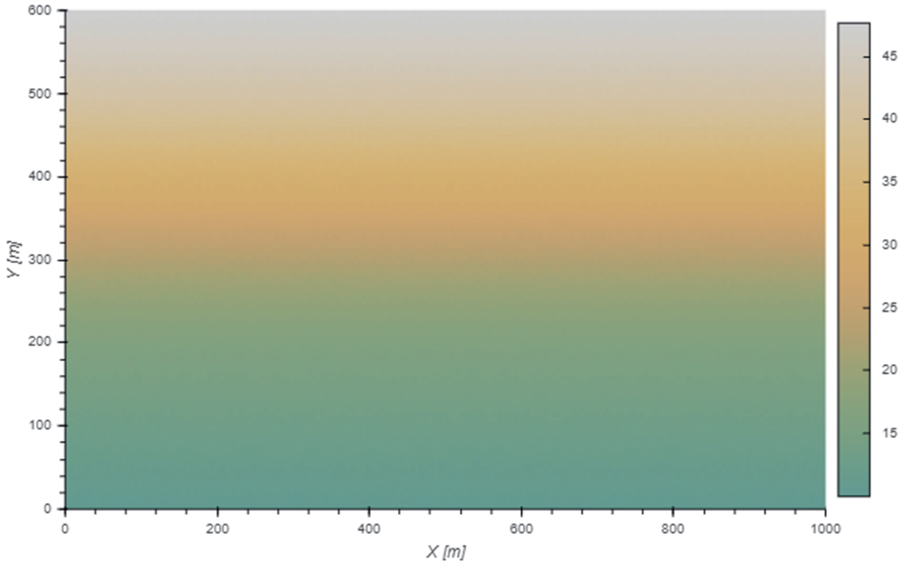


***Figure 5.1*** *Depicts a 2D hillslope topography having an S-shaped hillslope profile and a width of 1000 m, and a height of 600 m. The bar going from 15 to 45 depicts elevation variations.*

Setting the initial gully head locations

Gully heads will be inserted at the outlets of the ten largest channels. These channels are identified by running the flow accumulation component of landlab. The channel network is visualized by specifying a channel mask for raster cells exceeding a drainage area of 2000 square meters (Figure 5.2). Gully heads migrate along model-grid links that connect model-grid nodes. Runoff and topography information are stored at nodes with the transport of water and sediment occurring along links. Here, the gully heads are located immediately upstream of the outlets of the ten largest channels. They are located about midway (45% of the link length relative to the upstream node) and have a default height of 2 m.

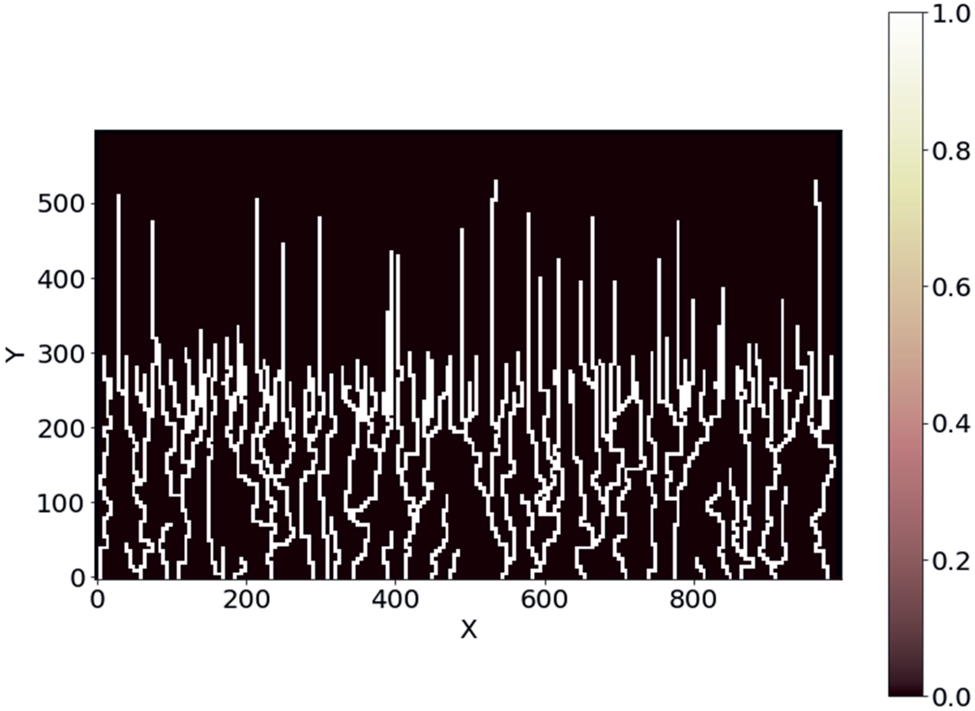


***Figure 5.2*** *Channel network for raster cells exceeding a drainage area of 2000 square meters (depicted by 1 in the bar) and the remaining cell with less than 2000 square meters are depicted by 0.*

Preparing the hydrologic computations

Runoff is calculated by the groundwater dupuit percolator landlab component, which requires the aquifer base (i.e., impervious layer) and land surface elevations set by the fields aquifer_base_elevation and topographic__elevation. The aquifer base was set to the bedrock elevation (i.e., 7 m), and the land surface elevation was set to 10 m, which means we have a soil depth of 3 m. The simulated groundwater table is stored in the field water_table__elevation ($\eta_g$), initialized as 0.5 m above the bedrock elevation. The surface water and groundwater fluxes are determined by the input recharge (m/day) and the soil properties (hydraulic conductivity (m/day) and drainable porosity (-)). The soil properties are set when creating the GEHM object. GEHM determines recharge from the input rainfall flux (m/day) and ground surface infiltration capacity. The latter is set during the creation of the GEHM object.

### *5.2.2 Model parameterization*

In this study, the GHEM was tested for the four head-cut retreat methods: constant, discharge, saturation, and q-sat methods. We set a five-year rainfall record *r*, which comprises, on an annual basis, four months of 0.02 m/day of rainfall and zero rainfall for the remainder of the year. A terrainbento clock is set consisting of 1825 days (five years) with a daily time step. The hydraulic conductivity of both soil layers is set at 0.5 m/day, whereas the drainable porosity of the upper and lower soil layer is 0.2. The infiltration capacity of the land surface is set to 1 m/day (~42 mm/hr). The erodibility of both soil layers equals 0.0005 1/m$^2$. Note, the unit of stream power as defined above is m/day. As the units of discharge $Q$ are m$^3$/day, the unit of $K$ is 1/m$^2$. GHEM can account for the increased erosion in the plunge pool downstream of the gully head by increasing erodibility by a factor plunge_pool_erodibility_factor, set here to 5. Soil creep is not accounted for ($D$=0).

For the constant retreat method, we set the gully heads to migrate at a constant rate of 0.2 m/day. In the discharge method following Rengers and Tucker (2014b), gully head retreat rate by water discharge is defined as $\mathrm{R_Q} = a\sqrt{\mathrm{Q}_h}$, where $a$ is a retreat rate coefficient (m$^{-1/2}$ day$^{-1/2}$) and $Q_h$ is the water discharge at the gully head. The coefficient $a$ is set such that the gully head retreats approximately 0.6 m/day when the square root of the discharge is about half the square root of the discharge at the gully channel outlet for the situation where all rainfall (uniform precipitation of 0.02 m/d) becomes surface runoff.

In the saturation test case, the gully head migration rate is a function of soil saturation. The gully head retreat rate is set such that the gully head retreats approximately 0.2 m/day when the soil saturation at the gully head is 50%. The q-sat method gully head migration rate is a function of linear combination of discharge and saturation method. The coefficient $a$ in the discharge method is set such that the gully head retreats approximately 0.2 m/day when the square root of the discharge is about half the square root of the discharge at the gully channel outlet for the situation where all rainfall (uniform precipitation of 0.02 m/d) becomes surface runoff. The gully head retreat rate for soil saturation is set to 0.05 m/day when the soil saturation at the gully head is 50%. For all the four cases, the gully heads only migrate upstream along the main stem of the drainage network.

## 5.3 Result

### *5.3.1 Sensitivity analysis*

The following sections will examine model sensitivity to various gully head erosion factors such as groundwater, hydraulic conductivity, drainable porosity, water erodibility, and height-cut height.

#### 5.3.1.1 Groundwater depth

The impact of groundwater depth on gully head retreat for the four gully head retreat methods (i.e., constant, discharge, saturation, and q-sat) was observed by setting groundwater at depths of 0.5, 1.5, and 2.5 m. The impact of groundwater on head-cut retreat is subtle by only looking at the total head-cut retreat at the end of the 5-year modeling period (Figure 5.3). However, the groundwater depth impacts are visible at the beginning of the modeling period for all head-cut retreat methods. For a higher groundwater height (2.5 m), gully head for the constant, discharge, saturation, and q-sat methods began incising at 12-, 12-, 8-, and 10-days since the simulation started. Whereas for smaller groundwater height (0.5 m), the head-cut retreat began later, on the 37$^{th}$ day since the simulation started.

Furthermore, cumulative soil erosion from the entire topography increases with increasing groundwater depth from 0.5 to 2.5 m for all four retreat methods. The term "sediment from the entire topography" refers to material eroded from both the hillslopes and gully heads. Figure 5.4 depicts the variations in cumulative erosion with varying groundwater heights for the discharge retreat method only, as all others produced similar results. The cumulative erosion increase as groundwater height declines from 1.5 to 0.5, 2.5 to 1.5, and 2.5 to 0.5 is about 3572, 6370, and 9940 m$^3$, respectively. Moreover, at groundwater heights of 0.5, 1.5, and 2.5, the topography started incising at 22-, 14-, and 4-day modeling periods, indicating that catchments with higher groundwater heights begin to erode faster than areas with smaller groundwater table depths.

Needless to say, soil with higher groundwater becomes saturated with incoming rainfall more quickly than soil with a lower groundwater height. Figure 5.5 shows how an initial aquifer thickness of 0.5, 1.5, and 2.5 m responded to the incoming rainfall flux at 5, 10, 15, and 20-day simulation periods. The aquifer thickness for a 2.5 m initial groundwater table height reaches the surface faster, as indicated by a darker blue color than for a 0.5 m aquifer thickness, as indicated by a lighter blue color.

The difference in cumulative soil erosion and total head-cut retreat over five years between the four head-cut retreat methods is subtle for varying initial groundwater heights (Figure 5.3). Unlike the other three retreat methods, the head-cut for the discharge-dependent retreat method begins incising after groundwater reaches the surface and stops eroding when the rainfall ceases. On the other hand, the remaining three methods begin incising the gully head even before the groundwater reaches the soil surface and continue eroding the head-cut for a short time after the rain stops.

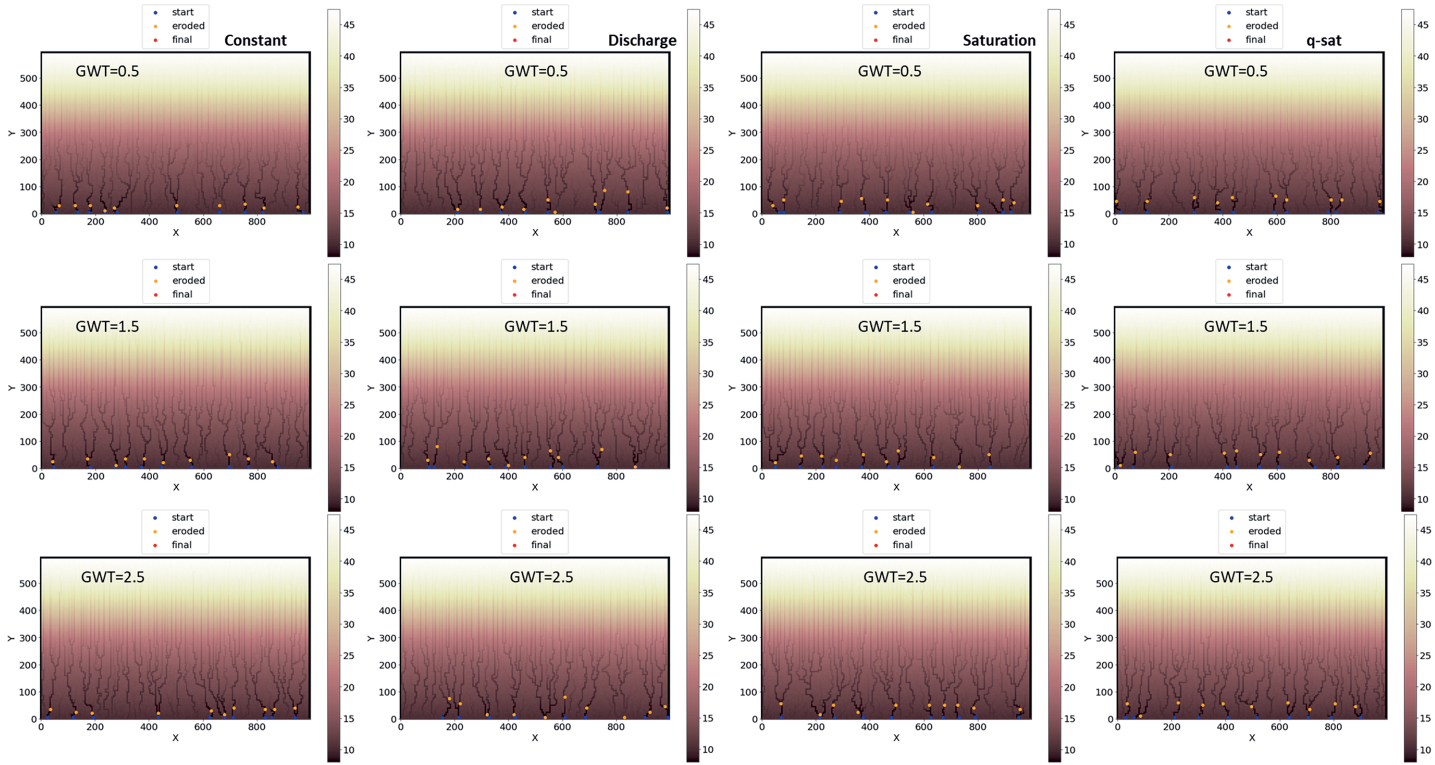


***Figure 5.3*** *depicts the location of the gully heads on the landscape's topographic elevation (the shading brown to light yellow represents topographic elevation) with a column containing each of the four retreat methods for groundwater heights of 0.5, 1.5, and 2.5 m. A blue circle marks the initial location of the gully heads. A red circle marks the final location (however, they are not visible in these plots as all gully heads are arrested). An orange circle indicates where a gully head gets arrested (insufficient upslope drainage area or eroded).*

