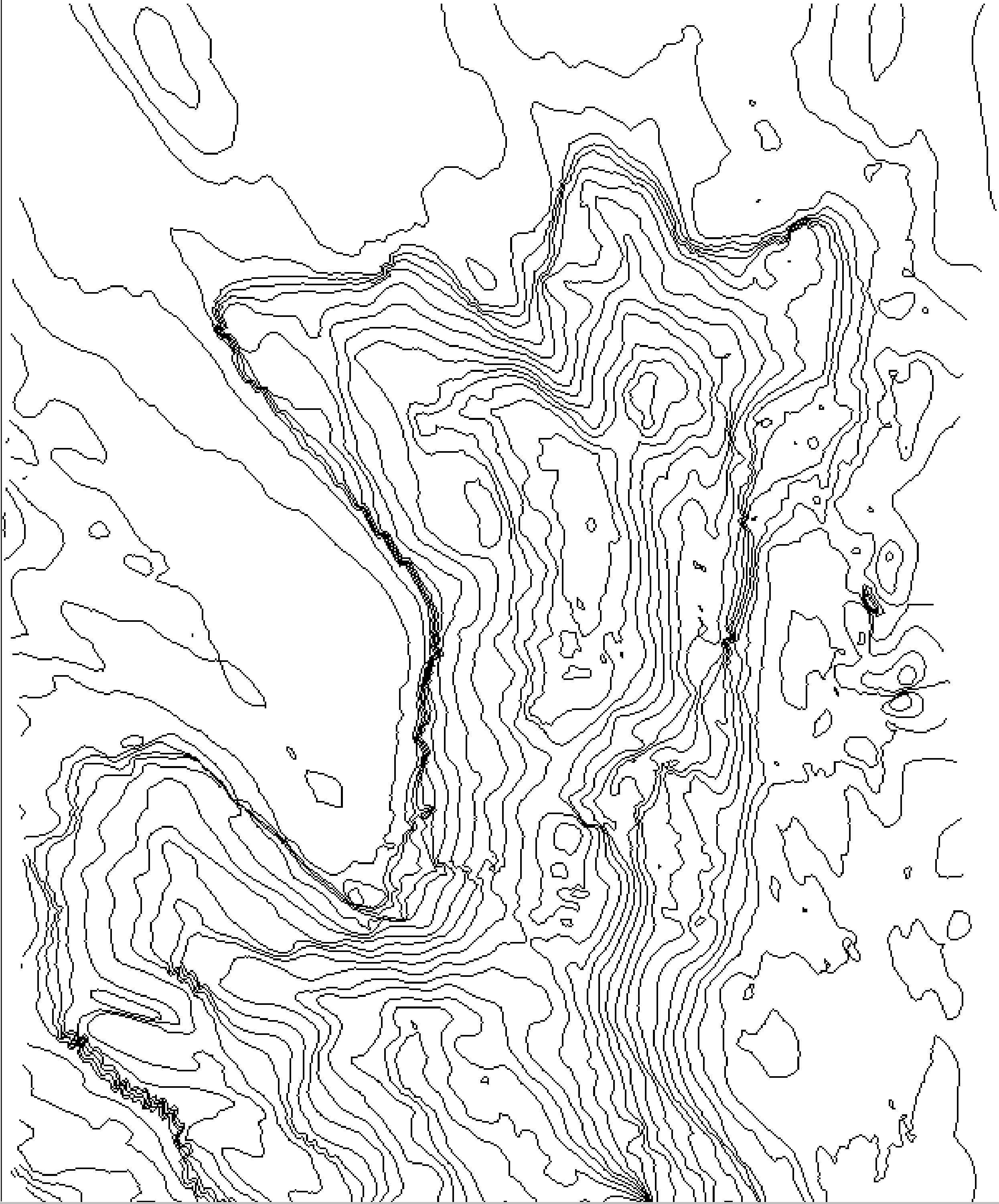
Low-land Gully Formation in the Amhara Region, Ethiopia

Visualizing the role of subsurface flows in gully formation in the Minizr sub-catchment of North-West Ethiopia



Pim Rijkee
MSc Minor thesis
Wageningen UR
SLM Group

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Visualizing the role of subsurface flows in gully formation in the Minizr sub-catchment of North-West Ethiopia

Pim Rijkee (891116721040)
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Supervised by Saskia Keesstra
Wageningen UR
Minor MSc Thesis
Soil Physics and Sustainable Land Management
SLM-80324
Wageningen, Netherlands

Preface

This thesis started way back in September 2014, when I arrived for a 4 month stay in Ethiopia's North-West. Now, more than a year later, the story has been completed. Albeit a cliché, this document is so much the better for the help and support of many people: Saskia Keesstra, my supervisor, for not only always finding me the places I want to go, but also for putting up with my consistent lack of any updates whatsoever; Mulatie Getahun, who provided amazing support and great conversation in all places Ethiopian, from the muddy motorbike tracks to fancy coffee corners; Walle Lakew, for the great times and his unmatched local resourcefulness. Of course, my thesis office mates, for never failing to distract me.

Finally, a long overdue thanks to my family and girlfriend, who never questioned me when taking a year to finish this thing.

Enjoy the read!

Pim

Abstract

Land degradation and related processes such as gullying, flooding and sedimentation, are global phenomena. However, the economic consequences of these processes are more severe in developing countries, which lack resources for prevention and mitigation. In Ethiopia, therefore, gully erosion as a form of land degradation is a prime issue. Over the past decade, gullies have formed in the foothills of the Minizr sub-catchment in the highlands of North-Western Ethiopia – a watershed draining into a reservoir constructed in 2011. On hillslopes in the catchment, government workers and NGOs have introduced extensive soil and water conservation measures to counter hillslope erosion. However, local extension workers have reported increased gully growth rates in the past five years in the downslope foothill areas, whose soils consist mainly of vertisols. Knowledge of the gully erosion rates and gully mechanism are lacking. To halt and mitigate gully erosion in the foothills, this thesis looked at the gully formation process and the root cause of the reported increased erosion rates to be able to make a justified selection of measures for mitigation and rehabilitation of the gullies. Three root causes were hypothesized to have influenced gully erosion mechanisms: reservoir construction, land use change and the implementation of soil and water conservation measures in surrounding hills from 2010 onwards.

For the physical field work, three representative gullies were selected for detailed analysis. All gullies were located in gently-sloped areas (0-5%). Gully shape and volume were derived using terrestrial photogrammetry in AgiSoft PhotoScan Professional. In addition to using photos captured one-by-one, still frames exported from video footage (shot with a stock IPhone 4) were used as input. To study the suspected influence of subsurface flow on the formation process, approximately 35 points per gully were sampled weekly for soil moisture content over the course of September, November, and December 2014. In addition, the sites were checked for signs of subsurface flow at the end of the rainy season and again 3 months into the dry season. Results show that the erosion rate has indeed increased compared to rates from before 2010, with a 74 tons/ha/year erosion rate over the 2014 rainy season. Extensive signs of subsurface flows are visible in and around all research gullies. Data and observations point to the following process: after rains, water infiltrates and flows downhill through a permeable layer towards the reservoir. In the foothills of the study area, these flows become perched on a less permeable layer of dense grey clay. This leads to positive pore water pressures, which in turn cause dispersion of clay particles. As an end result, soil cohesion is greatly reduced. In these conditions, gully formation is easily triggered by overland flow and slumping. Once a gully has been established, expansion is mainly through bank collapse: during the wet season as banks are saturated, and in the dry season as extensive cracking appears.

Three hypothesized root causes have been researched. First, the influence of the Koga Dam since its construction ended in 2011, which might have led to rising groundwater levels, which may saturate soils, lowering friction thresholds. However, historical data on ground water levels before, during and after construction of the Koga Reservoir were not available. After surveying water wells and interviewing farmers, no evidence has been found that the reservoir construction has influenced the hydrology of the study area. The same was true for land use change: no change was detected in the gully watershed for the 2010-2014 period, and literature research did not yield any evidence it had changed significantly between the 1980s and 2010. The most likely cause of the increased erosion rates lies with the implementation of stone bunds and *fanja yuu* on all fields on every hillslope surrounding the study area. These contour barrier type soil and water conservation measures have increased infiltration. Although this has decreased overland runoff on the hillslopes, it has increased ground water flows toward the study area and therefore made the area more susceptible to gully expansion through the described process.

The merit of this study is threefold. First, it shows the applicability of a fast, accessible and accurate way to digitally represent gullies and other landscape features through the use of video footage and photogrammetry. Secondly, it lends validation to claims by farmers and extension workers that the gully erosion issue has become more urgent since 2010. Finally, it shows the dominant processes in gully formation in the area, permitting future selection of measures to halt further gully growth and rehabilitate existing gullies based on research findings.