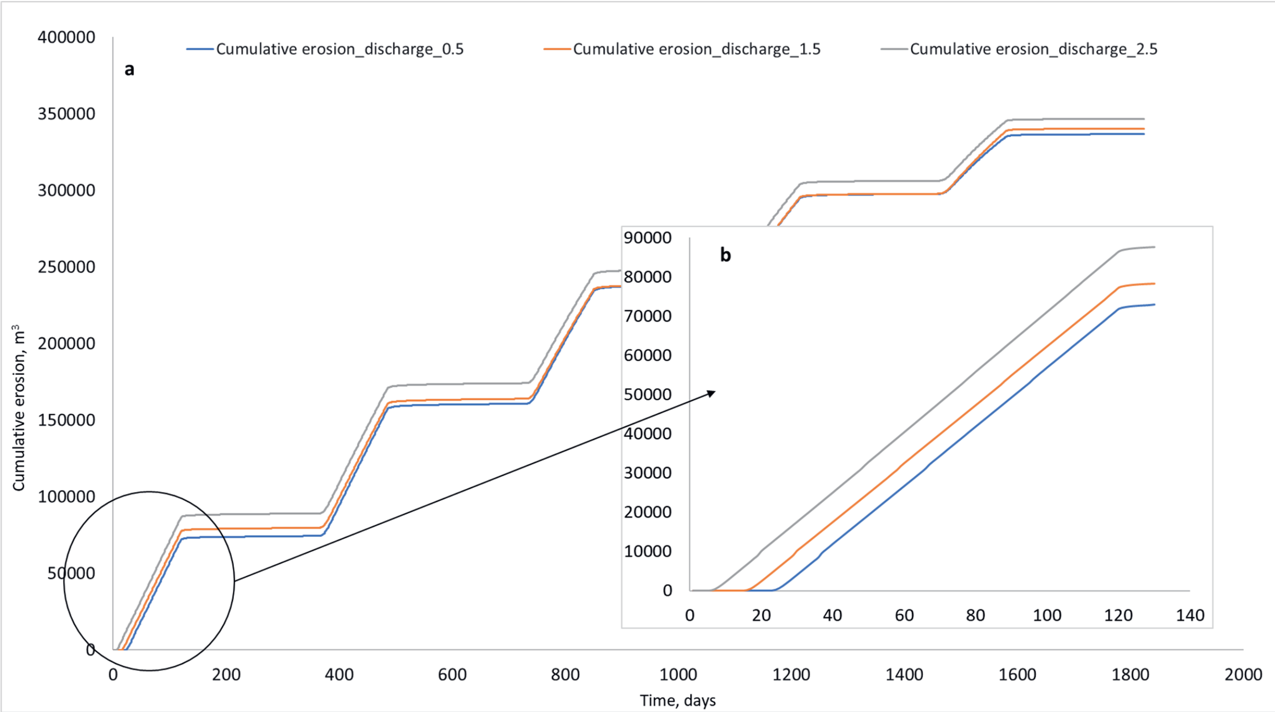


***Figure 5.4*** *a) Five-year cumulative soil erosion using a discharge-dependent retreat method at groundwater depths of 0.5, 1.5, and 2.5 m. b) Zoomed in on the first 130 days of simulation to show the variation in cumulative eroded sediment.*

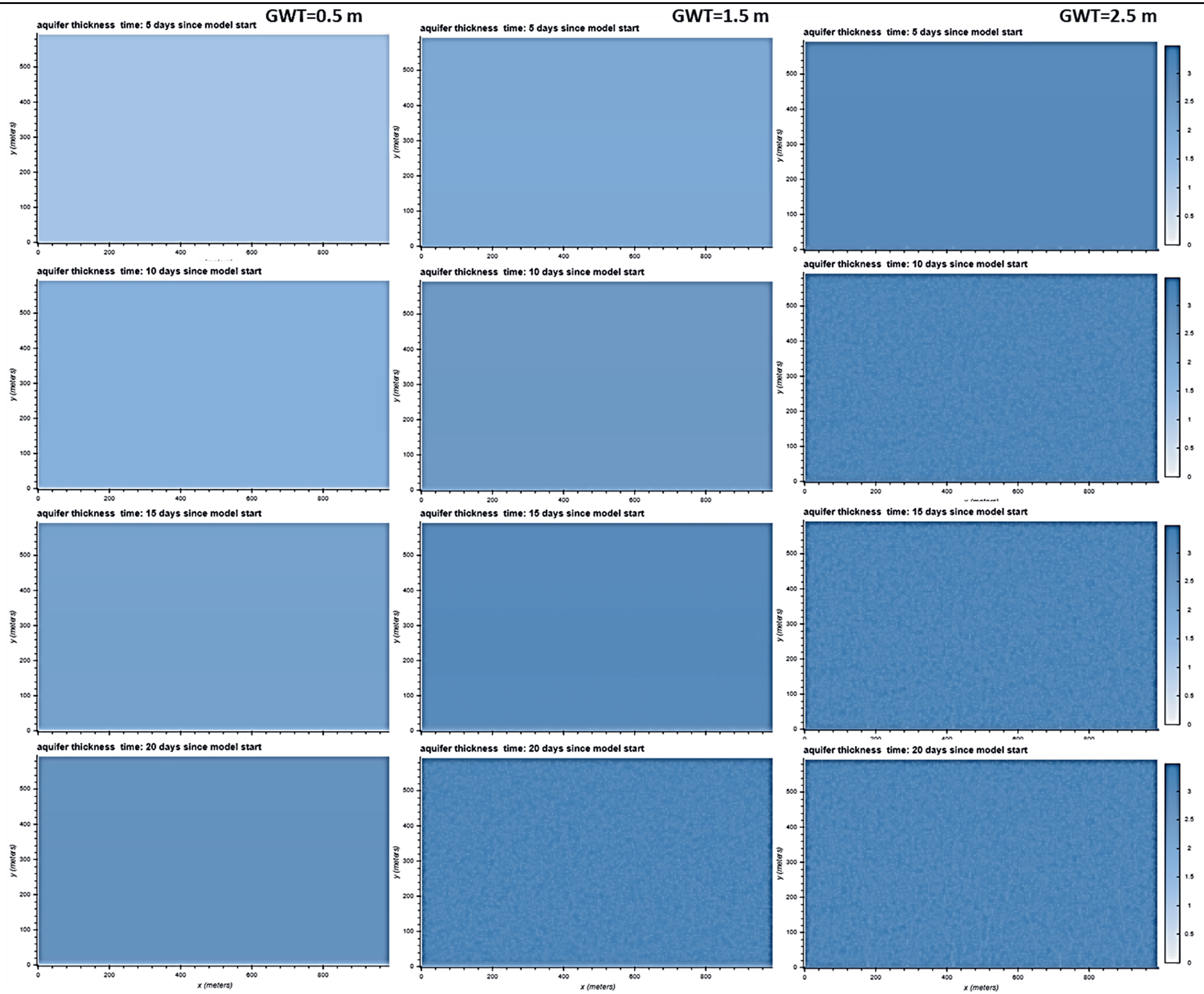
GWT=0.5 m
GWT=1.5 m
GWT=2.5 m
aquifer thickness time: 5 days since model start
aquifer thickness time: 10 days since model start
aquifer thickness time: 15 days since model start
aquifer thickness time: 20 days since model start
y (meters)
x (meters)

***Figure 5.5** Shows the aquifer thickness for 5, 10, 15, and 20-day simulation periods, with each column representing the initial groundwater height of 0.5, 1.5, and 2.5 m measured from the bedrock.*

### 5.3.1.2 Hydraulic conductivity, HC and drainable porosity, DP

Hydraulic conductivity (HC) and drainable porosity (DP) significantly impact gully head erosion. However, as seen in the groundwater case, these impacts are not apparent by only looking at the total head-cut retreat on the topography at the end of the 5-year modeling period (Figure 5.6). For all the four head retreat methods, for simulations having lower HC and DP (0.04 & 0.06, respectively) values, the gully head incision began earlier ($11^{th}$ day). In contrast, for simulations with higher HC and DP (0.5 & 0.2, respectively), the gully head incision started later on the $29^{th}$ day of the modeling period.

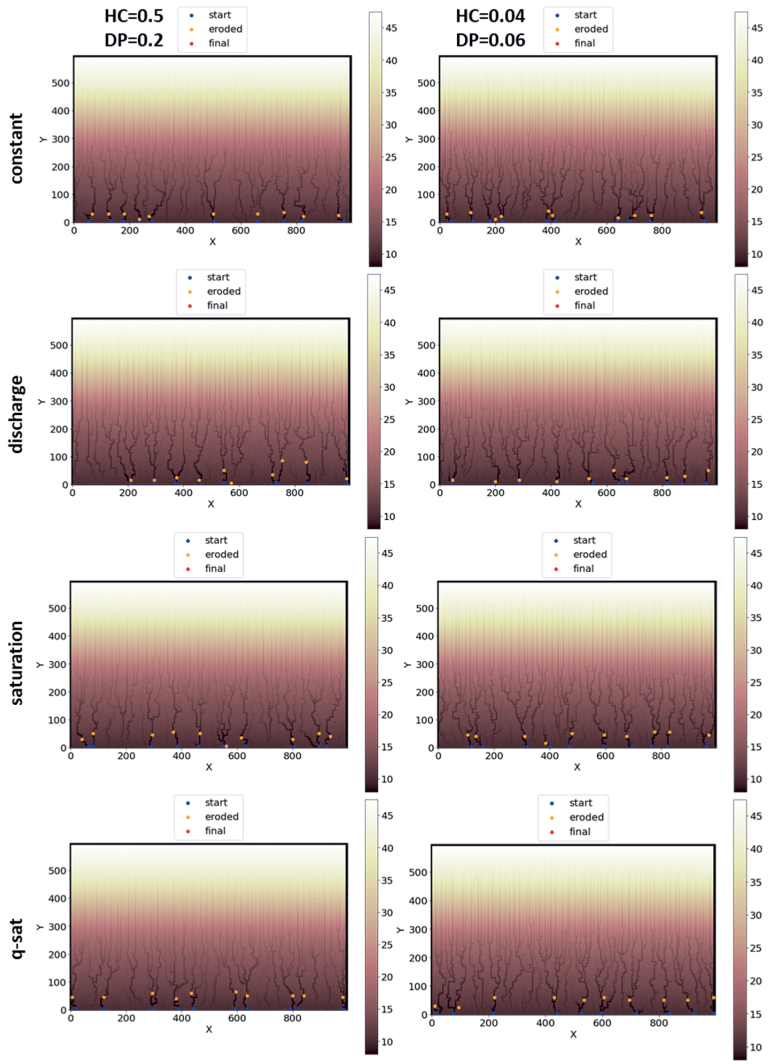


***Figure 5.6*** *Location of the gully heads on the landscape's topographic elevation, with the first and the second column containing a hydraulic conductivity and drainable porosity of (0.5 & 0.2) and (0.04 & 0.06), respectively. A blue circle marks the initial location of the gully heads. A red circle marks the final location (however, they are not visible in these plots as all gully heads are arrested), an orange circle indicates where a gully head gets arrested (insufficient upslope drainage area or eroded).*

Furthermore, the cumulative soil erosion in the case of lower HC and DP values is greater than in the case of higher values (see Figure 5.7). The cumulative erosion for areas with smaller hydraulic conductivity and drainage porosity is 53000 m$^3$ higher than those with higher values.

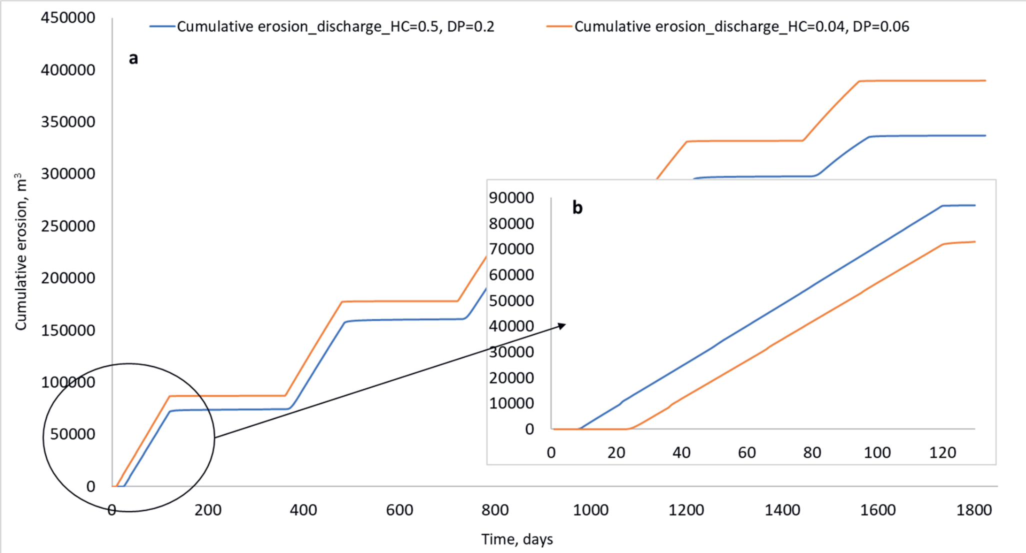


***Figure 5.7*** *a) Five-year cumulative soil erosion using a discharge-dependent retreat method with a hydraulic conductivity of 0.5 m/d & drainable porosity of 0.2 and with a hydraulic conductivity of 0.04 m/d & drainable porosity of 0.06 b) Zoomed in on the first 130 days of simulation to show the variation in cumulative eroded sediment.*

Varying the HC and DP values also significantly affected the time the GWT reaches the soil surface. As higher HC and DP means more space for the water in the soil, it took more time for the rainfall to fill all the soil void and for the groundwater to reach the soil surface (25-days since the model start), compared to smaller values of HC and DP having smaller soil pore space (the groundwater reached to the surface at the 7$^{th}$ day since the model start). As a result, there is more groundwater storage for the soil with higher HC and DP than smaller ones (see Figure 5.8). Despite using the same rainfall amount in both cases, groundwater declines sharply for higher HC and DP cases than for lower HC and DP cases.

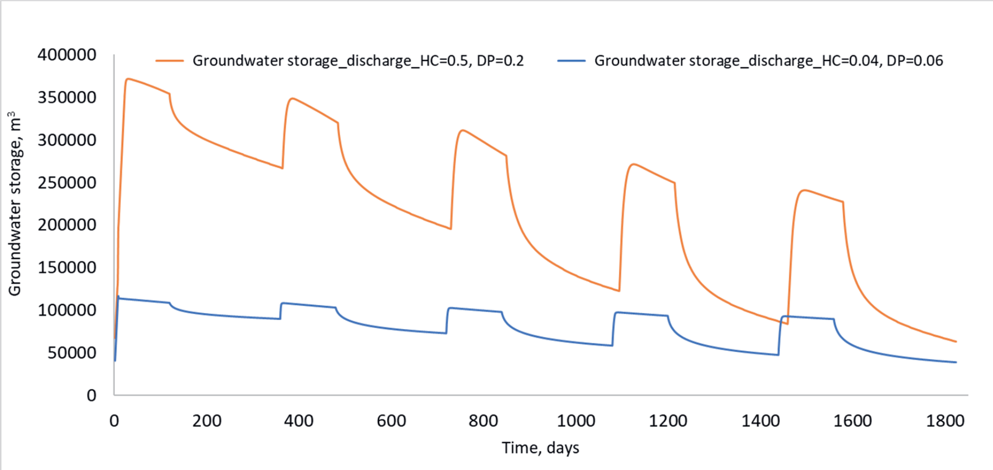


***Figure 5.8*** *Groundwater storage using a discharge-dependent retreat method with a hydraulic conductivity of 0.5 m/d & drainable porosity of 0.2 and, a hydraulic conductivity of 0.04 m/d & drainable porosity of 0.06.*

### *5.3.1.3 Water erodibility*

Water erodibility has a significant impact on both cumulative erosion and the total head-cut retreat. As shown in Figure 5.9, increasing the value of water erodibility from 0.0001 to 0.001 has increased the value of the cumulative sediment yield. Gully head also incised more for water erodibility value of 0.001 than 0.0001. Furthermore, as cumulative erosion increased, groundwater table storage declined. The decline is more pronounced for higher values of water erodibility than for lower values.

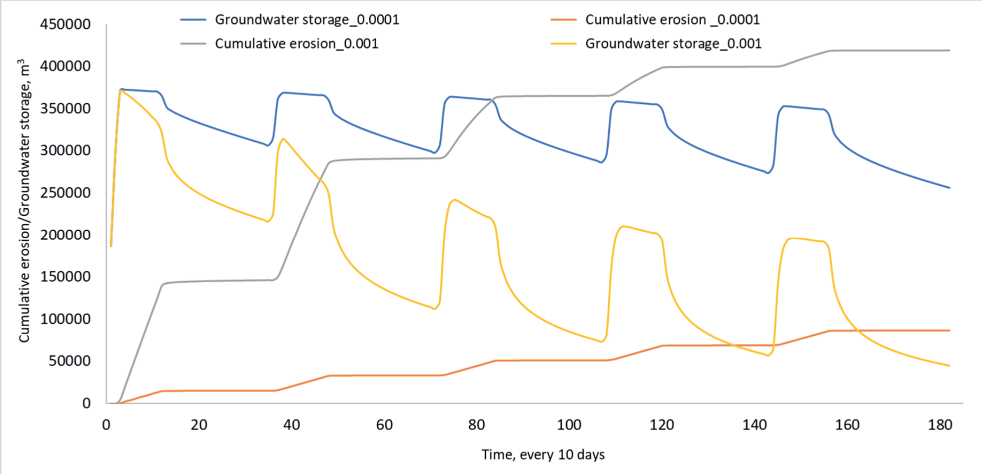


***Figure 5.9** Cumulative erosion and groundwater plotted every 10-days for five years, for 0.001 and 0.0001 water erodibility.*

### *5.3.1.4 Head-cut height*

Over the modeling period, the total gully head retreats increased with increasing gully head height. As shown in Figure 5.10, the total gully head retreat for a 1.5 m deep gully head was greater than for a 0.5 m deep gully head. For the 0.5 gully head height, most of the gully heads get eroded or arrested shortly after the onset of the first-year rainy season (i.e., the 60th day of the modeling period, which is the middle of the first-year modeling period). In contrast, the 1.5 m gully head height has a relatively sustained gully head retreat until the end of the five-year modeling period. As a result, a 1.5 m deep gully head caused 4000 $m^3$ more soil erosion than a 0.5 m deep gully head.