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Keywords: Erosion, gully formation, subsurface flow, photogrammetry, piping, seepage, low-land gully, Ethiopia,

Contents

1. Introduction 6
Research objectives 6
Background 7
Potential root causes 9
Study Area 10
Koga Reservoir 11
Soils 11
Land use change 12
Soil and Water Conservation Measures 12
Thesis structure 12
2. Methodology 13
How has the erosion rate in the Minizr sub-catchment changed since 2010? 13
What is the dominant process behind gully formation in the Minizr sub-catchment? 14
How has the construction of the Koga reservoir influenced this formation process? 15
How has changing land use influenced the gully formation process? 16
How have SWC measures, implemented uphill, influenced the gully formation process? 16
3. Results 17
Soil analysis 17
“Waterfall” gully 17
“School” gully 18
“Tentacle” gully 20
Pore water pressure distribution 23
“Tentacle” gully 26
“School” gully 27
Presence and impact of SWC measures 30
4. Discussion 33
Strenghts and limitations of the methodology 33
Comparing soil erosion rates 36
Determining gully formation processes 37
Finding root causes of erosion 38
5. Conclusion 40
6. Recommendations 41
7. References 42
8. Appendix 45
Evidence for piping 45

1. Introduction

Land degradation and related processes such as gullying, flooding and sedimentation, are global phenomena (Sadeghi *et al.*, 2008). They have been recognised as a major threat to the global environment: it impacts directly human health and livelihoods (Vogt *et al.*, 2011). The ratification of the United Nations Convention to Combat Desertification (UNCCD) by 193 affected nations shows its widespread effects (Vogt *et al.*, 2011). Soil erosion is the main form of land degradation: a threat that has destroyed nearly one-third of land suitable for agriculture since the 1950s (Pimentel *et al.,* 1995). Moreover, the economic consequences of these processes are more severe in developing countries, which lack resources for prevention and mitigation (Tameni and Vlek, 2008). One such developing country is Ethiopia, which the International Monetary Fund has identified as a low-income country (IMF, 2011: 81). Here, gully erosion is a prime issue (Mekonnen *et al.*, 2013), rendering an increasingly large area unsuitable for grazing and agriculture and leading to reservoir sedimentation (Gebreyohannis, 2009), threatening livelihoods. To protect livelihoods, cost-effective measures to prevent and mitigate gully erosion should be put in place. This requires both an intimate knowledge of gully erosion processes (Daba *et al.*, 2003 and Poesen, 2011) and gully growth rates (Daba *et al.,* 2003).

Research objectives

Residents in the study area have complained with extension workers that recent gully formation is taking away grazing land, threatening their livelihood (M. Getahun, pers.comm.). Extension workers are willing to halt gully erosion and mitigate its effects. To do so, it is important to select effective soil and water conservation (SWC) measures. It is however unclear how the mechanics behind low-land gully formation have changed over the past decade to account for the increase in gully formation. The construction of the Koga reservoir, changes in land use, and the construction of SWC measures uphill possibly influence the mechanism behind the formation of lowland gullies over the past decade in the lowlands of the Minizr sub-catchment.
Since no research has been carried out on the root cause of the gully formation in this area, nor have the gullies been mapped and measured, this research aims to find the extent and root cause of low-land gullies in the Minizr sub-catchment. It will do so through literature review and field research. The main research question is as follows:

What is the root cause of gully formation over the last decade in the low-lands of the Minizr sub-catchment?

Working towards answering the main research question, several sub-questions have been established. These have been coupled directly to the Methodology section.

1. How has the erosion rate in the Minizr sub-catchment changed since 2010?
2. What is the dominant process behind gully formation in the Minizr sub-catchment?
3. How has the construction of the Koga reservoir influenced the gully formation process?
4. How has changing land use influenced the gully formation process?
5. How have SWC measures, implemented uphill, influenced the gully formation process?

Background

As the main source of soil erosion, water erosion can be divided in rill, inter-rill and gully erosion (Poesen *et al.*, 1996). Both rill and interrill erosion have been studied extensively and are relatively well understood (Tebubu *et al.*, 2010). However, with the increased attention since the 1980s on off-site effects of erosion, the need for a closed sediment budget became clear (Poesen *et al.*, 1996). Therefore, gullies and their function as a sediment source and pathway became a more prominent research topic. On-site effects of gully erosion are loss of land and decreased water holding capacity of the soil (Tamene and Vlek, 2007). The main off-site effect of gully erosion is sedimentation of lakes and reservoirs, hindering their functioning (Tebebu et al., 2010; Gebreyohannis, 2009). Grouping these effects, the occurrence of gullies often indicates “an extreme form of land degradation warranting special attention” (Daba *et al.*, 2003).
In general, gullies have been defined as recently developed drainage lines of ephemeral streams with steep banks and a nearly vertical gully head (Poesen, 2003). Active gullies are characterised by a retreating head (Daba *et al*., 2003; Nyssen *et al.*, 2006). Several definitions for the initiation point of gullies exist and these can be used to map the start of a gully. Earlier fieldwork into gully erosion in Victoria, Australia, showed gully initiation to be a zonal instead of a point process (Rijkee, 2013). It found that it is difficult both from aerial footage and in-field observation to determine a single initation point of a gully and that is does not represent the flow processes and forces acting on the soil. Instead, these lead to a slope tract or zone upslope of an established gully of up to several meters where soil removal is visible but not consistently. Often, short stretches of the original soil surface would still be present. Therefore, the study concluded that to acknowledge this reality, the definition of gully initiation should be that a certain minimum depth should be reached over a length of at least 5 meter. The 5-meter zone suffices to eliminate pools that may precede gullies (Rijkee, 2013). A common minimum depth is the 'ploughing depth' (Poesen, 2003), set to 0.3m by the FAO (Geyik, 1986).

Hillslope and lowland gullies form differently (Tebebu, 2010). Historically, gully research has focused on hill slope gullies (Tebebu *et al.*, 2010). In these, the main trigger is surface run-off (Ziemer and Albright, 1987), with the erosion potential of a slope locality dependent on the contributing area and local slope. Channel initiation occurs when the erosion potential exceeds the soil cohesive strength, and the gully head moves uphill through the incisive power of the stream flow concentrated at this head (Daba *et al*., 2003; Nyssen *et al.*, 2006). The Stream Power Index (SPI) expresses the erosion potential (Daba *et al*., 2003). An additional mechanism is at play in lowland gully formation: slopes are gentler, and here subsurface flows directly and indirectly influence erosion potential. In their review of the role of subsurface flow in hillslope and stream bank erosion, Fox and Wilson (2010) mention the confusing naming of various subsurface flow processes. For the sake of clarity, this thesis will use the definitions used in their article. Two distinct subsurface flow processes directly influence erosion: piping and seepage. First, this section discusses seepage (non-abrasive flow), followed by piping (abrasive flow), and then relevant mechanisms that have a more indirect effect on erosion.
Seepage is the diffuse subsurface flow of water towards stream channels (Fox *et al.*, 2007). Seepage exists in situations where high infiltration leads to perched water tables, either above an impermeable soil layer, or between soil horizons with a different hydraulic conductivity. By itself, seepage does not move soil particles through the soil. The effects of seepage on gully erosion are retreating of the gully head and gully bank failure caused by undercutting. These effects stem from the same core mechanic: the negation of soil shear strength by positive pore pressures (Tebebu *et al.*, 2013; Fox *et al.*, 2007). The positive pore pressures lower the stream power necessary to cause gully formation and expansion, compared to soils with low soil moisture content (Fox and Wilson, 2010; Tebubu *et al.*, 2013; Daba *et al.*, 2003).
The term piping describes a subsurface flow that occurs in a local, focused fashion in the form of tubular cavities. Faulkner (2006) describes these tubular cavities as mostly parallel to the slope and as of sufficient length, size, and connectivity to influence flow at the hillslope scale. Pipes tend to develop in duplex soils, soils with a contrasting texture between soil layers (Fox and Wilson, 2010). Piping has been well established as playing a major role in gully initiation (Faulkner, 2006) and embankment collapse (Richards and Reddy, 2012).
Process-wise, it follows seepage as at the critical seepage rate – depending on the soil’s stress state, pore pressure, initial void ratio, and seepage direction – finer soil particles start to wash through a soil with a coarser skeleton (Richards and Reddy, 2012). This is called suffusion and constitutes the first stage of piping. With increasing seepage velocities, the larger particles will start to flow, too, and the process has moved to a stage called backward erosion piping (Richards and Reddy, 2012).
In collapsible soils, erosion initiates when the pipe ceiling collapses, leading to mass movement of soil when runoff concentrates at the newly formed depression. Soil losses can be especially high since pipes may be in an advanced state (e.g. below a vegetated slope) before the pipe collapses. The rapid flow that can occur through soil pipes is an important cause of debris

flows and landslides. When flow exceeds the transport capacity of the pipe or when eroded material blocks the pipe. Both will lead to a build-up of pore pressure in the soil pipe.

In some soils these increased pore pressures are more likely to dislodge and transport soil particles along the flow direction. These soils are characterized by a “double layer” or 2:1 clays[*], through a process called dispersion. Dispersion is a process that occurs when a deflocculant, often a form of sodium (Na), is present in a soil at near-saturation levels of the soil’s monovalent exchangeable cations. Consequences relevant for the erosion potential are swelling, and the subsequent reduction in permeability; and deflocculation, the loss of soil aggregates (Faulkner, 2006). Soils that are vulnerable to dispersion include those with smectite clay minerals, such as Vertisols. Sumner and Naudu (2007) go into depth about the exact conditions for a soil to become prone to dispersion, and show that a variety of factors related to the clay-mineralogy and the soil development is crucial: soil type per se is not enough to rule out or consider dispersion.

In their review, Fox and Wilson (2010) and Faulkner (2006) do not discuss the role of macropores, which possibly facilitate focused subsurface flow, implying they are not significant at hillslope scales. However, several studies have shown their importance in influencing piping and seepage erosion (Nieber et al., 2006); Nieber and Sidle (2010); Tsuboyama et al., 1994), especially in situations of soil saturation and even when macropores are not connected and continuous.

In addition to the direct effects of piping and seepage erosion, subsurface flow can indirectly influence erosion through the interaction of soil properties with soil water pressure (Fox and Wilson, 2010). This pressure, when greater than the soil strength, lowers the effective weight of a particle. The pore pressure thus decreases drag forces and particles will be more easily detached. In existing gullies, slumping at the head and side of the gullies can occur rapidly when eroded material clogs pipes (Fox and Wilson, 2010). Several indicators can serve as both direct and indirect evidence for the presence of subsurface flow (Hagerty, 1990). Direct evidence consists of holes at the exfiltration face. Hagerty (1990) describes primary, secondary and tertiary indirect evidence of piping. Tertiary indicators should not be relied on as the sole evidence for subsurface flow, as the indicators may be caused by other mechanisms. A description and examples of each have been added to Table 4 in the Appendix.

Tebebu *et al.* (2010) present a case where direct and primary indirect evidence of piping have led to of suitable SWC measures in the Debre-Mawi watershed, a catchment South of Lake Tana, Ethiopia. Policy makers implemented these measures after research had shown that gully formation in the watershed has been caused by subsurface erosion, driven by high soil pore water pressure. Figure 1 provides examples of piping evidence found in the Debre-Mawi watershed that correspond to those in Table 4.

Figure 1: Evidence of piping processes in the Debre-Mawi watershed: pothole and smaller pipe (left) and a concentrated water outflow in a rill bank (right). Source: Mengisti, 2011.

On the interaction between pore pressure and soil properties, Vieira and Fernandes (2004) make note of a Brazilian case study where a high pore pressure itself might be sufficient to initiate landslides. They based their conclusion on a difference in

[*] The names refer to the mineral structure of some clay soils, where an octahedral hydroxide layer or sheet is found between two tetrahedral silicate layers. They are contrasted with 1:1 clay minerals, which have one layer of each. Wikipedia provides an accessible and referenced further introduction to clay minerals (link).

saturated hydraulic conductivity (K) of 10 orders of magnitude between two soil layers. In a 2007 study, Fox *et al.* argue that even small differences in K of less than an order of magnitude could lead to pore water pressure high enough to cause lateral soil movement.

It should be mentioned that pore water pressure is temporally and spatially variable: Rinaldi and Casagli (1999) studied the influence of the phreatic level on soil stability in stream banks. When most of the bank is above the phreatic level, the shear strength of the soil is greatly enhanced by matric suction. However, when during “severe rainfalls and floods” matrix potential becomes positive, cohesion can become very low or disappear altogether. Keppeler *et al.* (1994) suggested factors explaining these changes in their study on post-logging responses in pore-pressure along a hill-slope. They measured elevated pore water pressures above impermeable layers during rainy periods, particularly at positions low on the hillslope. They hypothesize reduced canopy interception and compaction-induced reductions in pore space, or the collapse of soil pipes due to felling as causes for increases in soil water pressure. On the same subject, Crosta and di Prisco (1999) warned that the chain of events leading up to soil instability is complex and that interacting factors often cannot be separated. However, Fox and Wilson in their 2010 review on the role of subsurface flow on hillslope erosion provide more tangible examples of the knowledge gap. On hillslope scale, they indicate that it is unclear what the effect is of “[…] vegetation, and soil management and land use” on soil instability in lowland gully erosion.

Potential root causes

Following on this and the conclusions by Keppeler *et al.* (1994) and Rinaldi and Casagli (1999), possible root causes for increased lowland gully erosion through elevated pore water pressure have been listed in Table 1. Each fits with the notion that the cause of gully formation lies in a mix of natural and anthropogenic factors (Nyssen *et al.*, 2006; Poesen, 2003).

Table 1: Possible root causes for increases in lowland gully formation, including mechanisms.

Possible root cause	**Mechanism**
Rising phreatic levels	Rising groundwater levels may saturate soils, lowering friction thresholds (*Salama* et al., 1999; Tebebut *et al.*,2013).
Changing land-use	Land-use change in the study area may increase sediment detachment or connectivity (Poesen *et al.*, 2002) or increase infiltration (Keppeler *et al.*, 1994)
Implementation of uphill SWC measures	Soil water conservation structures can increase infiltration rates and changing the water table (Nyssen *et al.*, 2007).

Study Area

Research takes place in the Minizr sub-catchment, part of the larger Koga catchment. The Koga catchment is one of the major river watersheds of the Lake Tana basin in the Amhara Region of North-Central Ethiopia (Figure 2). Average annual rainfall is 1200 mm, with 90% of rainfall occurring during the June-September wet season. Water flows to Lake Tana through the Koga River and the Blue Nile. The upstream area is characterized by hilly terrain up to 3,200m AMSL. The field site consists of a 22 km^2 area in the foothills near Meshenti, at approximately 2,100m AMSL. Within the study area, several gullies in the foothills form a gully system (Figure 3). Within the study area, three active, representative gullies were selected. The positions and course of the selected gullies in the study area have been indicated in Figure 3. The characteristics of these gullies will be elaborated upon in the Results chapter.

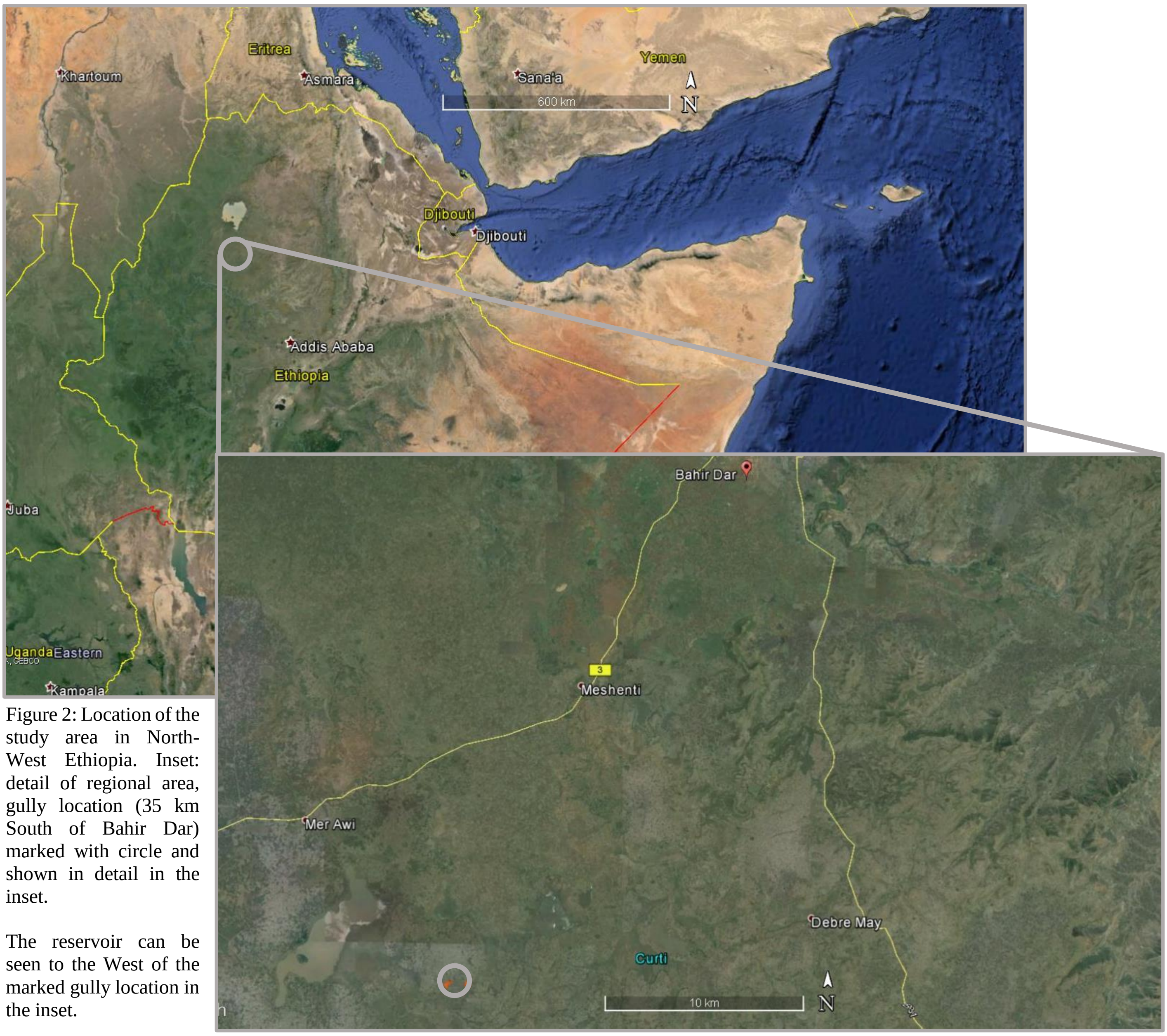


Figure 2: Location of the study area in North-West Ethiopia. Inset: detail of regional area, gully location (35 km South of Bahir Dar) marked with circle and shown in detail in the inset.

The reservoir can be seen to the West of the marked gully location in the inset.