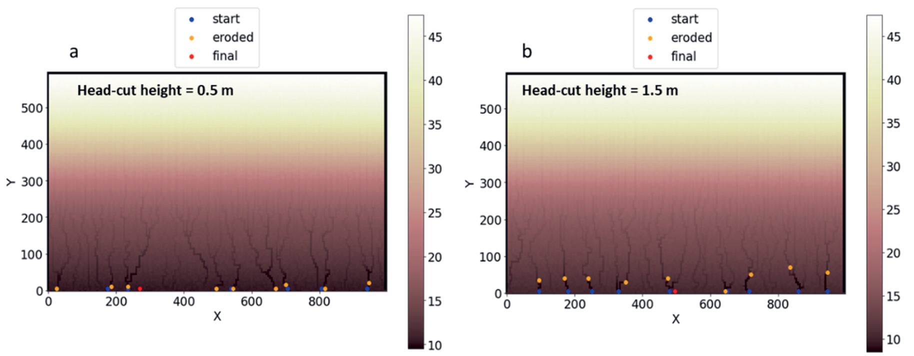


***Figure 5.10** a) and b) show the location of the gully heads on the topographic elevation of the landscape for a 0.5 and 1.5 m head-cut height, respectively.*

## 5.4 Discussion

The sensitivity analysis in section 3.1.1 revealed that gully head erosion was affected by changes in groundwater levels. This is especially true at the start of the modeling period when various initial groundwater heights saturate and reach the soil surface at different times. Higher groundwater heights (e.g., 2.5 m) saturate the soil faster and begin incising the gully head earlier than lower groundwater heights (e.g., 0.5 m), which take longer to saturate the soil and thus take longer to cause gully incision. Similarly, the cumulative sediment from topography is more significant in simulations with higher groundwater elevations than those with lower groundwater elevations. This is consistent with studies that have found that areas with higher groundwater depths are more prone to gullying (Addisie et al., 2017b; Amare et al., 2020). Increased head-cut retreat for areas with elevated groundwater has been linked to increased porewater pressure that weakens the soil cohesion and facilitates more gully wall collapse. Rockwell (2002) reported a rise in groundwater table in unsaturated soil causes one order of magnitude erosion due to increased unsaturated pore water pressure that lowers soil cohesion.

Simulations with lower HC and DP experienced head-cut retreat early during the modeling period, resulting in more gully head incisions than simulations with higher HC and DP, which later began incising the gully head. The increased head incision in the case with smaller HC and DP could be due to: (1) a smaller pore space and impaired hydraulic conductivity that facilitate higher surface runoff, which leads to more erosion; and (2) the groundwater stored in the soil is nearly intact and showed slight drawdown over time even during dry periods (Figure 5.8), which promote more erosion due to increased pore water pressure. This finding is consistent with previous research that found soils with low hydraulic conductivity have low infiltration rates, and water runoff will cause soil losses (Dexter et al., 2004). In the case with higher DP and HC, the smaller gully head incision could be due to: (1) a relatively larger pore space and hydraulic conductivity that promote infiltration and allows for lesser surface runoff causing smaller soil erosion; and (2) larger pore space and hydraulic conductivity could also promote rapid drawdown of groundwater through the pores (Figure 5.8) reducing pore water pressure buildup in the soil and consequently cause a lesser erosion.

An increase in the value of water erodibility resulted in increased cumulative soil erosion and reduced groundwater storage. The reduced groundwater storage can result from increased soil erosion from areas draining to the gully head, as well as gully head erosion, which thins the soil thickness and reduces its ability to store water. In addition, the increased head-cut retreat facilitates rapid drawdown of groundwater from the soil to the channels, which again contributes to reduced groundwater storage. Groundwater depletion increases with gully head erosion (Poesen et al., 2003).

Furthermore, the sensitivity analysis revealed that as gully head height increases, so does gully head erosion and sediment loss. This is consistent with previous research that found an increase in gully head erosion and sediment yield with increasing over-fall height at the head-cut (Bennett & Casalí, 2001; Robinson & Hanson, 1996).

In addition to modeling gully head evolution at the landscape scale, the GHEM model can be employed to model changes in groundwater storage caused by soil losses from gully heads and hillslopes, which can be used as input in the planning and design of land and water resource management activities. In the current module of GHEM we have not included the changes in width and depth of the gully channel in the model, which remain to be resolved in the future.

### 5.5 Conclusion

This study developed a new model called Gully Erosion by Headcut Migration (GEHM), which accounts for various environmental and climatic factors, and models gully head erosion at a landscape scale over a period spanning tens of years or less. The model uses multiple terrainbento and landlab model components in combination with the gully head migration model. The model will save outputs including topographic elevation, aquifer thickness, soil saturation, surface water discharge, sediment transport rate, and gully head location at user-specified time intervals. The sensitivity analysis for selected gully erosion parameters showed that the model is sensitive to changes in groundwater level, hydraulic conductivity, drainable porosity, water erodibility, and head-cut height. In future use of the model, calibration of the model based on accurate field observation on the input parameters are necessary for better prediction of gully evolution at a landscape scale. In addition to modeling gully head evolution at a landscape scale, the GHEM model can be employed to model changes in groundwater storage due to soil losses from gully head and hillslope erosions, which can be used as input in designing and planning of water resource management activities.

# 6. Synthesis

Gully erosion is an important environmental and food security issue that the globe is faced with, particularly in developing countries like Ethiopia. Despite the significant on-site (e.g., arable and pastureland loss) and off-site (e.g., reservoir sedimentation and pollution) damages caused by gully erosion, comprehensive research on the formation and evolution of gullies in sub-humid Ethiopia is limited. This is especially true for valley bottom gullies (VBG), which form under conditions and processes distinct from those found on hillslopes. Gullies in the Minzir catchment, part of the upper Abay (Nile) river basin, cause sedimentation problems in downstream water bodies. In this area, soil and water conservation activities do not prevent gully expansion, particularly at the valley bottom (VB), where the soil is periodically saturated and concentrated flow occurs. Therefore, this study aims to understand VBG erosion processes using field measurement and modeling approaches.

In the 2017 and 2018 Ethiopian rainy seasons, the geomorphic change of two gullies, one eroding on Nitisol and the other on Vertisol, representing the dominant valley bottom soils in the Minzir catchment, was studied. A literature review across different agroclimatic conditions supports the identification of parameters for further field investigation. Soil hydrological, meteorological, and gully morphological parameters were monitored to assess the impact of various interacting factors on gully erosion. Secondary data such as digital elevation model (DEM), soil, and land cover were used to locate gully erosion hotspots and rank factors based on their importance to gully erosion. Finally, we used a Python programming tool to develop a landscape gully erosion model called Gully Erosion by Head-cut Migration (GHEM).

This chapter presents a synthesis of the research findings from the previous chapters (Figure 6.1). First, concise response to the research question posed in Chapter 1 will be provided. Following that, the scientific implications of each chapter's research findings are described. Afterwards, the implications of this research for sustainable land management, gully erosion monitoring, experimentation, and modeling are discussed. The final section discusses the limitations/challenges encountered while conducting this research, as well as future research directions.

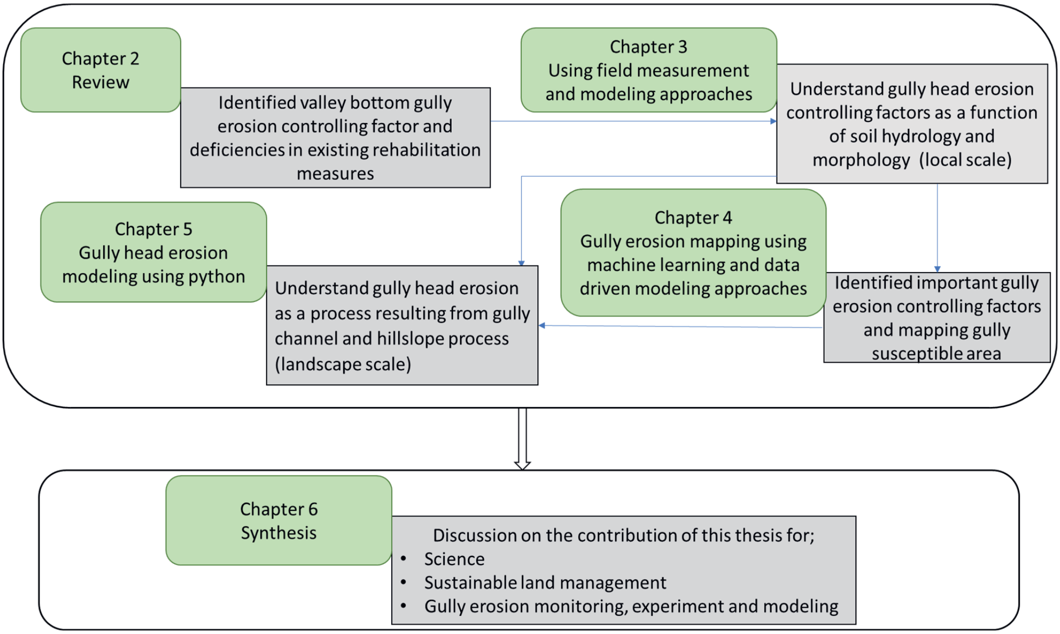


***Figure 6.1*** *A diagram of the research findings. The methods are presented in green boxes for each chapter, while the results/findings are presented in grey boxes.*

## 6.1 Brief answer to the research questions

### *6.1.1 What factors govern valley bottom gully erosion worldwide, and what are the flaws in current rehabilitation measures?*

A literature review in Chapter 2 identified the causes and controlling factors of VB gullies. It also assessed flaws in existing rehabilitation measures. Valley bottom gullies appear as incisions in the lower periodically saturated part of the landscape where surface and subsurface flow concentrates (Gallant & Dowling, 2003). They become saturated because both the hydraulic gradient is less than in the upper parts, and a large area drains to it. For the same reasons, VBs are the most agriculturally productive areas and provide significant economic services (Fagbami & Ajayi, 1990; Keïta et al., 2014; Lidon et al., 1998).

Valley bottom gullies are determined by watershed characteristics such as slope gradient, drainage area, precipitation, groundwater, surface runoff, soil, land-use change, alluvium, and colluvium formation. Increased rainfall impacts gully development due to increased water transported from the watershed and indirectly due to increased soil pore-water pressure, resulting in increased gully bank mass-wasting (Addisie et al., 2017b; Gómez-Gutiérrez et al., 2012). Although the initiation of gullies is independent of the amount of precipitation, the rate of gully expansion increases with increasing rainfall amounts. Because VBGs are located in gently sloping areas, the propensity of soil saturation increases as water has more time to infiltrate into the soil (Gallant & Dowling, 2003), and smaller hydraulic gradients cause the groundwater table to rise. At the VB, the drainage area is relatively larger than the upper part of the watershed. The increasing flux of water associated with increasing drainage area (Mukai, 2016b) not only erodes the gully boundary materials but also aids in the evacuation of soil deposited after gully head and bank collapses, thereby accelerating gully head (Torri & Poesen, 2014) and gully volume (Frankl et al., 2013b) expansion.

Vertisols and Loess are the most common soil types from which VB gullies are reported. Vertisols are characterized by deep and wide cracks (Tilahun et al., 2014) that allow preferential water flow into the soil, which increases soil pore-water pressure and promotes gully formation (Nyssen et al., 2004b). Loess soils have a high silt content (up to 60%) and low clay and organic matter content (Zhang et al., 2011), resulting in little cohesion that promotes gully formation. Furthermore, alluvium and colluvium are the dominant formations where VB gullies are reported. At the VB, alluvial and colluvium deposits have greater soil depth and well-sorted fine-textured materials (Mukai, 2016b; Tebebu et al., 2010). These characteristics may enhance gully development as gully volume was directly related to soil thickness and inversely associated with surface roughness and stoniness (Descroix et al., 2008).

Changes in land use were also mentioned most frequently as the cause of gully incision and widening. Examples of land-use changes related to gully formation are eucalyptus plantation, cultivation of previously untilled land, cropland conversion to pasture, deforestation, and road construction (Nyssen et al., 2002; Nyssen et al., 2006). In summary, in all cases, the unifying principle is that the land-use change caused increased runoff or wetness in valley bottoms, which enhances gully development.

Valley bottom gully reclamation measures are generally effective in arid and semi-arid areas with the limited subsurface flow and deep groundwater tables. Similar remedial actions are not successful for humid regions as their design does not account for subsurface flows effects. Moreover, while existing topographical threshold predictors for VBGs have worked well for Hortonian overland flow-controlled gullies, similar approaches may be flawed for VBGs controlled by subsurface flow processes. As a result, it is critical to re-evaluate existing gully erosion topographical threshold predictors for humid and sub-humid regions to define gully incision threshold better and allow for effective preventive and rehabilitation plans. An integrated landscape approach that accounts for combined subsurface and surface drainage is also required to successfully implement rehabilitation measures, particularly in humid regions.

### *6.1.2 How do various hydrological, soil, and morphological factors influence gully head stability in Nitisol and Vertisol?*

Despite having a larger drainage area and steeper and taller gully walls, the Nitisol's gully was more stable than the Vertisol's, which had shallower and less steep sidewalls. In the Nitisol, soil pipes drain excess water from the gully banks to the gully channel, explaining the relatively deeper groundwater and lower soil moisture content in this soil than in the Vertisol. Although studies have associated the occurrence of soil pipes with unstable gully banks (Chaplot, 2013; Collison, 2001a; Deng et al., 2015; Wilson, 2009), we found that for the Nitisol gully, the drainage provided by soil pipes prevented a sizeable saturated zone in the unconsolidated soil and contributed to the smaller gully head erosion rate.

The impact of soil pipes and cracks in the Vertisol was the opposite of what was observed in the Nitisol, promoting water recharge into the soil. At the beginning of the rainy period, cracks occupied 4% of the soil volume, and then a 1 mm rainfall event would lead to apparent groundwater level variations of 25 mm. This is consistent with the findings of Drumm et al. (1997) and Collison (2001b), who found that cracks promote preferential water flow and increase flow velocity through the gully wall by order of magnitude. According to studies conducted in a similar region on Vertisol, cracks cause both an increase in positive pore water pressure (Tebebu et al., 2010) and an increased groundwater level (Addisie et al., 2017b), eventually promoting gully bank collapses. Thus, soil cracks and pipes may have weakened Vertisol's resistance to fluvial erosion and mass wasting by increasing preferential water flow into the soil and elevating the groundwater table.

The gully bank stability analysis using the Bank Stability and Toe Erosion Model (BSTEM) model showed that groundwater and soil cracks were found to affect gully head stability. However, tension cracks had a significant impact on gully head stability when compared to GWT. The presence of a soil crack in the Vertisol reduced the FS by 85% compared to results obtained without cracking, making the gully head unstable. As a result, cracks explain why the Vertisol has a higher head cut retreat than the Nitisol. Our findings support those of Langendoen et al. (2014) and Zegeye et al. (2020), who found that tension crack and GWT depths significantly impact gully bank stability. Furthermore, according to Klavon et al. (2017), cracks weaken bank materials, exposing them to fluvial erosion and geotechnical failures.

For Vertisol, rehabilitation measures should safely remove excess water from both the catchment and the gully bank to reduce bank collapses, in addition to structurally stabilizing the gully head and sidewalls. For Nitisol, reducing upslope runoff and stabilization of the gully head and sidewalls may be sufficient.

### *6.1.3 Which topographic, geological, and hydrologic factors best forecast gully location along the landscape?*

The frequency ratio (FR) and random forest (RF) models were identified in Chapter 4 as valuable techniques for determining the most important gully erosion predictor factor and mapping gully erosion vulnerable areas. All the selected 14 gully-erosion predictor factors were found to determine gully location in the Minzir catchment at different levels of importance. However, gully erosion prediction using the FR and RF models showed that the best gully prediction accuracy could be obtained using the top four most important gully-predictor factors: drainage density (DD), elevation, land use, and groundwater table (GWT). This means that these four parameters accurately represent the impact of the remaining ten factors on gully erosion.

The most important factor determining gully location in the study catchment was drainage density, which agrees with studies that show gully erosion susceptibility increases with increasing DD (Akgün & Türk, 2011; Rahmati et al., 2016c). Elevation was discovered to be the second most important predictor of gully erosion. The two lowest elevation classes (2030–2070 and 2070–2104 m a.s.l.) had the most gullied area. This finding aligns with previous research that found low-elevation areas to be more vulnerable to gullies due to concentrated flow (Zabihi et al., 2018). Land use/cover was the third most important gully-erosion predictor factor, which agrees with the findings of (Arabameri et al., 2019b; Hosseinalizadeh et al., 2019). While grazing land (13.2%) is smaller than cultivated land (82.7%) in the Minzir catchment, grazing land has the highest proportion of gullies, as revealed by a high FR value. Studies have stated that grazing lands are more susceptible to gully-erosion than other land-use groups (Amare et al., 2019; Zabihi et al., 2018). The higher susceptibility of grazing land to gully erosion has been linked to reduced infiltration and increased surface runoff, which has increased saturated area and subsurface flow in valley bottoms, leading to gully development (Marinho et al., 2006). GWT is the fourth most important factor influencing gully erosion. Gullies have been observed in all GWT classes, but FR values show that areas with GWT depths shallower than 2 m are the most vulnerable to gullies. This is consistent with most studies in subhumid Ethiopia, where elevated groundwater increases soil pore water pressure and speeds up gully erosion (Ayele et al., 2018).

The FR models' ability to accurately predict gully location ranged from average to good, whereas the RF model achieved excellent prediction accuracy. This suggests that, despite the importance of all fourteen predictor factors, gully erosion can be successfully predicted using only DD, elevation, land cover, and GWT. Excluding GWT and soil type as gully erosion predictor factors had a minor effect on RF model performance but excluding GWT from the FR model resulted in a 7% reduction in prediction accuracy. This demonstrates the GWT parameter's high explanatory power on the FR model. As a result, accounting for this parameter in future gully erosion prediction research can improve gully erosion prediction accuracy, particularly in subhumid areas. Leaving out the soil type from the models did not affect model performance. Despite this, soil type being the sixth most important factor determining gully development suggests its significance for gully erosion. The excellent prediction accuracy achieved by the RF model agrees with (Arabameri et al., 2019b; Hosseinalizadeh et al., 2019), who successfully mapped gully erosion and gully head susceptible areas. The FR model used in this study outperforms other statistical models, such as weight of evidence and index of entropy (Rahmati et al., 2016a; Zabihi et al., 2018). Current approaches for mapping gully erosion susceptibility in the Ethiopian highlands rely on topographical threshold factors such as topographic wetness index (TWI) and stream power index (SPI). Applying these thresholds is flawed because streams and saturated-bottom lands are regarded as the most vulnerable to gullies. Furthermore, our findings indicate that TWI and SPI have a limited impact on gully erosion.

Separate variable importance analyses for Nitisols and Vertisols revealed that land cover and drainage densities were the most important factors determining gully location in each soil. The land cover was ranked ninth in Vertisols, indicating its little significance for gully erosion. Other important gully erosion factors (elevation, TWI, and GWT) are similar for both soils. Further research is needed on the fact that land cover is the most important gully-erosion factor for Nitisols. Furthermore, this study suggests that future planning and implementation of conservation measures in subhumid regions of Ethiopia should target areas with higher drainage density, low-lying areas, grazing land, and shallower groundwater table, which are vulnerable to gully erosion.

### *6.1.4 How does gully head erosion model at a landscape scale responds to changes in groundwater, hydraulic conductivity, drainable porosity, water erodibility, and head-cut height?*

Chapter 5 developed a new numerical model called Gully Erosion by Headcut Migration (GEHM), which accounts for various environmental and climatic factors, and models gully head erosion at a landscape scale. GEHM is a new python package that enables gully head erosion to be modeled along with other earth surface processes. The model uses the terrainbento and landlab model components in combination with the gully head migration model. The model will save outputs including topographic elevation, aquifer thickness, soil saturation, surface water discharge, sediment transport rate, and gully head location at user-specified time intervals. The sensitivity of the GHEM model to various gully head erosion factors such as groundwater, hydraulic conductivity, drainable porosity, water erodibility, and height-cut height was investigated.

The sensitivity analysis revealed that gully head erosion was affected by changes in groundwater levels. Higher groundwater heights saturate the soil faster and begin incising the gully head earlier than lower groundwater heights, which take longer to saturate the soil and thus take longer to cause gully incision. Furthermore, the cumulative sediment eroded from the topography is more significant in simulations with higher groundwater elevations than those with lower groundwater elevations. This is consistent with studies that have found that, due to increased pore water pressure that lower soil cohesion (Rockwell, 2002), areas with higher groundwater depths are more prone to gullying (Addisie et al., 2017b; Amare et al., 2020).

Simulations with lower hydraulic conductivity (HC) and drainable porosity (DP) experienced head-cut retreat early during the modeling period, resulting in more gully head incisions than simulations with higher HC and DP, which later began incising the gully head. The increased head incision in the case with smaller HC and DP could be due to: (1) a smaller pore space and impaired hydraulic conductivity that facilitate higher surface runoff, which leads to more erosion; and (2) the groundwater stored in the soil is nearly intact and showed slight drawdown over time even during dry periods, which promote more erosion due to increased pore water pressure. This finding is consistent with previous research that found soils with low hydraulic conductivity have low infiltration rates, and water runoff will cause soil losses (Di Prima et al., 2018; Lucas-Borja et al., 2018). In the case with higher DP and HC, the smaller gully head incision could be due to: (1) a relatively larger pore space and hydraulic conductivity that promote infiltration and allows for lesser surface runoff causing smaller soil erosion; and (2) larger pore space and hydraulic conductivity could also promote rapid drawdown of groundwater through the pores reducing pore water pressure buildup in the soil and consequently cause a lesser erosion.

An increase in the value of water erodibility resulted in increased cumulative soil erosion and reduced groundwater storage. The reduced groundwater storage can result from increased soil erosion from areas draining to the gully head, as well as gully head erosion, which thins the soil thickness and reduces its ability to store water. In addition, the increased head-cut retreat facilitates rapid drawdown of groundwater from the soil to the channels, which again contributes to reduced groundwater storage (Poesen et al., 2003; Vanmaercke et al., 2021).

Furthermore, the sensitivity analysis revealed that as gully head height increases, so does gully head erosion and sediment loss. This is consistent with previous research that found an increase in gully head erosion and sediment yield with increasing over-fall height at the head-cut (Bennett & Casalí, 2001; Robinson & Hanson, 1996).

In addition to modeling gully head evolution at the landscape scale, the GHEM model can be employed to model changes in groundwater storage caused by soil losses from gully heads and hillslopes, which can be used as input in the planning and design of land and water resource management activities.

## 6.2 Discussion

### *6.2.1 Scientific contribution*

This study utilized data from field measurement, field observation, and secondary sources to explore and develop new methods for understanding gully erosion processes at a landscape and local scales (at the valley bottom). Valley bottom gullies constitute a substantial source of sediment in catchments (Amare et al., 2019). Previous research found that, unlike the hillslope form of gullies, rehabilitation efforts such as check dam construction did not stop gully erosion at the valley bottom (Nyssen et al., 2004c). As a result, sediment generated by valley bottom gullies undermines hillslope conservation efforts (Zegeye et al., 2018). Inadequate knowledge of the dominant hydrological processes controlling gully erosion is one of the reasons for the valley bottom conservation effort's failure (Dagnew et al., 2015). This PhD reviewed the current knowledge of valley bottom gully erosion and assessed how hydrology, especially subsurface flow, together with topographic factors, determine the vulnerability of valley bottomlands to severe gully erosion. Moreover, this research identified deficiencies in existing rehabilitation measures. This PhD research differs from previous gully erosion studies in that it not only explicitly looked at gully erosion at the valley bottom, but it also looked at how differences in soil type (Nitisol and Vertisol) can lead to differences in soil hydrology and morphology, which affected the rate of gully head expansion. This scientific evidence may contribute to sustainable land and water resource management at the valley bottom.

Machine learning algorithms and data-driven models are increasingly being used to map gully erosion susceptibility and identify the most critical factors affecting gully erosion in various regions worldwide (Arabameri et al., 2019a; Hosseinalizadeh et al., 2019; Rahmati et al., 2017b). Depending on data availability, the parameters used to map gully erosion susceptible areas varied from place to place. This PhD study included new gully erosion parameters (i.e., soil type and groundwater) and the existing gully erosion parameters used in previous studies to map gully susceptibility areas and identify the most critical factors of gully erosion. The newly added parameter, e.g., groundwater, appears to improve the data-driven model accuracy by about 7%. The notion that **the groundwater table is one of the critical gully predictor factors** is a novel and significant quantifiable finding that contributes to our current understanding to critically design effective catchment soil and water management plans.

This PhD study also developed a new model called Gully Erosion by Headcut Migration (GEHM), which accounts for various environmental and climatic factors, and models gully head erosion at a landscape scale. Despite several attempts that have been made to develop empirical and process-based models for predicting either gully subprocesses or gully erosion rates, there are still no reliable models available for predicting the effects of environmental change on gully erosion rates at various temporal and spatial scales (Poesen et al., 2011). Furthermore, mathematical models for gully erosion are far less developed than sheet erosion and rills (Mircea et al., 2015). In addition to modeling gully head evolution at the landscape scale, the GHEM can model changes in groundwater storage due to soil losses from gully head and hillslope erosion, which can be used as input in the design and planning of land and water resource management. The results derived from this research can be used to assess the impact of different hydrologic, climatic, and morphologic factors on gully evolution at a landscape scale over a time spanning ten years or less.

### *6.2.2 Implications for sustainable land management*

Even though only a tiny percentage (5%) of the terrestrial surface suffers from gully erosion (Ionita et al., 2015b), gullies pose a serious environmental problem with critical consequences. Gullies constitute a significant sediment source in watersheds, accounting for 10 to 94% of total sediment yield, affecting multiple watershed functions (Amsalu & de Graaff, 2007; Poesen et al., 2003). There is currently insufficient data available on time series analysis of gully erosion in combination with rainfall records and other environmental data (Vanmaercke et al., 2016). For example, of the total published soil erosion studies worldwide, less than 10 percent address gully erosion (Casalí et al., 2009). A critical first step in addressing this challenge is understanding the rate and factors that control gully head-cut retreat (Vanmaercke et al., 2016). Gullies depend on site-specific conditions such as soil type, climate, and slope among others (Vandekerckhove et al., 2000; Vanmaercke et al., 2016). This thesis improved our understanding of the controlling factors and rate of gully head erosion and provided an efficient strategy for identifying gully erosion hotspot areas. This understanding is an important step forward for designing and planning successful sustainable land management, as summarized in Figure 6.1.

Gully erosion studies worldwide, particularly in Ethiopia, are based on aggregated investigations that fail to account for process variations across the landscape. Gullies at the valley bottom landscape of the Minzir watershed (the study watershed) caused sedimentation problems in downstream water bodies. Soil and water conservation (SWC) activities in this watershed do not prevent gully expansion, particularly at the valley bottom of the watershed. Valley bottom gully reclamation measures are generally effective in arid and semi-arid areas with limited subsurface flow and deep groundwater tables. In contrast, similar remedial actions are ineffective in (sub) humid regions like Minzir as they do not account for the effects of subsurface flows. Hence, prior knowledge of the gully erosion factor is required for effective gully management strategies.

This PhD study found that VB land is sensitive to gully erosion affecting the sustainable use of land and water resources. This is because they are frequently found on thick alluvial and colluvium soils with enhanced soil moisture due to a lower hydraulic gradient and a larger drainage area than hillslope area (Descroix et al., 2008; Stavi et al., 2010; Thomas et al., 2009b), making them more vulnerable to gullies. For the same reason, valley bottoms have multiple economic and ecological functions (Keïta et al., 2014; Lidon et al., 1998; Rebelo et al., 2015). This thesis's findings could be used to design a better and more informed gully management strategy at the VB. Furthermore, an integrated landscape approach that accounts for combined subsurface and surface drainage is required to ensure the effective implementation of rehabilitation measures.

The current gully erosion conservation approach in the Ethiopian highlands is based on a one-size-fits-all approach, with the majority of them being exported from a foreign country and applied without being tailored to the local environment and erosion processes (Bekele-Tesemma, 1997; Bewket, 2007; Mitiku et al., 2006; Reij, 1991). Major causes of unsustainable land management are the lack of understanding of the underlying cause of erosion and poor design and planning of reclamation measures. The outputs of gully susceptibility mapping and gully erosion controlling factors at a local and landscape scales in this thesis can be used to devise appropriate gully reclamation measures. Moreover, it is necessary to use an integrated landscape approach that considers the combined subsurface and surface drainage into the valley bottomlands, among other things. Furthermore, this research and previous research findings on soil erosion can be consulted to prepare technical guides and manuals for developing an integrated landscape approach that ensures sustainable land management. The output of this PhD study will also contribute to the government's database for better implementation of conservation activities in other places having the same problem as Minzir. This PhD research also benefits downstream countries where the Blue Nile river drains into. Most importantly, the findings of this research will benefit the farmers of  Koga watershed who irrigate their lands from the Koga dam and who lost their lands due to severe gully erosion.

### *6.2.3 Implications for gully erosion monitoring, experimentation, and modeling*

As gully head retreat is influenced by factors such as topography, material type, and land use (Istanbulluoglu et al., 2004; Poesen et al., 2011), this study looked at gullies located at the same land use and landscape position (i.e., valley bottom) but different soil types (i.e., Nitisol and Vertisol). Despite receiving the same amount of rainfall, the magnitude of gully head erosion differs between the two soils. Vertisols with a crack network and a groundwater table close to the soil surface were more vulnerable to severe gully head incision than Nitisols with groundwater tables deep from the ground surface and no evidence of crack. Our findings agree with those of Hancock & Willgoose (2001); Huddart & Bennett (2000); Martínez-Casasnovas et al. (2004), who found that gullies heads are destabilized by cracks, which promotes preferential flow into the bank while also facilitating soil saturation and significantly lower the factor of safety. Therefore, it is critical to tailor rehabilitation measures to differing material types, even if two gullies are located on the same landscape and land use type.

Although machine learning algorithms and data-driven models have been successfully used to locate gully vulnerable areas in various regions, their applicability to a more degraded Ethiopian highland was limited. Previous studies identify gully susceptible areas using multiple environmental parameters (Hosseinalizadeh et al., 2019; Javidan et al., 2019; Zhao & Cheng, 2019). However, this PhD study is unique because it initially used multiple gully erosion parameters to suggest a few parameters that gave excellent model prediction accuracy. The parameters proposed in this study for gully prediction are drainage density, elevation, land use, and groundwater table. Using a small number of parameters for gully susceptibility mapping is indispensable, especially in low-income countries like Ethiopia, where data are scarce and resources are limited for detailed field measurement and monitoring. The gully erosion susceptibility map developed in this study can be used to plan informed gully erosion rehabilitation and prevention measures in the Minzir catchment. This eliminates the need for exhaustive field data collection. The methodology may also be used in other catchments that are susceptible to gully erosion.