Figure 3: detail of marked area in Figure 2 (inset), location of the selected gullies in the study area. The course of the gullies as of year-end 2014 has been indicated in orange, on aerial imagery dated 2013. Image source: Google Earth, imagery copyright CNES/ASTRIUM 2015.

Koga Reservoir

The study area is bound downstream by a wetland, draining into the Koga Reservoir, an artificial waterbody containing $83.1x10^6$ m^3 water to feed the Koga Irrigation and Watershed Management Project. The project is part of the 2002–2016 government plan to develop the irrigation sector to meet the increasing needs and secure food production (Ministry of Water Resources, 2008).

This project provides 7,000ha of arable land with irrigation water. Construction of the dams in the Koga River finished in 2011: one main dam (length: 1730m, height: 21m) and a saddle dam (length: 1162m, height: 9m). Inundation turned 1,042 ha of woody vegetation and agricultural land into water (Yasheneh, 2013). This will hopefully lead to food self-sufficiency and security, foreign exchange earnings and eventually in improvement of farmer's livelihoods (Ministry of Water Resources, 2006 in Eriksson, 2012). It is the country's first large-scale irrigation project and has gained international attention (Marx, 2011). It serves as a pilot irrigation project in the Blue Nile. If successful, more irrigation projects will follow as a result of increased investments in the country's agricultural sector (Ministry of Water Resources, 2008). In the lowland leading to the reservoir, some 30-50 gullies have been developed in the past decade (M. Getahun, pers. comm.), distributed over 22 km^2 and oriented from the surrounding hills to the stream channel. Aerial photography (Google Earth Pro, imagery 2/2015) shows the studied gullies are all tributaries to one of the main gullies in the reservoir hinterland, and stretch for over 6,600 m on a surface of 5.45 km2. The depth and width of the major gullies were reported to be up to 20 meters wide and 5 meters deep (M. Getahun, pers. comm.). Aerial imagery is available from 2011 onwards, rendering further analysis of the gullies on system scale through this data impossible before that date.

Soils

Black Vertisols (locally referred to as *Walka*) cover the gentle slopes (0-5%) of the study area (Tebebu *et al.*, 2010; Tilahun, 2012). These soils form deep, wide cracks during the dry period, while swelling and becoming sticky during the rainy season. Infiltration is then between 6 to 36 mm/hour (Tilahun, 2012). Tilahun (2012) studied a close-by and hydrogeologically similar sub-watershed and noted that there the soil is usually saturated during the rainy season and covered with grass, with many "large and expanding" gullies with depths of up to 10m and widths of 30m.

Land use change

The advent of agriculture in the Ethiopian Highlands, planting of eucalyptus trees, cultivation of new land and the degradation of vegetation cover on steeper slops have all influenced gully erosion (Tebubu *et al.*, 2013). In the larger Koga Catchment, woody vegetation decreased from 5,576 ha to 3,012 ha between 1950 and 2010 (Yeshaneh *et al.*, 2013). Deforestation was most severe in the 70s and 80s of last century, but since then woody vegetation has been on the rise. Settled land has risen drastically, whereas land for agriculture and pasture has not increased since the 1950s. All bare land had been converted to a land use by 2010. These land use changes were driven by population pressure and land use policies (Yeshaneh *et al.*, 2013). Currently, the main land use is rain-fed smallholder agriculture in a mixed farming system, dotted with indigenous tree species (Tebebu *et al.*, 2010). In the study area, the main crop is the food crop teff (*Eragrostis tef*), a lovegrass species that yields small grains (NRC, 1996). Land close to the wetland is used as grazing land. A study by Desta *et al.* (2000: pp. 58-59) note that the area located between the cities of Dejen and Bahir Dar has a high agricultural potential and good market access.

Soil and Water Conservation Measures

To counter gully erosion, soil and water conservation measures have been implemented uphill in the highlands of the Koga watershed (Mengstie, 2009). He refers to the concept of soil and water conservation measures as "any physical measure implemented in the study area to conserve soil and water resources". The same study (pp. 27-34) includes a list of measures in the Koga catchment (Table 2), which includes the study area.

Table 2: Implemented SWC measures in the Koga Watershed, per type and percentage of total land. Source: Mengstie (2013: 27)

	Description of SWC practices in the area	Traditional SWC practices	Newly introduced SWC practices	Koga Watershed	
				Number of plots	Percentage of total land
1.	Application of manure		▲	189	67%
2.	Traditional Cut-off drain	▲		184	65%
3.	Improved cut-off drain		▲	183	65%
4.	Plantation of both improved and traditional different trees	▲	▲	185	66%
5.	Soil/Stone bund terraces	▲	▲	173	61%
6.	Leaving crop residues on the field	▲		212	75%
7.	Contour farming	▲		126	45%
8.	Fallowing	▲		23	8%
9.	Fanya juu terraces		▲	0	0%

Thesis structure

The thesis will continue with the Methodology. It consists of the information necessary to duplicate the results with a separate section for each research question. After, the Results chapter shows the output of the steps in the methodology. The results need to be put in perspective with the literature presented in the Introduction. Together with the limitations of the methodology and their impact on the validity of the results, this will form the Discussion chapter. The Discussion has been organized to work from the modular approach of the results to the broader themes of the research (sub-)questions and includes the limitations of the methodology.

Finally, the conclusion provides an answer to each sub question, leading up to main research question. It includes some recommendations for future research and approaches to selecting SWC measures.

2. Methodology

This section describes the methodology that has been used to gather data for each sub-question. For each sub-question, several objectives need to be met to deliver this data. For ease of reading, these objectives have been added in a table, with their respective methods, the required equipment and the output. Further details and justifications on the choices that were part of establishing the methodology have been described below these tables.

How has the erosion rate in the Minizr sub-catchment changed since 2010?

Objective	Method	Equipment	Output
Characterize gullies	DEM creation / Soil analysis / visual interpretation of soil horizons	Idem as below / soil laboratory	Soil horizons and DSMs for each gully
Determine individual gully dimensions for 2010 - 2014	Terrestrial photogrammetry / analysis of aerial imagery	Iphone 4 / measurement tape / Agisoft Photoscan Pro / ArcScene / Google Earth Pro / Adobe After Effects CC2014	Yearly erosion rates in t/ha/year from 2010 – 2014
Determine historical erosion rates	Literature review	Tebebu *et al.* (2012)	Baseline erosion rate in t/ha/year before 2010

The gullies in the study area have a clearly defined head, which makes the plough depth (0.3m) indicator suitable to select the gully initiation point. Traditional gully surveying entails measuring the areas of several cross sections along a gully to determine volume. Depending on the spacing between cross sections, errors in calculated eroded volume can reach 30% (Casali *et al.*, 2006). There is no bias towards over- or underestimation in this error (Casali *et al.*, 2006), so it cannot be corrected. To limit the error margin, many cross sections would need to be taken. Since most field work was done by one or at most two persons, this would require many man hours in a rather remote field setting.
As an alternative, terrestrial photogrammetry potentially limits field time and increases the accuracy. Here, a consumer-grade camera is used to capture erosion features from several angles. This study used a stock Iphone 4. Photogrammetry software analyses the photos, recognizes common features in multiple photos and stitches these together to create a 3d-model. The 3d-mesh will be analysed in ArcScene to determine total volume of a gully. The advantages in surveying speed and accuracy of photogrammetry on aerial photography for erosion surveys have been recognized for over a decade (Marzolff and Poesen, 2009). Recently, several free or affordable software that offers fully-automated photo stitching capability increases the accessibility of photogrammetry (Opitz *et al.*, 2012). The most commonly used software packages are Eos Systems' PhotoModeler Scanner, AutoDesk's 123D Catch and AgiSoft's PhotoScan. This study has used Agisoft Photoscan, as 123D Catch needs a server connection to analyse the photos, which was deemed impractical in Ethiopia; Photomodeler did not have an option to directly export a 3d model as a DEM. For each gully, between 70 and 180 photos of a gully have been analysed. For both the "School" and "Tentacle" gully, photos were derived from video footage. This was done by exporting a video frame as a still image every 1/3 second using Adobe After Effects CC 2014. The length of the gullies drove this choice, as shooting video footage makes it easier to ensure no angles are missed. Figure 4 shows the activities done to derive gully volumes.

As for the analysis of historical aerial photography, the date of the imagery varied over the years: to assess the gully length for a given year, the first imagery dated after the wet season for that year was used. For 2010, this was April 2011; for 2011, this was March 2012; and for 2012, this was October 2012. Google Earth did not have imagery for the 2013 rainy season available. The length of the gully after the 2013 rainy season was therefore estimated through field observations, in cooperation with farmers, extension workers and a local PhD-student. This was possible because these people remembered the state of the gully at the time, and because the vegetation in these sections had developed more than in the 2014-eroded area.