Gullies increase landscape connectivity (Poesen et al., 2003; Vanmaercke et al., 2012; Vanmaercke et al., 2011), but there is a lack of models that integrate gully channels with hillslope processes. The interactions between gully erosion and hydrologic and other soil erosion processes must be better understood to improve predictions of hydrological response and land degradation rates under various environmental conditions. This improved understanding serves as the foundation for taking appropriate and effective soil erosion control measures (Poesen et al., 2011). An integrated landscape approach that accounts for the combined subsurface and surface drainage is needed to implement rehabilitation measures effectively, especially for humid regions. The GHEM model developed in this study allows one to play with different surface and sub-surface parameters to see their impact on gully evolution at a decadal time scale or less. The development of the GHEM model in this study contributes to understanding landscape process as integrated hillslope and gully channel process. Understanding the gully erosion process and evolution at a shorter time scale is important for informed catchment management interventions.

### 6.2.4 Research challenges and directions for further research

- Reclamation of valley bottom gullies appears to be effective in arid and semi-arid areas where Hortonian overland flow is the dominant runoff process. In humid areas where gullies are caused by subsurface or saturation-excess-induced erosion, stabilizing gullies with existing hillslope gully reclamation measures is problematic. An integrated and informed landscape approach that accounts for combined subsurface and surface drainage is required to ensure the effective implementation of rehabilitation measures, particularly in humid regions.
- Our experiment to study the impact of soil hydrological and morphological characteristics on valley bottom gully erosion was limited to two soil types, Nitisol and Vertisol, with measurements taken over two years. We recommend similar studies for areas with dominant soil types other than the one we studied here, as the hydrological process and morphology causing gully erosion might be affected by varying soil types.
- The GHEM model's sensitivity to parameters such as groundwater level, hydraulic conductivity, drainable porosity, water erodibility, and head-cut height was tested. The model was found to be sensitive to these parameters. The GHEM model is designed to a set of model programs that incorporate alternative transport laws related to four processes: hillslope processes, surface-water hydrology, erosion by flowing water, and material properties. This allows the model to be tested and calibrated for its sensitivity to other factors not included in this study but was found to affect gully erosion rate and magnitude in other climatic regions.
- In this study, the GHEM model was tested for a five-year simulation period, with daily time steps. The model can also be used to study gully erosion processes over a period spanning tens of years or less. As a result, the GEHM can be used to investigate gully head evolution at a landscape scale and with temporal flexibility based on specific interests.
- Gully head retreats in this study were measured for only 2-years. We recommend extended gully head retreat measurement along with other hydrological and meteorological data.
- The gully erosion susceptibility mapping and identification of the most important gully erosion predictor factors were carried out for an 18 km$^2$ catchment area having the same rainfall pattern and geological setting. Studies showed that geology and rainfall pattern variability could be a critical predictors of gully erosion. As a result,

we recommend that similar studies be conducted in a larger catchment area to see how different geology and rainfall patterns affect gully erosion susceptibility.

- This study mapped the gully erosion susceptibility mapping and identified the most critical gully erosion predictor factors for sub-humid Ethiopia. According to studies, the dominant gully erosion predictor factor varies between arid and humid regions. This affects our selection of gully erosion parameters used for developing gully erosion susceptibility maps and management strategies for halting gully erosion. We recommend similar studies for arid climatic regions to better understand gully erosion and accurately predict gully location.

# 7. Appendix


***Figure 7.1*** *(a) is a soil crack observed in the soil profile. (b) and (c) shows photos of the cracks before the onset of the rainy season each depicting straight shaped crack, and cracks intersecting each other and become wider. Figure d shows cases where cracks grow into soil pipes.*

***Figure 7.2*** *Soil pipe evidence in the gully bank that discharges water to the channel*

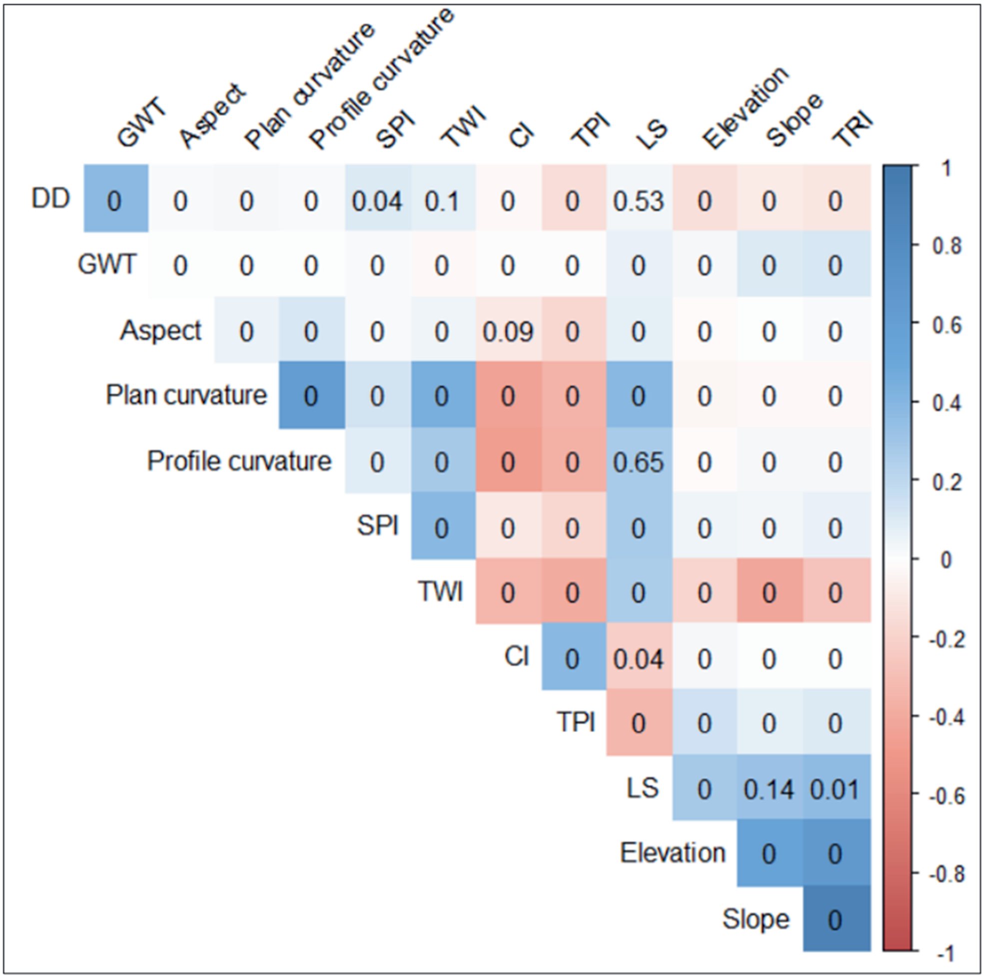


***Figure 7.3*** *A plot of p-values. The color ramp indicates correlation strength between parameters, whereas the numbers in each box are the p-values. A correlation with a corresponding p-value > 0.01 is considered insignificant.*

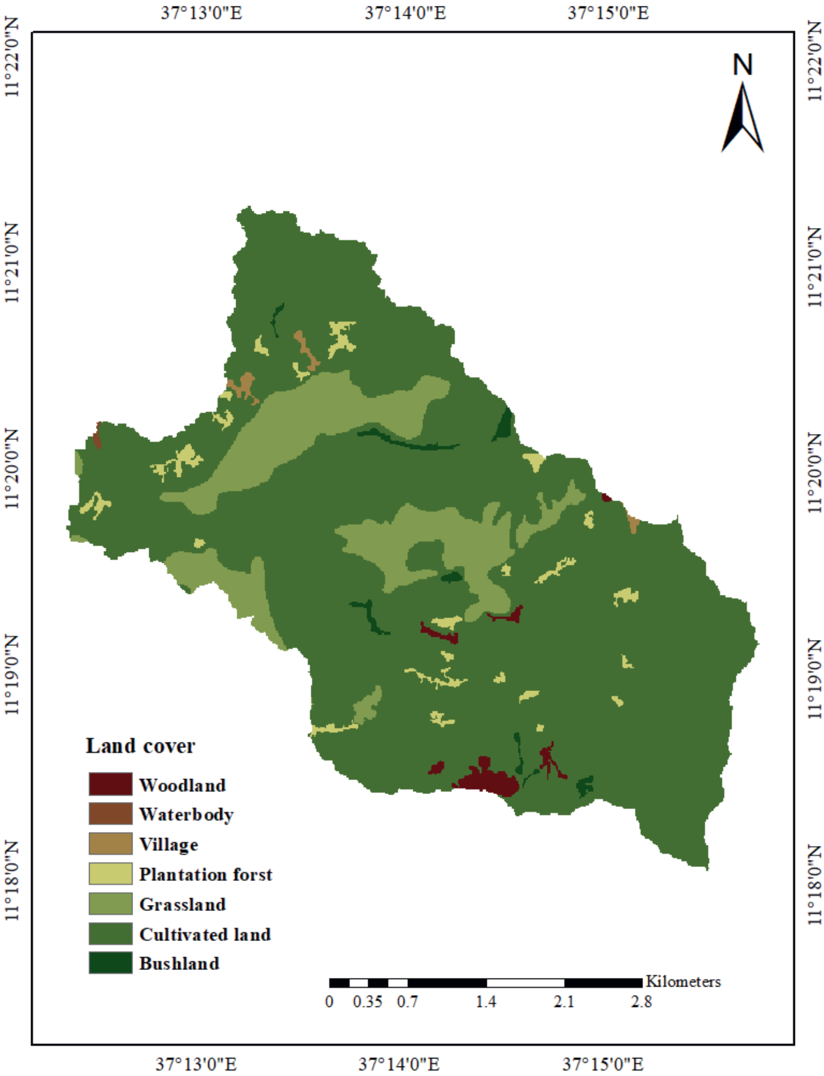


***Figure 7.4** Land cover map*

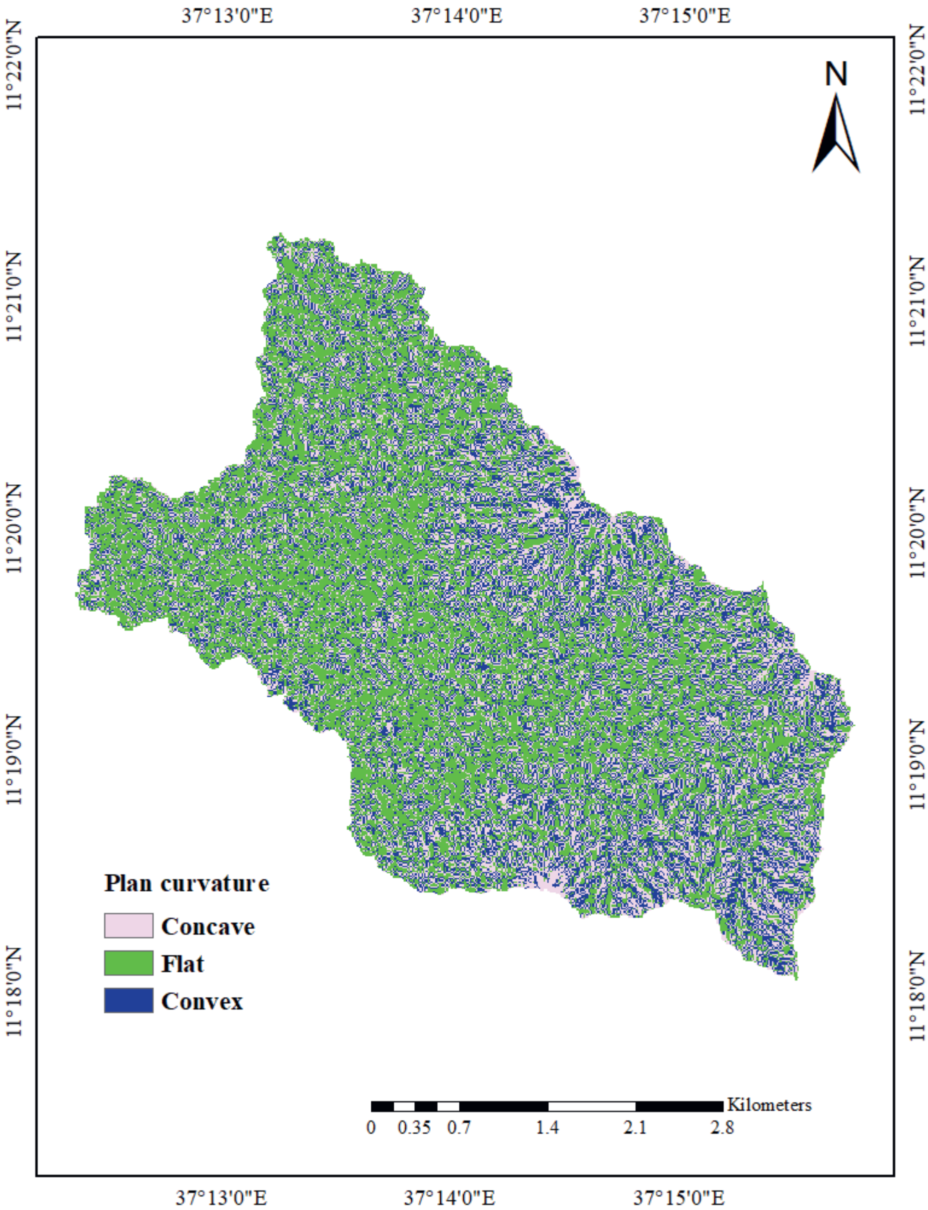


***Figure 7.5*** *Plan curvature map*

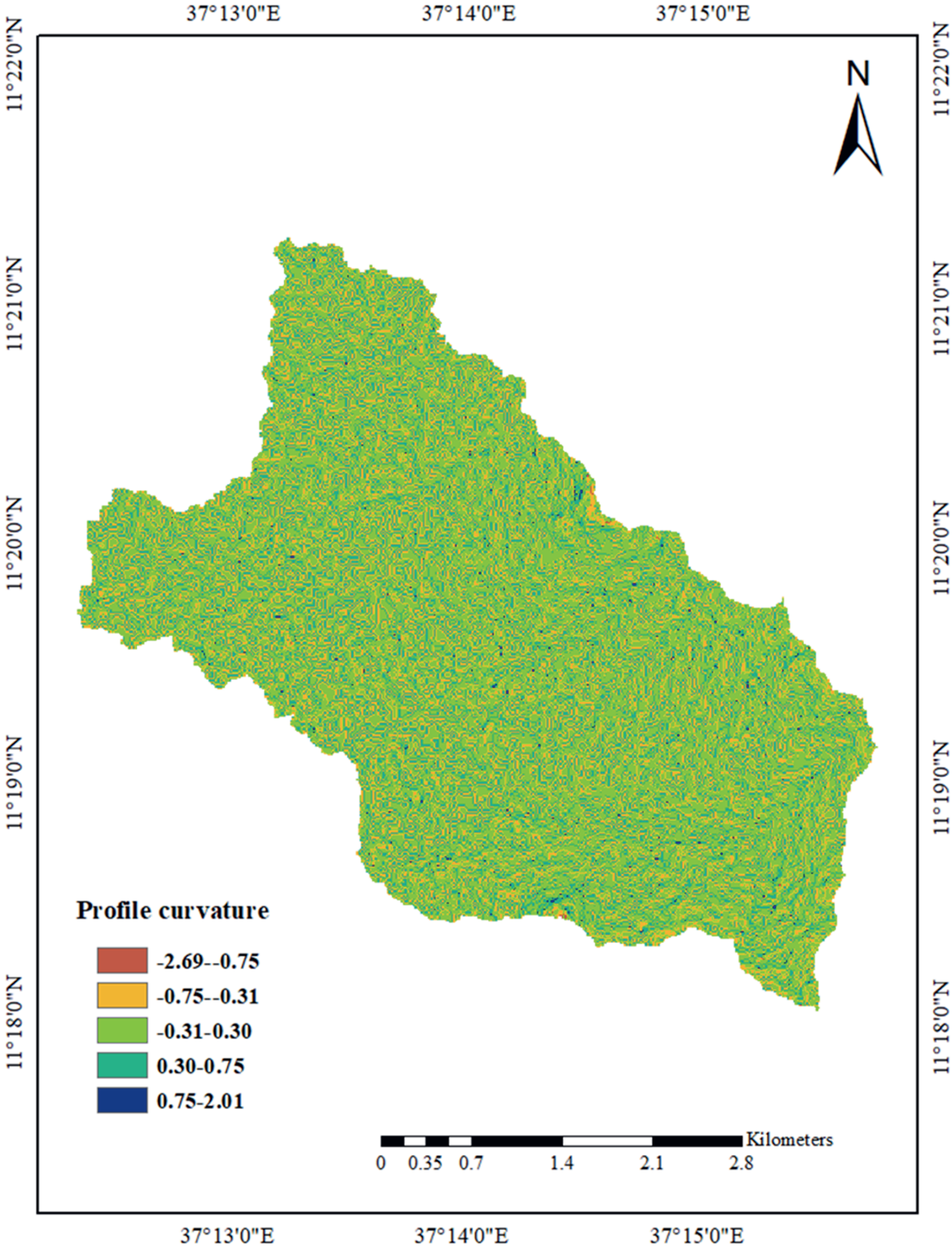


***Figure 7.6*** *Profile curvature map*

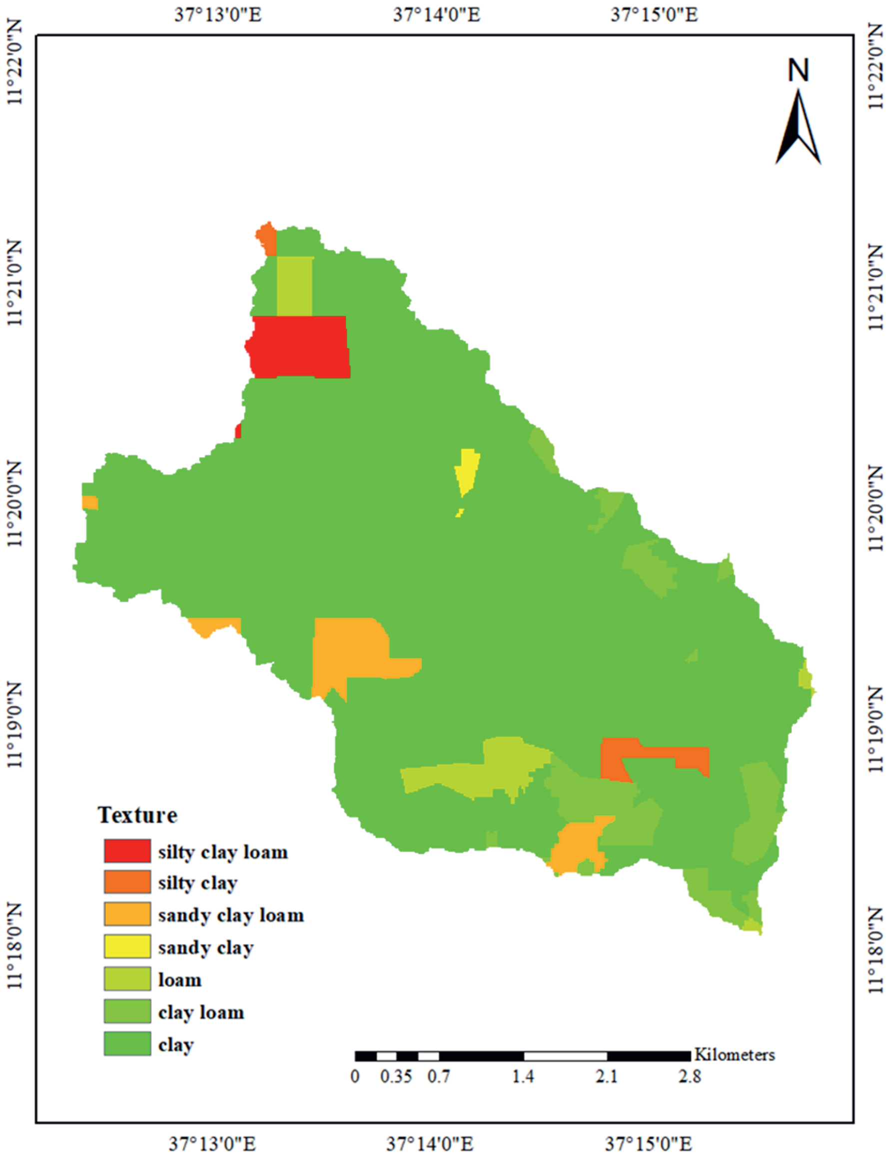


***Figure 7.7*** *Soil texture map*

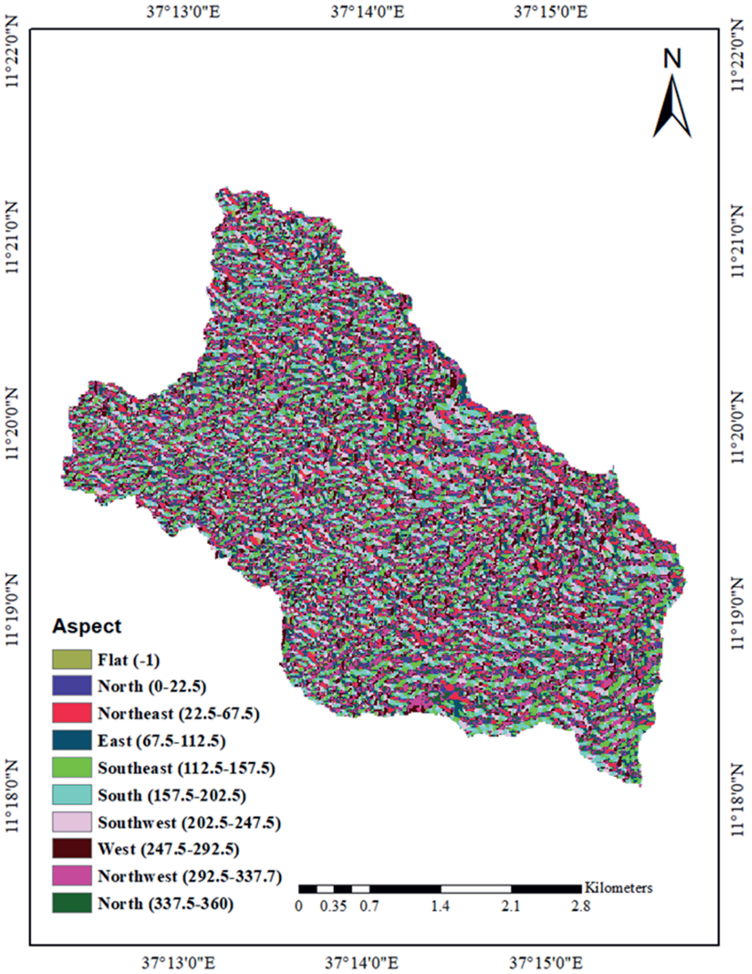


***Figure 7.8*** *Aspect map*

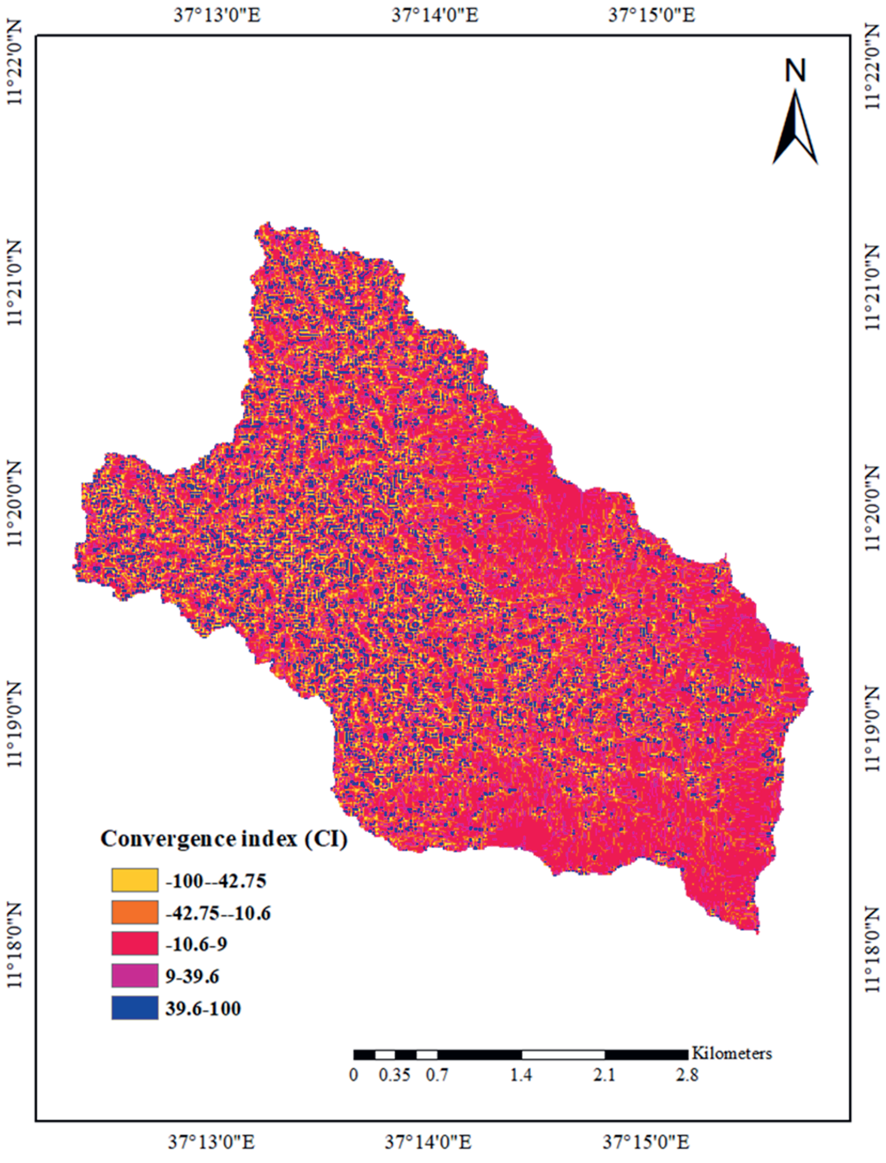


***Figure 7.9*** *Convergence index map*

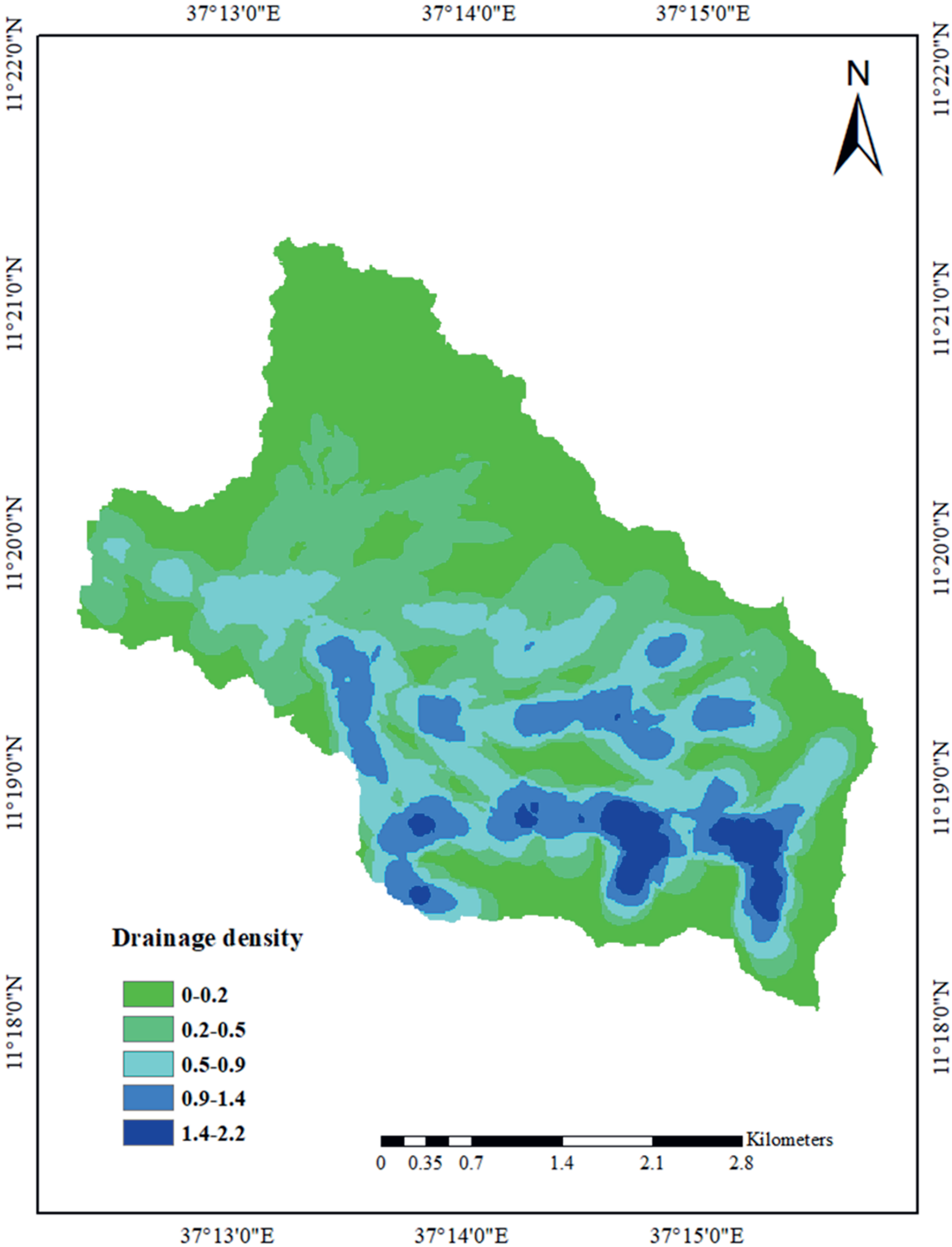


***Figure 7.10*** *Drainage density map*

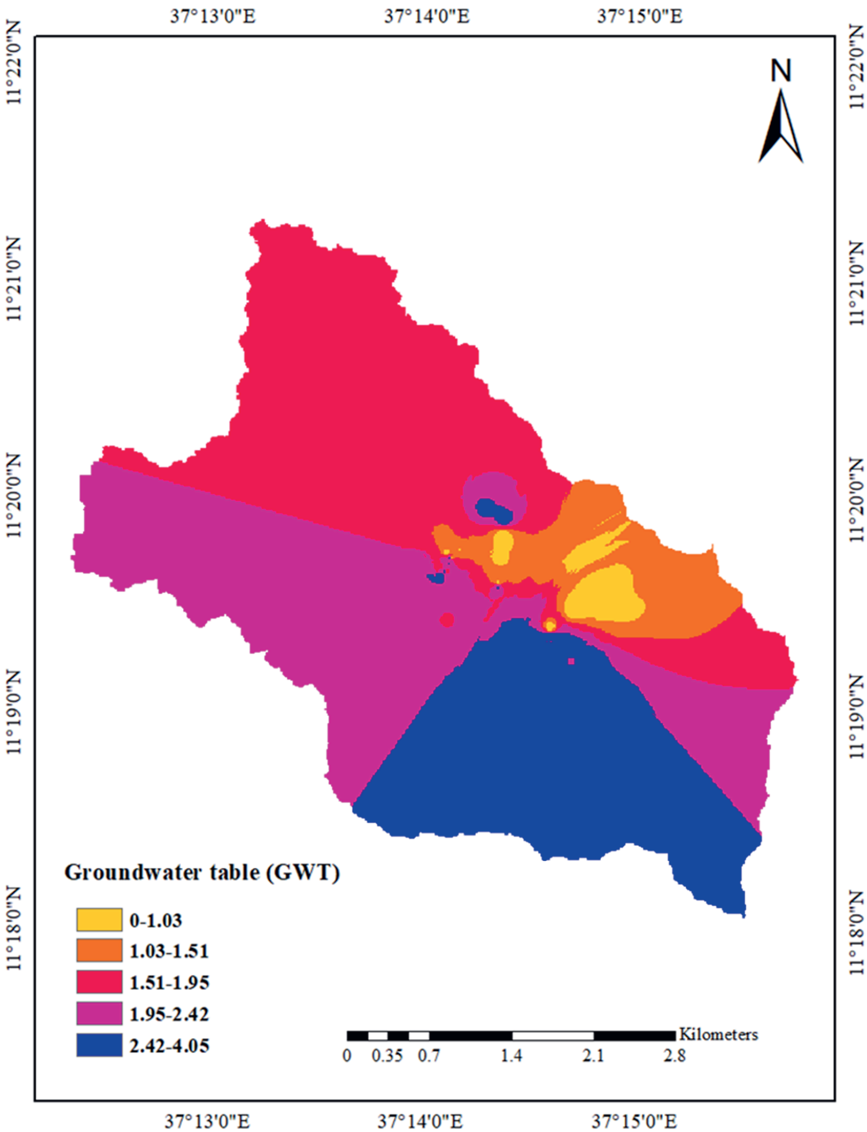


***Figure 7.11*** *Groundwater table map*

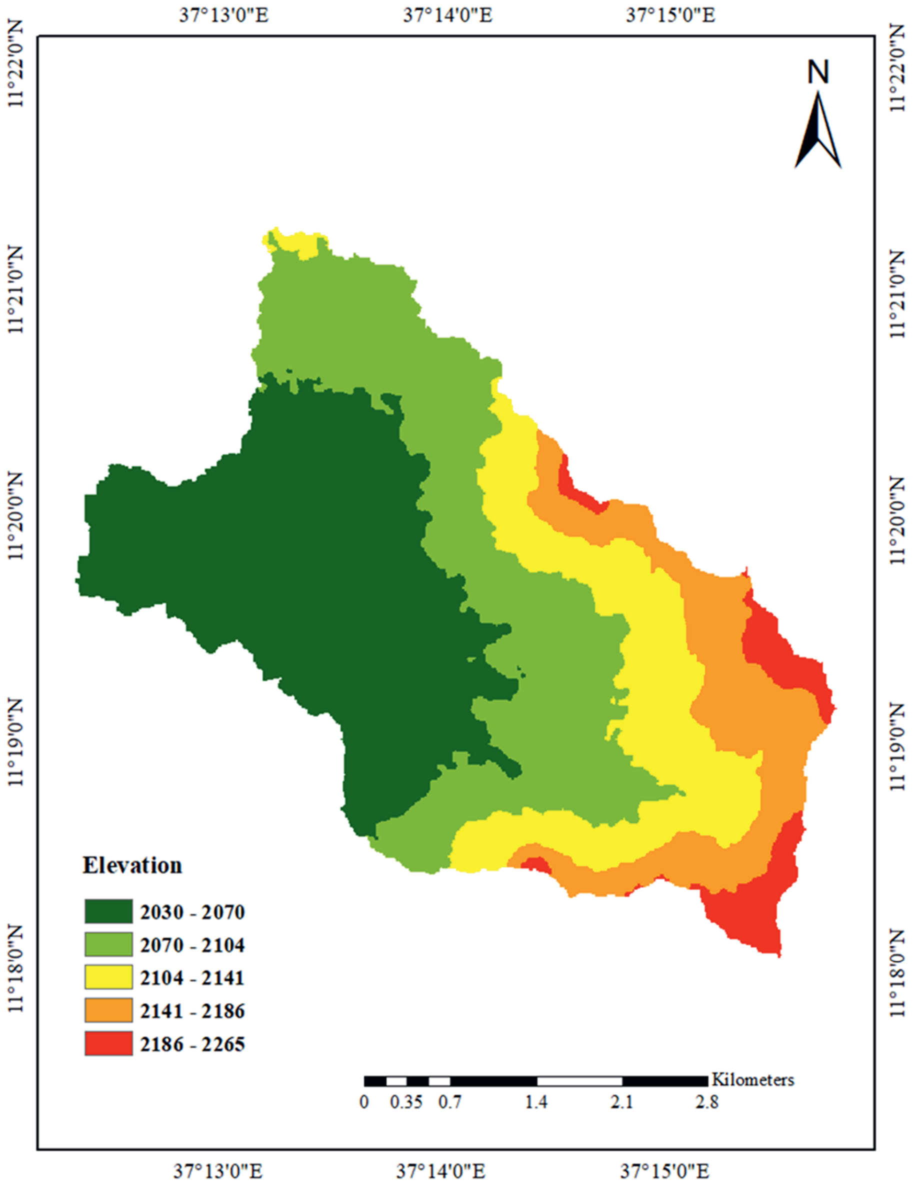


***Figure 7.12** Elevation map*

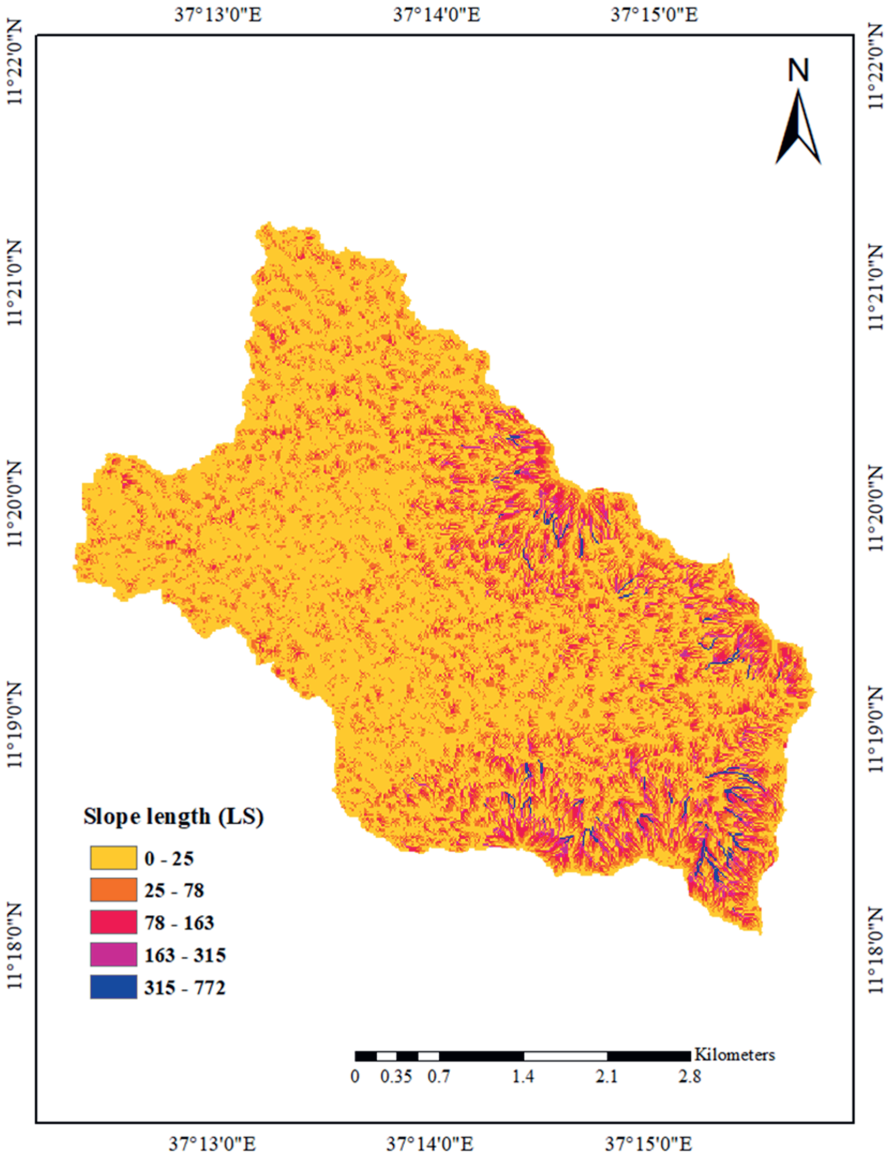


***Figure 7.13*** *Slope length map*

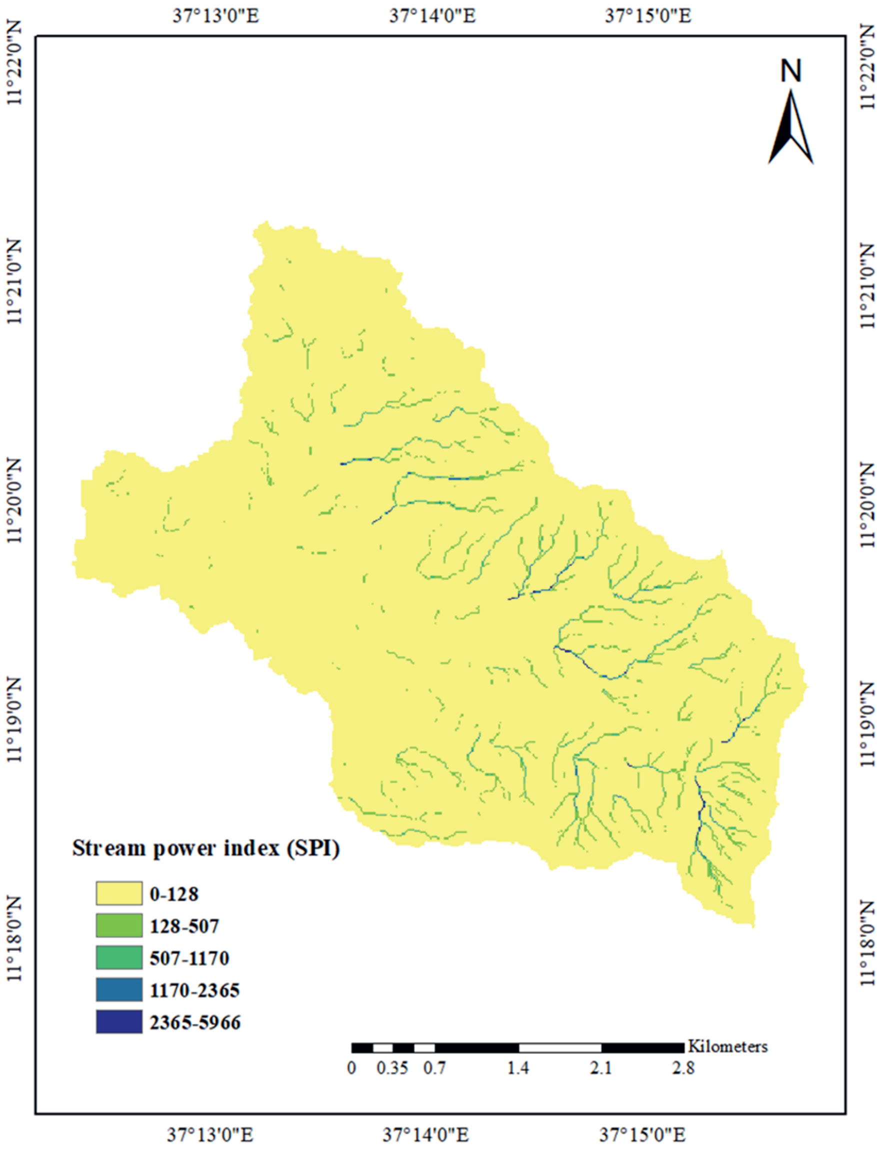


***Figure 7.14*** *Stream power index map*

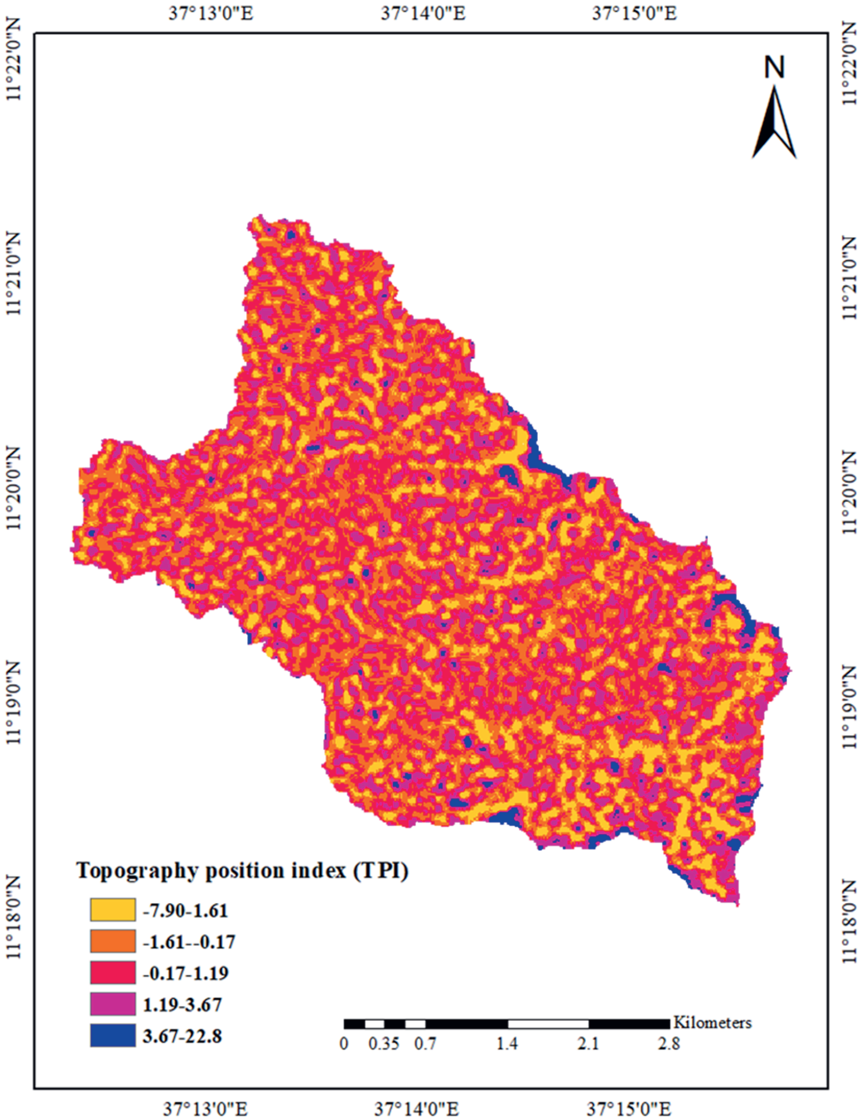


***Figure 7.15*** *Topography position index map*

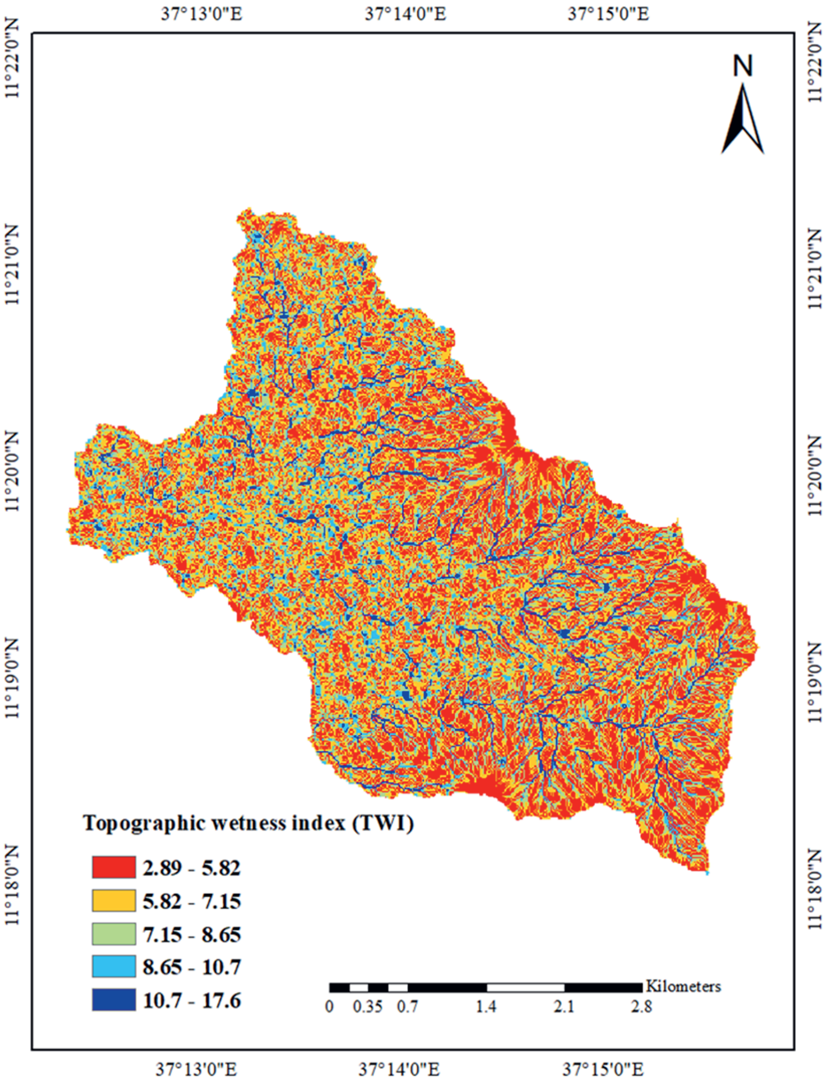


***Figure 7.16*** *Topographic wetness index map*

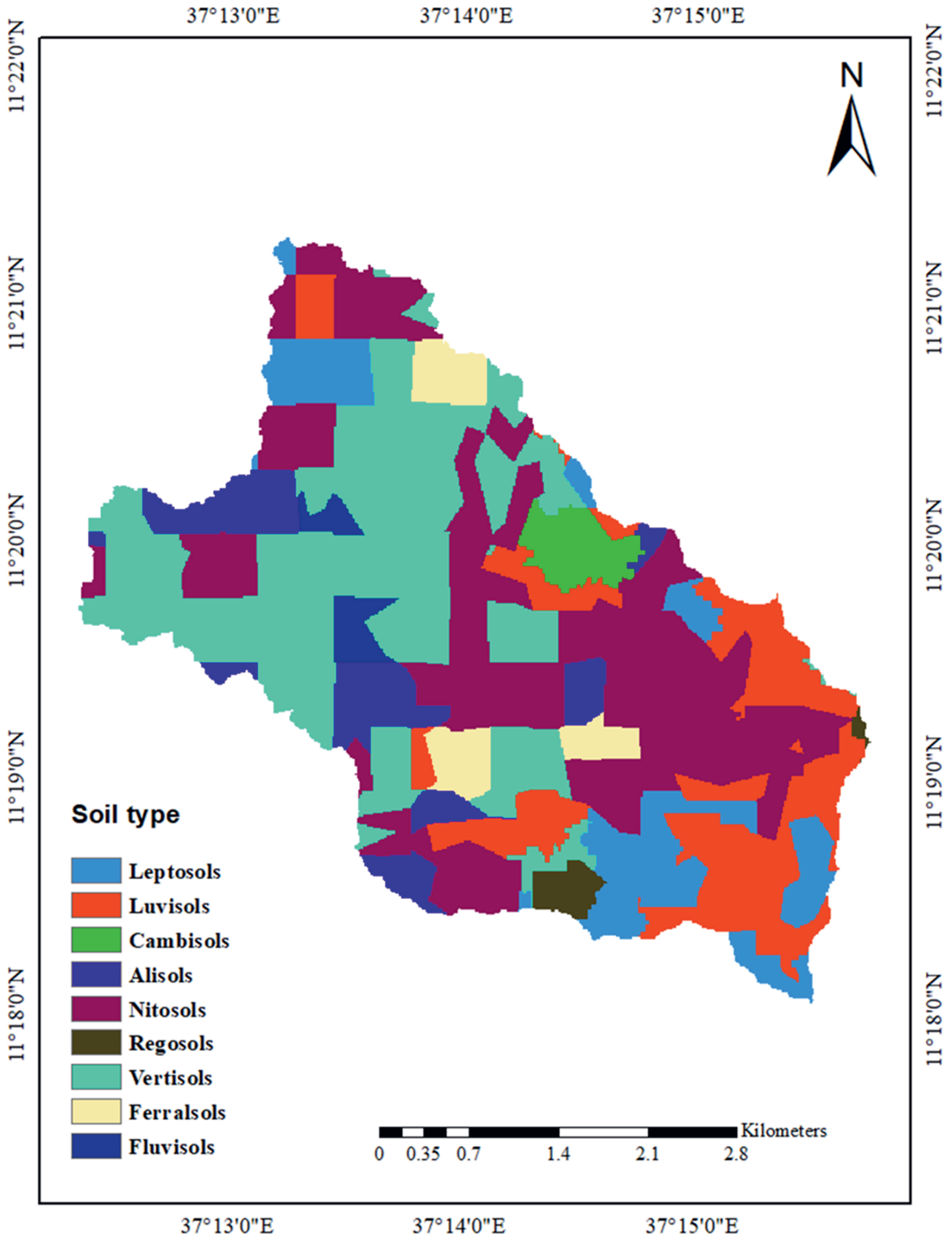


***Figure 7.17*** *Soil type map*

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# English summary

Gully erosion is one of the most severe land degradation processes in Ethiopia's highlands, posing a significant threat to people and the environment. It destroys the environment and the economy by disrupting various soil and land functions. Gully conservation efforts did better in semi-arid regions than in humid ones. Due to a lack of understanding of the erosion process, which results in a poor technical quality of soil and water conservation measures, and a lack of integrated approach, gully restoration efforts in sub-humid Ethiopia were unsuccessful. Understanding the soil and hydrological processes that control gully erosion and identifying gully hotspot areas is critical for successfully implementing gully reclamation measures. Furthermore, understanding the gully erosion process in a landscape through modeling and field measurement techniques is vital.

In Chapter 2, a literature review identified the causes and controlling factors of valley bottom gullies. It also found deficiencies in existing rehabilitation measures. Peer-reviewed articles were searched in the CAB Abstract and Scopus databases. Valley bottom gullies appear as incisions in the lower periodically saturated landscape where surface and subsurface flow concentrates. From the literature review, we found the following general trends: watershed characteristics determine the location of valley bottom gullies; an increase in water transported from the watershed initiates the formation of gullies; the rate of change of the valley bottom gullies, once formed, depends on the amount of rainfall and the soil and bedrock properties. In a humid climate, subsurface flow greatly enhances bank slippage and the advancement of gully heads. Valley bottom gully reclamation is generally effective in arid and semi-arid areas with a limited subsurface flow and deep groundwater tables. Similar remedial actions are ineffective in humid regions because they are not designed to account for the effect of subsurface flows. For successful implementation of rehabilitation measures in humid areas, an integrated landscape approach that accounts for combined subsurface and surface flow is required.

In Chapter 3, we looked at the impact of soil hydrological and morphological characteristics on the formation of valley bottom gullies on Vertisol and Nitisol. Despite having a larger drainage area and steeper and taller gully walls, the Nitisol gully was more stable than the Vertisol, which had shallower and less steep sidewalls. In the Nitisol, soil pipes evacuate excess water from the gully bank to the gully channel, explaining the relatively deeper groundwater and lower soil moisture content in this soil than in the Vertisol. The drainage provided by soil pipes in the Nitisol prevented a sizeable saturated zone in the unconsolidated soil and contributed to the smaller gully head erosion rate. The impact of

soil pipes and cracks in the Vertisol was the inverse of what was observed in the Nitisol (i.e., promoting water recharge into the soil). Furthermore, the discontinuous nature of the crack may promote pressure build-up, which can result in gully slumping. The Bank Stability and Toe Erosion Model (BSTEM) model was used to analyze gully bank stability, and it was found that groundwater and soil cracks affect gully head stabilities. Tension crack had a significant impact on gully head stability compared to GWT. For Vertisol, in addition to structurally stabilizing the gully head and sidewalls, rehabilitation measures should safely remove excess water from both the catchment and the gully bank to reduce bank collapses. Reduced upslope runoff and stabilization of the gully head and sidewalls may be sufficient for Nitisol.