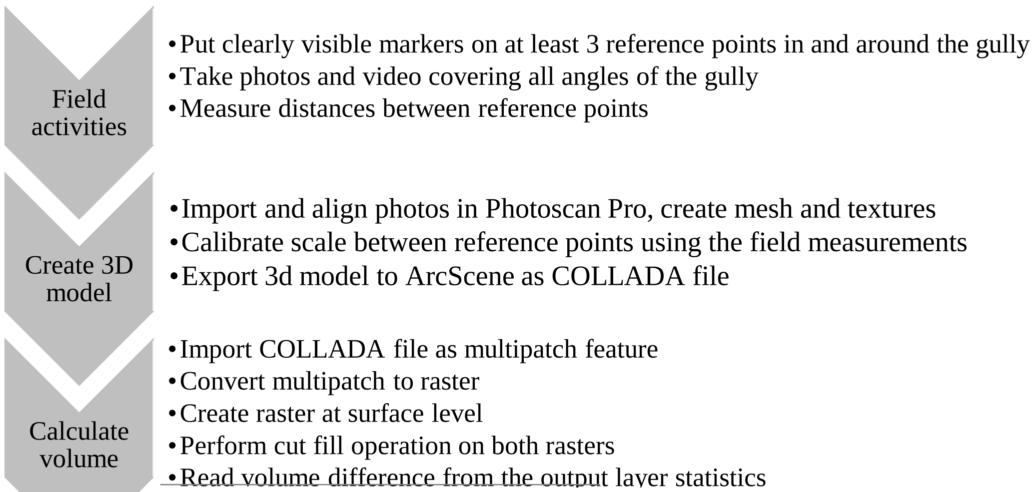


Figure 4: Workflow and activities in calculating gully volumes using terrestrial photogrammetry.

What is the dominant process behind gully formation in the Minizr sub-catchment?

Objective	Method	Equipment	Output
Determine if piping/sapping occurs	Observations at gully banks	Checklist from Field Data form (Hagerty 1991)	Presence of piping/ sapping per gully
Determine pore water pressure in gullies	Literature study + TDR samples + porosity samples	Time-domain Reflectometer (TDR) + pF-curve + soil sample rings	Pore water pressure distribution in gullies
In case of sapping/piping, determine the physical cause	Bulk density measurements through soil layers.	Sample rings, oven, scale	Bulk density distribution over soil layers for gully heads.

To test if high pore water pressure is indeed leading to gully formation, it will be measured by proxy. Since tensiometers are too fragile for prolonged field work, TDR soil moisture values will be compared with the pF-curve for Vertisols to determine the pore water pressure. TDR measurement have been taken at the gully head and then in at three cross-sections, increasingly further away from the head. Figure 5 shows the general sampling scheme.

The timing of the measurement depended mainly on practicalities: the availability of transport and a translator limited the amount of field days to one or two each week. In addition, a long hiatus in October

meant there were no measurements during this period. The sampling values were visualized in ArcMAP 10.2.2, according to the flowchart in Figure 6 (next page)

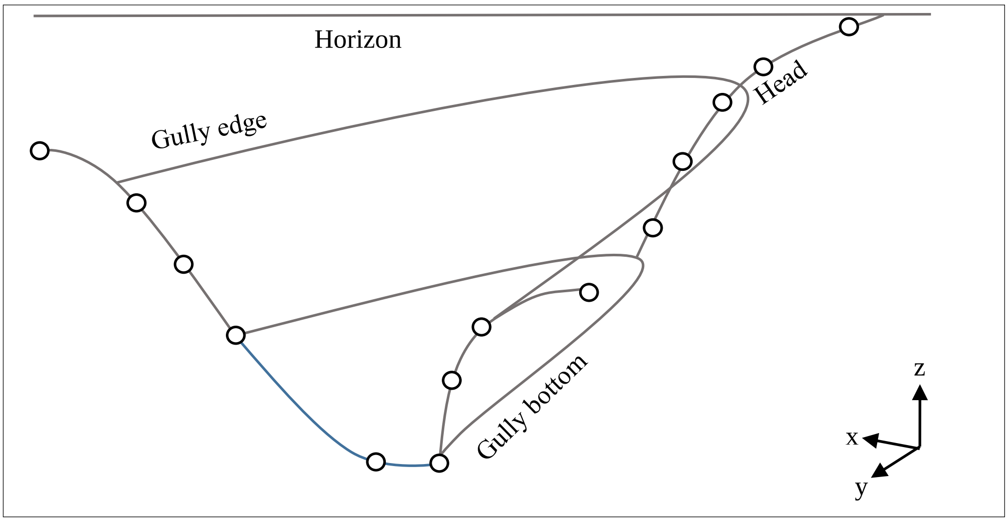


Figure 5: General sampling scheme for soil moisture measurements with a TDR, as a semi-3d visualisation of a gully head. Each circle represents the location in a gully where a TDR reading has been taken. Samples across another 2 cross-sections, further down the x-axis, are not displayed.

In addition, the gullies and immediate surroundings have been checked for signs of subsurface flow in the forms of piping and sapping, according to the checklist in presented in Table 4 (Evidence for piping, in the Appendix). This has been done in September and again in December 2014.

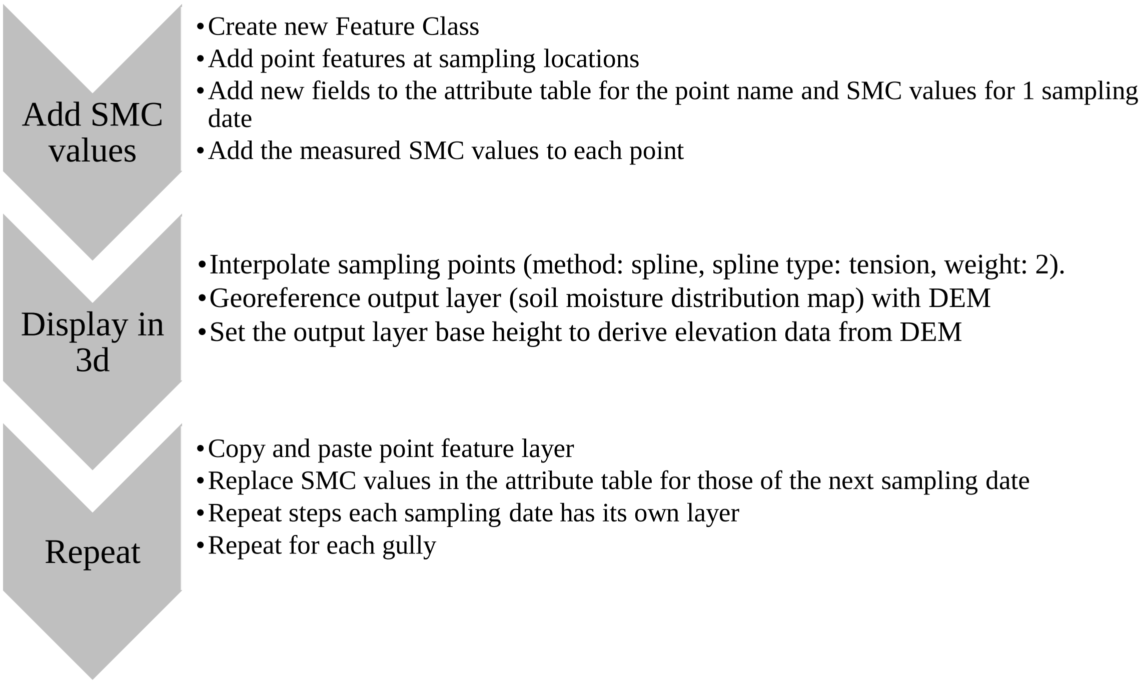


Figure 6: Workflow in creating 3d soil moisture distribution maps from SMC samples.

How has the construction of the Koga reservoir influenced this formation process?

Objective	Method	Equipment	Output
Determine water level change since Koga Reservoir construction	Measure December water level in farmer wells + farmer interviews	Measurement tape, GPS, weight.	Relation between distance from gully system and highest ground water level + change since 2010

Eriksson (2012) mentions that 8 piezometers have been installed by the Koga Irrigation Project team at the construction of the reservoir, to monitor the water level. It is unclear where exactly these piezometers have been installed. Historical data have been requested at the project office. However, the piezometers had never been monitored. First thought of as a back-up, construction design documents by Mott MacDonald (2004), supposedly available in hardcopy at Merawi Koga Project Office, would list the maximum water height in the reservoir, from which water table changes could be estimated. These documents were not available. As a last option, December water table levels have been derived from farmer wells at increasing distances from the gully system, and farmers were asked on changes in the water level since 2010. The implications of these choices for the results will be talked about in the Discussion chapter.

How has changing land use influenced the gully formation process?

Objective	Method	Equipment	Output
Determine land use change	Literature study / Field observations / AP analysis	Yeshaneh (2013) / GPS / AP data (listed in Yeshaneh, 2013)	Land use change from 1950-2010

Historical land use change in the Koga catchment have been derived from Yeshaneh (2013). The historical land use maps in this study were not detailed enough to see the land use for the Minizr sub-catchment in which this study has been done. Therefore, the land use percentages provided in tables (which were for the Koga catchment as a whole) were compared with the land use percentages in the catchments of the gullies. Although these catchments were only a very small subset of the Koga catchment, this method was preferred over doing a land use analysis for the entire Koga catchment in 2014 for two reasons. First, the Yeshaneh study (2013) used automated image analysis on various satellite imagery to classify the land: the software to do so was not available, thus their method could not be replicated. The second reason was the construction of the reservoir, which had led to significant land use changes (cropland to water) that in itself did not impact the gully system. Since there was high-resolution satellite imagery available for 2010 and 2014, it was deemed more relevant to the research question to only evaluate land use change for the catchments of the studied gullies. Similarly, increase in land use intensity, specifically grazing intensity after reservoir construction, could not be measured but will be discussed in the *Finding root causes of erosion* section of the Discussion chapter.