In Chapter 3 gully erosion susceptibility map (GESM) was developed using frequency ratio (FR) and random forest (RF) models for the Minzir catchment. In addition to GESM, the RF model was used to rank gully predictor factors based on their importance to gully erosion. Among the initially selected sixteen gully predictor factors, soil type and groundwater table (GWT) are new variables introduced to the models that were not used in previous studies. Both models produced the best gully erosion prediction when the four most important gully erosion predictor factors were used: drainage density, elevation, land use, and groundwater table. The finding that the groundwater table is one of the most important gully predictor factors in Ethiopia is a novel and significant quantifiable finding and is critical to the design of effective watershed management plans. The performance of the FR models to accurately predict gully location ranged from average to good, whereas for the RF model, excellent prediction accuracy was obtained. Thus, the FR and RF models were identified as valuable techniques for determining the most important gully erosion predictor factor and mapping gully erosion vulnerable areas. The findings of this study suggest that future planning and implementation of conservation measures in subhumid regions of Ethiopia should focus on areas with higher drainage density, low-lying areas, grazing land, and shallower groundwater table, which are vulnerable to gully erosion.

We developed a new numerical model called Gully Erosion by Headcut Migration (GEHM) in Chapter 5 that accounts for various environmental and climatic factors and models gully head erosion at a landscape scale. GEHM is a new python package that enables gully head erosion to be modeled along with other earth surface processes. The model uses terrainbento and landlab model components in combination with the gully head migration model. At user-specified time intervals, the model will save outputs such as topographic elevation, aquifer thickness, soil saturation, surface water discharge, sediment transport rate, and gully head location. The sensitivity analysis for selected gully erosion parameters showed that the model is sensitive to changes in groundwater level, hydraulic conductivity, drainable porosity, water erodibility, and head-cut height. Model outputs such as gully head retreat, cumulative soil erosion, aquifer thickness, and groundwater storage for a given input parameter change showed a similar trend with previous studies. Finally, the GHEM model can model changes in groundwater storage caused by soil losses from gully heads and hillslopes, which can be used as input in the planning and design of land and water resource management activities.

In Chapter 7, the findings from the research chapters are discussed and linked together. Overall, the results of this study contribute to a better understanding of the gully erosion process and provide information for successful sustainable land management. This study assessed current knowledge of valley bottom gully erosion and examined how hydrology, particularly subsurface flow and topographic factors, influence the vulnerability of valley bottomlands to severe gully erosion. Deficiencies in existing rehabilitation measures were also identified. This study looked specifically at gully erosion at the valley bottom and how differences in soil type (Nitisol and Vertisol) can lead to differences in soil hydrology and morphology, affecting the gully head expansion rate. Moreover, gully susceptibility areas were mapped, and the most critical factors of gully erosion were identified by including new gully erosion parameters such as soil type and groundwater. Finally, by incorporating different geomorphological, soil, and hydrological parameters, the development of the GHEM model, advances state of the art in the numerical modeling of gully erosion at a landscape scale.

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# About the author

Selamawit was born in Dessie, Ethiopia, in May 1990 but spent the majority of her childhood in Kelela, Wollo, Ethiopia. She received her Bachelor's Degree in Soil and Water Resources Management from Wollo University in 2011. She was among the top 5 (2$^{nd}$ in her class) students throughout her bachelor's degree, which gave her the opportunity to be employed as a Graduate Assistant by the Ethiopian Ministry of Education at Bahir Dar University.

After serving for one year as a Graduate Assistant, she pursued her MSc degree in Water Resources Engineering (Engineering Hydrology) at Bahir Dar University from 2013 to 2015. From 2013 to 2015, she also worked as a research assistant in Carbo-Part and Carbon Offset Project Exclosure projects at Amhara Regional Agricultural Research Institute. As part of these projects, she coordinated a group of female farmers to identify their perceptions of forest degradation and climate change. In 2015, she worked as a lecturer at Bahir Dar University, where she taught courses such as hydrology and soil and water conservation.

In 2016, she was admitted to a Ph.D. program at Wageningen University and Research at Soil Physics and Land Management group. Her Ph.D. was sponsored by Nuffic Netherland Fellowship Program and Schlumberger Foundation Faculty for the Future Program. She employed both field measurement and modeling approaches (data-driven and numerical models) to investigate the gully erosion process and identify gully erosion hotspot areas.

## Publications

### *Peer-reviewed papers*

**Amare, S.**, Keesstra, S., van der Ploeg, M., Langendoen, E., Steenhuis, T., & Tilahun, S. (2019). Causes and controlling factors of Valley bottom Gullies. Land, 8(9), 141.

**Amare, S.**, Steenhuis, T., Ploeg, M. V. D., Langendoen, E., Keesstra, S., Belete, W., Carranza, C., Tilahun, S., & van der Zee, S. E.. Hydrological and soil controls on valley bottom gully head erosion in the Ethiopian highland, Minzir catchment. Earth Surface Processes and Landforms (to be submitted).

**Amare, S.**, Langendoen, E., Keesstra, S., Ploeg, M. V. D., Gelagay, H., Lemma, H., & van der Zee, S. E. (2021). Susceptibility to Gully Erosion: Applying Random Forest (RF) and Frequency Ratio (FR) Approaches to a Small Catchment in Ethiopia. Water, 13(2), 216.

**Amare, S.**, Langendoen, E., Keesstra, S., Ploeg, M. V. D. & van der Zee, S. E.. Landscape Evolution by Combined Hillslope Erosion and Gully Head Migration. Earth Surface Processes and Landforms (to be submitted).

### *Professional publications*

Zegeye, A. D. Langendoen, E. J., Guzman, C. D., Dagnew, D. C., **Amare, S. D.**, Tilahun, S. A., Steenhuis, T. S (2017). Gullies, a critical link in landscape soil loss: A case study in the sub-humid highlands of Ethiopia Land Degradation and Development. Land Degradation & Development, 29(4), 1222-1232.

András Darabant, Birgit Habermann, Kibruyesfa Sisay, Christopher Thurnher, Yonas Worku, **Selamawit Damtew**, Mara Lindtner, Leisa Burrell & Abrham Abiyu (2020). Farmers' perceptions and matching climate records jointly explain adaptation responses in four communities around Lake Tana, Ethiopia. Climatic Change, 163(1), 481-497.

**PE&RC Training and Education Statement**

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

**Review of literature (4.5 ECTS)**

- Gully erosion inventory and proposal for a modelling activity; Joint Research Centre, Ispra, Italy

**Writing of project proposal (4.5 ECTS)**

- Understanding the process of valley bottom gully formation and development to reduce reservoir sedimentation, the case of Northwest highlands of Ethiopia

**Post-graduate courses (5.1 ECTS)**

- Summer school on flow and transport in terrestrial systems; Technical University of Clausthal, Germany (2016)
- Introduction to R for statistical analysis; PE&RC (2016)
- Preconference tour: Mediterranean environmental issues, Spain; TERRAenVISION (2018)
- Geostatistics; PE&RC (2018)

**Deficiency, refresh, brush-up courses (9 ECTS)**

- Sustainable land and water management; WUR (2016)

**Competence strengthening / skills courses (4.1 ECTS)**

- Techniques for writing and presenting scientific papers; WGS (2016)
- Information literacy, including EndNote introduction; WGS (2016)
- Introduction / critical thinking and argumentation; WGS (2018)
- Intercultural communication; WGS (2021)
- Reviewing a scientific manuscript; WGS (2021)
- Scientific publishing; WGS (2021)
- Project and time management; WGS (2021)

**Scientific integrity / ethics in science activity (0.3 ECTS)**

- Ethics in plant and environmental sciences; WGS (2020)

**PE&RC Annual meetings, seminars and the PE&RC weekend (1.5 ECTS)**

- PE&RC First year weekend (2016)
- PE&RC Midterm weekend (2018)

**Discussion groups / local seminars or scientific meetings (3.6 ECTS)**

- Workshop on soil erosion; Ethiopia (2016)
- World bank group-Africa fellowship BBL series; USA (2019)
- Presentation on watershed management (USA) (2019)

**International symposia, workshops and conferences (9.5 ECTS)**

- 4$^{th}$ Bio-hydrology conference walking on drylands; Spain (2016)
- American Geophysical Union (AGU) fall meeting; USA (2017)
- TerraENVISION conference; Spain (2018)
- Faculty for the future fellows and alumnae forum; United Arab Emirates (2018)
- Water for food global conference; USA (2019)

**Lecturing / supervision of practicals / tutorials (2.4 ECTS)**

- Introductory hydrology and hydrometery; Ethiopia (2021)

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