How have SWC measures, implemented uphill, influenced the gully formation process?

Objective	Method	Equipment	Output
Determine the SWC measures that have been implemented in the study area	Digitally map SWC measures in the area.	Aerial photography, ARCgis	Digital map of SWC measures present in the study area.
Determine impact of SWC measures	Literature study	DESIRE Project descriptions of SWC measures.	Qualitative impact of SWC measures on lowland gully erosion

The first step consisted of field observations and discussions with extension workers to select which were present in the area and when they were constructed. Only those that could reasonably be expected to influence the area's hydrology (due to their number or covered area) were then selected for mapping and further analysis. A shapefile containing the digitized contour barriers were available through ongoing PhD-research in the Koga catchment by M. Getahun. These were imported into ArcScene and georeferenced using the Koga catchment DEM. Total length was determined through the layer statistics function. The DESIRE for a Greener Land project descriptions guide provided the classification and potential effects of the SWC measures. Detailed (potential) effects of measures were from more diverse sources and have been referenced in the Results and Discussion chapter where applicable.

3. Results

This section describes the results obtained through the methodology as listed in the previous chapter. For ease of reading, the results have presented grouped in the same order as the methodology chapter: first, the soil analysis, followed by DSMs and soil profiles of the gullies, and finally the baseline erosion rate in t/ha/year in the 2010-2014 period compared to pre-2010 rates. Illustrations showing soil horizons use the six master soil horizons (O, A, E, B, C, and R) and have been explained in relevant captions.

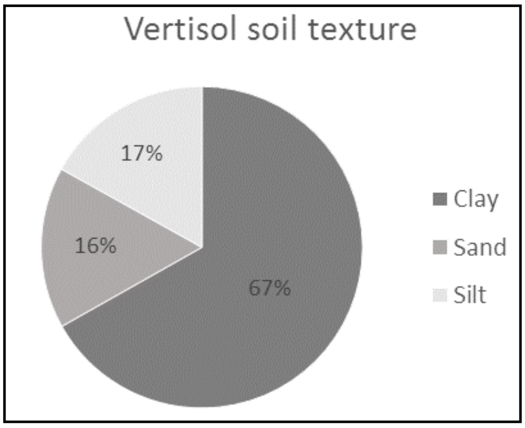


Figure 7: Mean volumetric content for clay, sand and silt for Vertisols in the study area.

Soil analysis

At three sites spread through the study area, samples were taken at 15 cm depth. The Bahir Dar Regional Soil Laboratory analysed these samples. Since there were some doubts on the proper identification of other samples in the set (not used for this study), all samples were analysed twice. This means that the 95% confidence interval for the values could be derived. All data was provided by the laboratory in the form of a measurement report. As Figure 7 shows, clay is the main texture class taking up 67% (±6pp) of the volume, with sand and silt at 16% (±5pp) and 17% (±5pp), respectively.

“Waterfall” gully

The “Waterfall” gully (Figure 8) is a medium size gully with clear subsurface flow streaming out of several pipes near the gully head, including an active pipe of 3 cm diameter, meriting the name “waterfall”. The gully exits in a bend of a large gully system with extensive slumping. There is some vegetation around the walls near the gully exit, and a 2 m x 1 m patch of Wanza tree (*cordia Africana*) saplings can be found in the gully itself. The remainder of the gully edge and surrounding land is fully covered grassland.

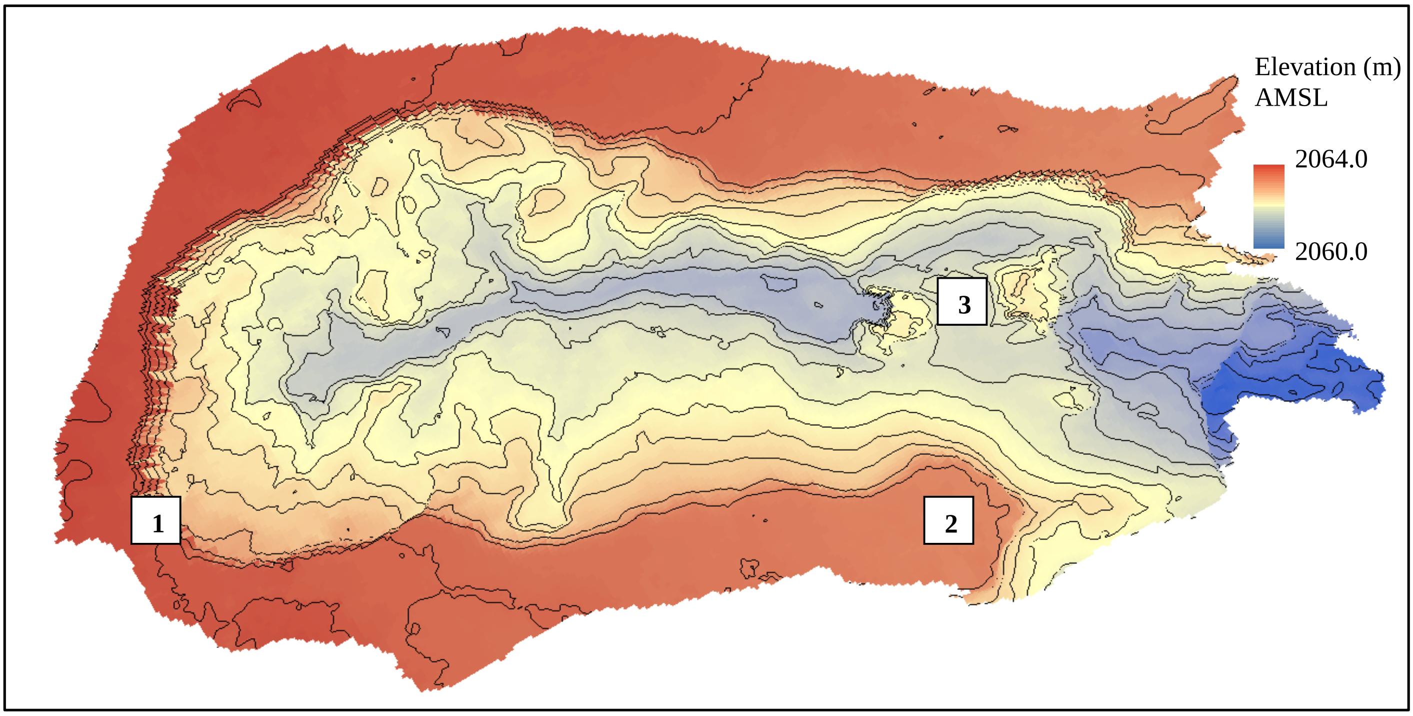


Figure 8: Top view for "Waterfall" gully with contour lines projected on a DSM derived through photogrammetry in September 2014. Pipes are present in the gully head (1), with trees on the banks near the exit (2) and bushes up to 1 m in height at (3).

Figure 9 shows a triple display of the gully head. It represents the soil profile at location (1) in Figure 8. In characterizing a gully head, structures such as overhang, ridges or protruding parts are important. However, these are not always visible in photos. The images in Figure 9 have been derived from a 3d composite of 24 photos, allowing for view angles that could not have been photographed because of the confined space. The gully head has steep, practically perpendicular walls with a 10 cm overhang at surface level. The transition towards the gully bottom is visible in the bottom. The topsoil if followed by a bleached layer, from which minerals have been deposited in a thick subsoil. It lies upon a layer of heavy grey clay, which upon first look seemed like stone. A multitude of exfiltration holes ranging from 1 mm to 3 cm are present in the lower 30 cm of the B-layer. This same zone was saturated with water, flowing over the exposed clay towards the gully exit.

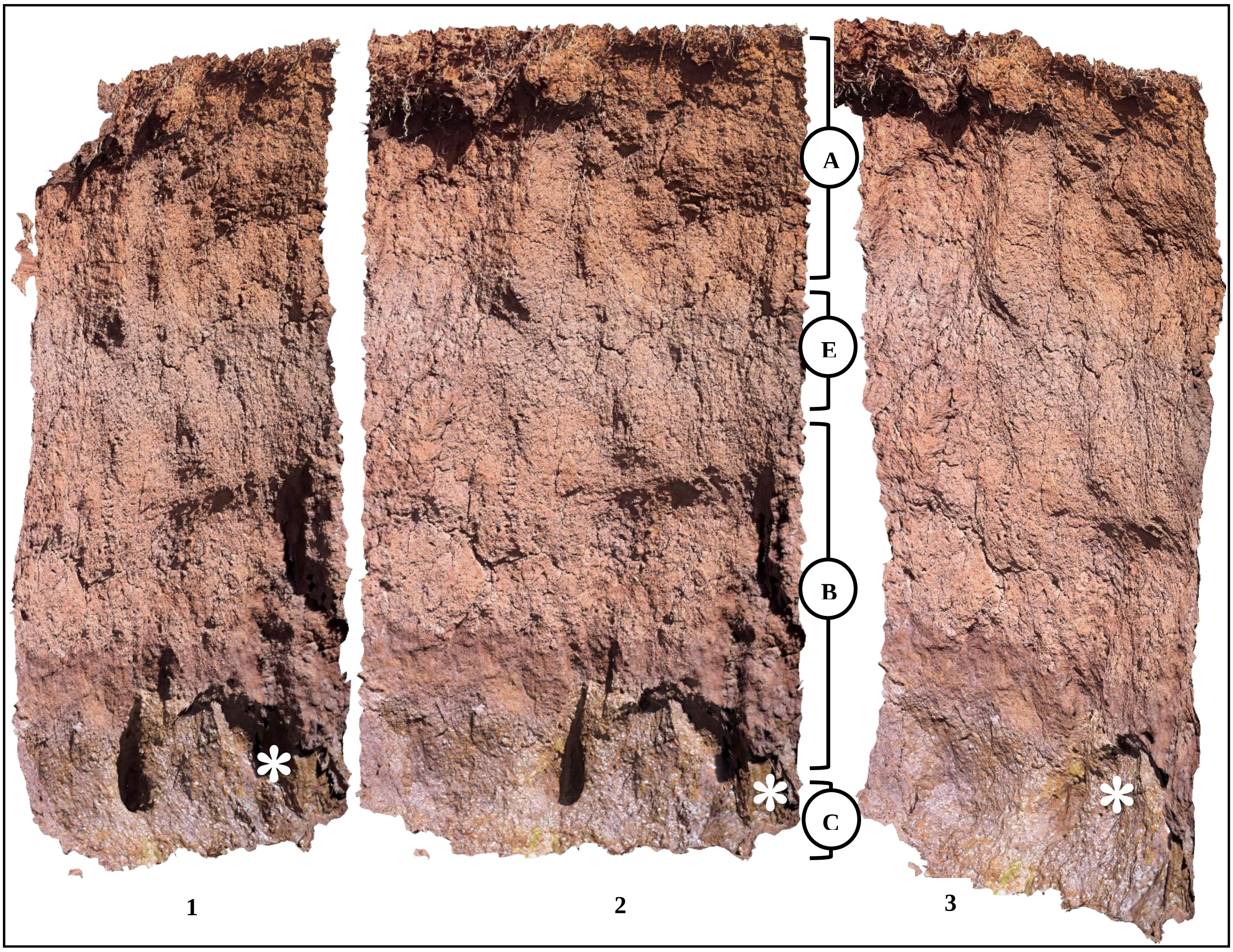


Figure 9: Soil texture for the gully head in the "Waterfall" gully. All three parts display the same section of the gully head, first seen from left (1), in a front view (2), and from right (3). The main pipe has been indicated in the three parts with an asterisk. The soil horizons have been indicated: A) mineral topsoil, E) eluviated soil, B) Subsoil, C) parent material. Water table below visible profile, saturated soil visible up to halfway the B horizon.

"School" gully

School-gully (Figure 10 and 11, next page) is a small-to-medium-sized gully in front of a primary school building. It starts 20 m downstream of a stabilized older gully. Between the two gullies there is a heavily vegetated depression that serves as a flowpath. It is littered with plastic and pieces of wood, deposited by school kids or employees. In the inactive downstream gully section, shrubs cover most of the banks that are not vertical. Extension workers reported this gully had grown "extremely fast". In its course, the gully bends to the South-East and connects to the main gully (the largest gully in the study area, to which most other gullies connect and that runs towards the wetland in a South-Western direction).

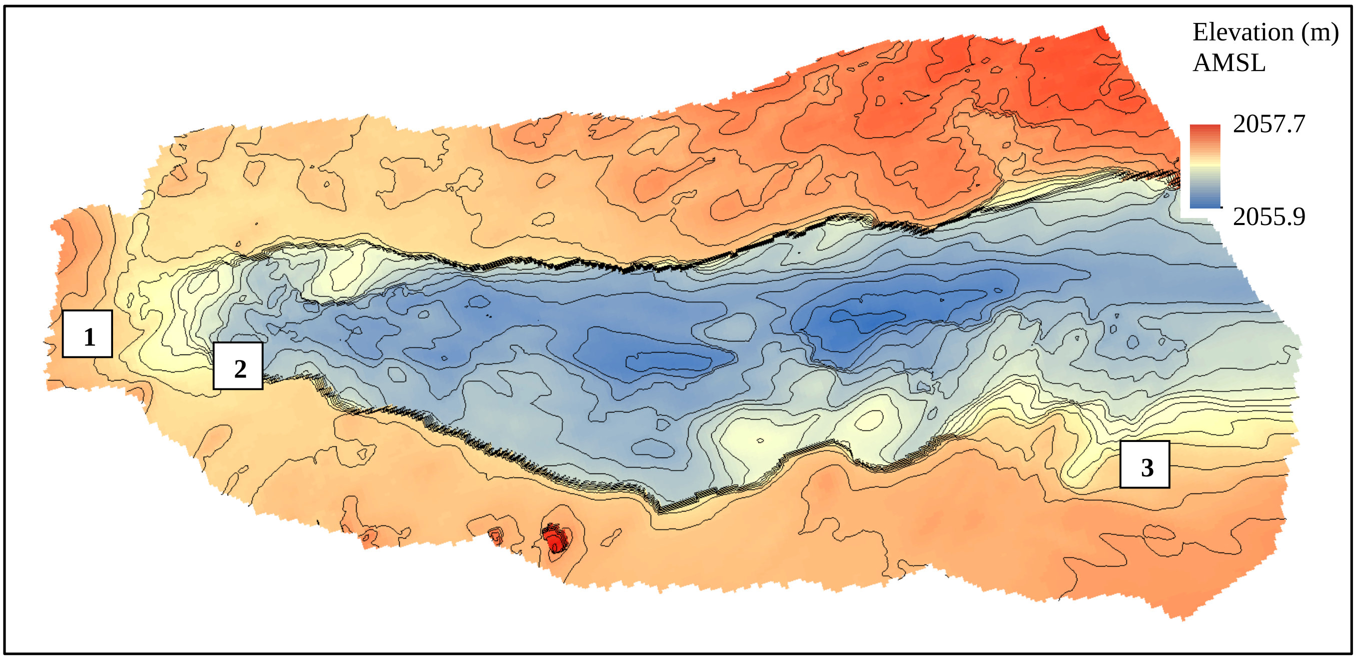


Figure 10: Top view for "School" gully with contour lines projected on a DSM derived through photogrammetry in September 2014. The gully is connected via a depression (1) to an upstream stabilized gully, the overhang at the gully head at (2) is not visible in the DSM. Away from the gully head, the side bank become less steep (3).

The soil profile composite on was located at the (2) mark in Figure 10. Two soil horizons show over the 1.6 m depth of the soil profile. Surface cover, also including the overhanging gully edges, at the time consisted yellow, short grass. First, the topsoil, which consist of 0.8 m of red soil, with an abundance of grass roots up to 0.7 m depth, as well as visible worm holes. The subsoil consists of 0.8 m of greyish clay with no traces of animal activity. The majority of cracks appeared in this layer. (see also Figure 11). The gully bottom was covered mostly with the remains of collapsed bank sections, mixed with large branches, natural and man-made debris.

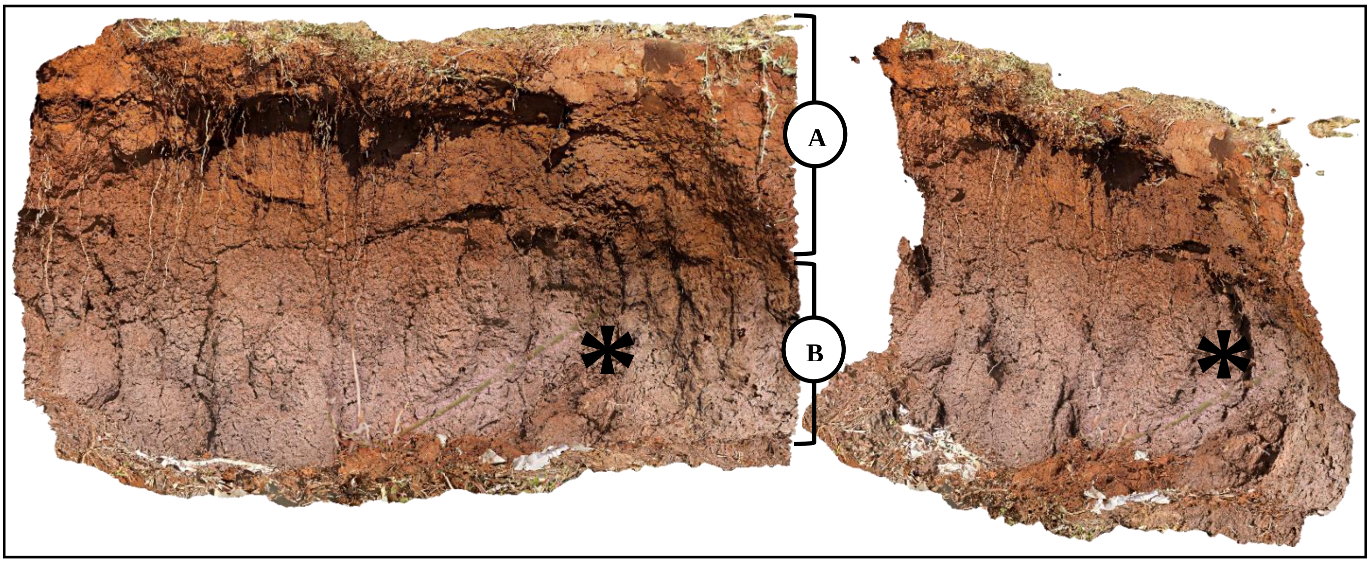


Figure 11: composite of the soil column in "School" gully, from photographs taken in December 2014. Views are from the front (left) and right (right when standing in the gully center ((2) in Figure 10). Note the major crack, visible on both angles and the rubbish on the gully bottom (asterisk). The soil horizons have been indicated: A) mineral topsoil, B) Subsoil. Ground water level below gully bottom.

"Tentacle" gully

The "Tentacle" gully differs from the other two gullies because of its complexity. Rather than one, it has 4 separate gully heads. The heads are elevated above the gully trunk, but quickly drop down to its level. The main gully head (in Figure 12, see caption note (1)) has a depression above the head that functions as a preferential flow path. There is no vegetation in this gully. The gully bends South-East and connects to the study-area's main gully.

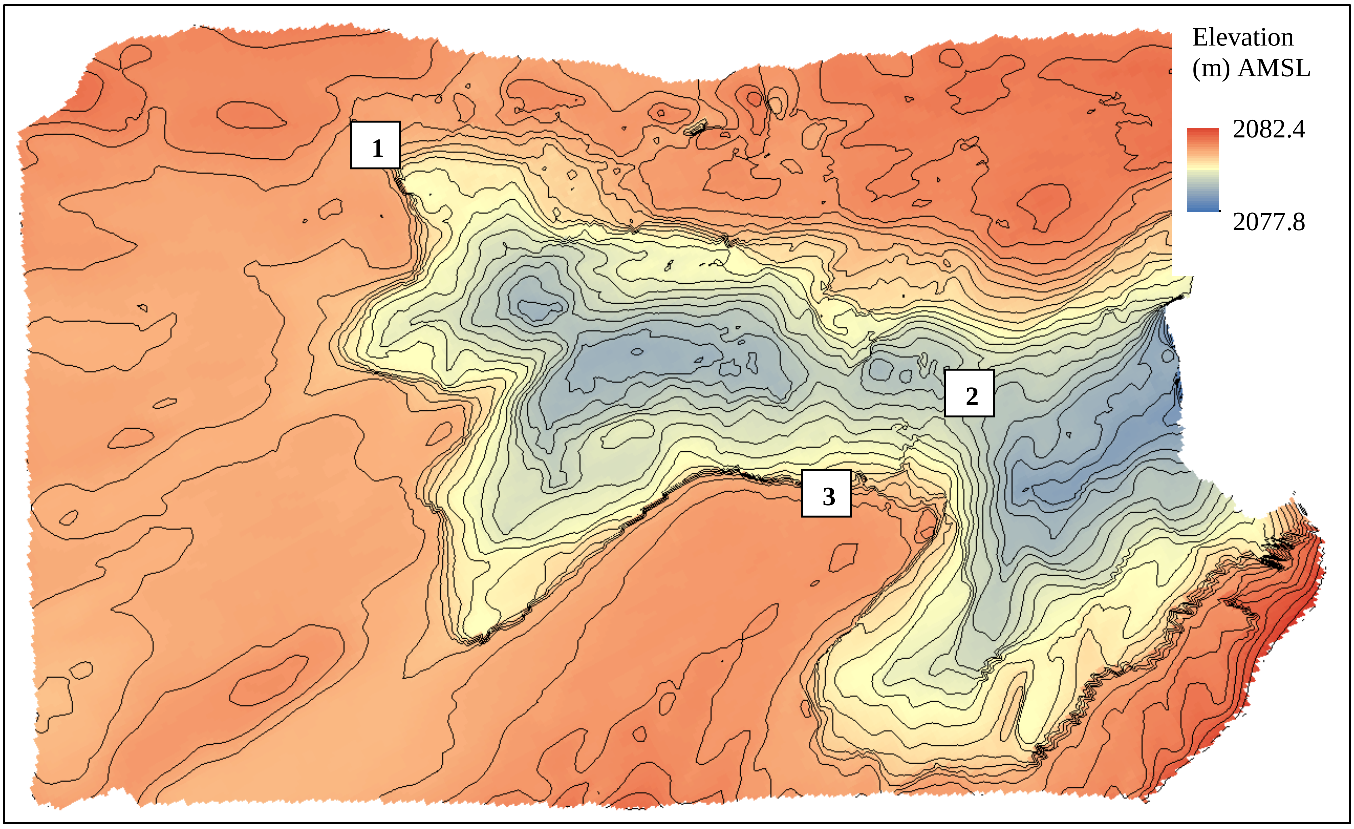


Figure 12: Top view for "Tentacle" gully with contour lines projected on a DSM derived through photogrammetry in September 2014. The most active gullyhead.has been indicated by (1). The main trunk of the gully continues downstream from (2). Side slopes on the main trunk were covered with very sticky black clay.

Its soil profile was taken at the sidewall of the main gully trunk (indicated with (3) in Figure 12), since the gully heads were too shallow, around 30 cm, and had too much overhang to photograph the wall properly without extensive digging. As opposed to the other soil profiles, this gully did not have a representative straight wall to show a proper soil profile. The side slope was covered with porous material, very sticky black clay. When digging, there was an extremely compact layer with a high percentage of stone fragments at a depth of approximately 10 cm from the gully floor. Based on these characteristics and known presence in the region, this would be the impermeable saprolite layer of weathered bedrock as also found by Tebebu (2009: pp. 6-7) in a close, geologically similar area.

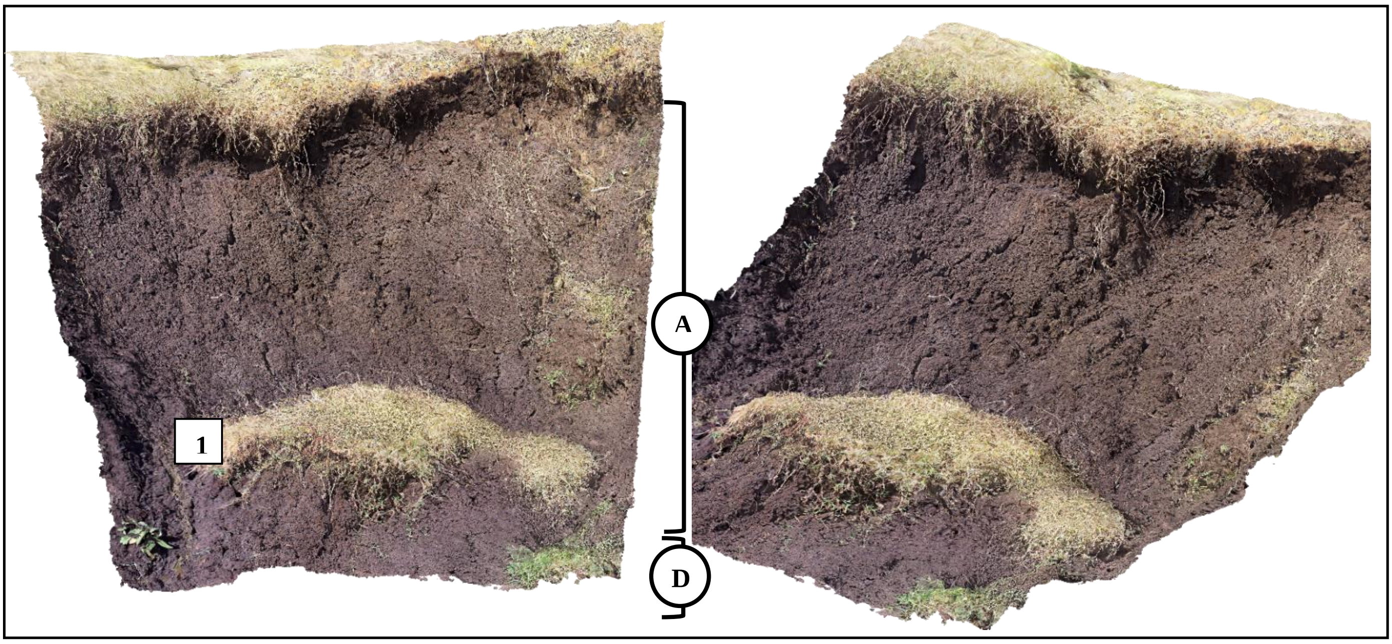


Figure 13: Gully wall for "Tentacle" gully, composite showing the front view (left) and view front the right (right) viewing from the gully centre. Sticky clay forms the side slopes, with extensive slumping (1) along the gully slopes. The soil horizons have been indicated: A) mineral topsoil, D) consolidated layer, referring to the impenetrable layer in the gully bottom. Groundwater level below surface, not visible.

Gully volume and erosion rates over time

The next step was to determine gully volume growth. Figure 14 shows the gully volumes over time. The aerial imagery of the gully system proved suitably detailed to measure the gully lengths for subsequent years. To measure the volume (cm^3 precision) of the open-ended geo-referenced 3d-models resulting from the photogrammetry, they had to be bound by a plane closing the end of the gully zone eroded in 2014, and a plane as close to the surrounding ground surface. The output of the cut-and-fill volume operation in ArcGIS was in cubic centimetres. Accumulating the results from both methods yielded the total gully volume over time

The volume has grown for all three gullies. The “Waterfall” gully showed the biggest jump in eroded volume, in the 2014 rainy season.

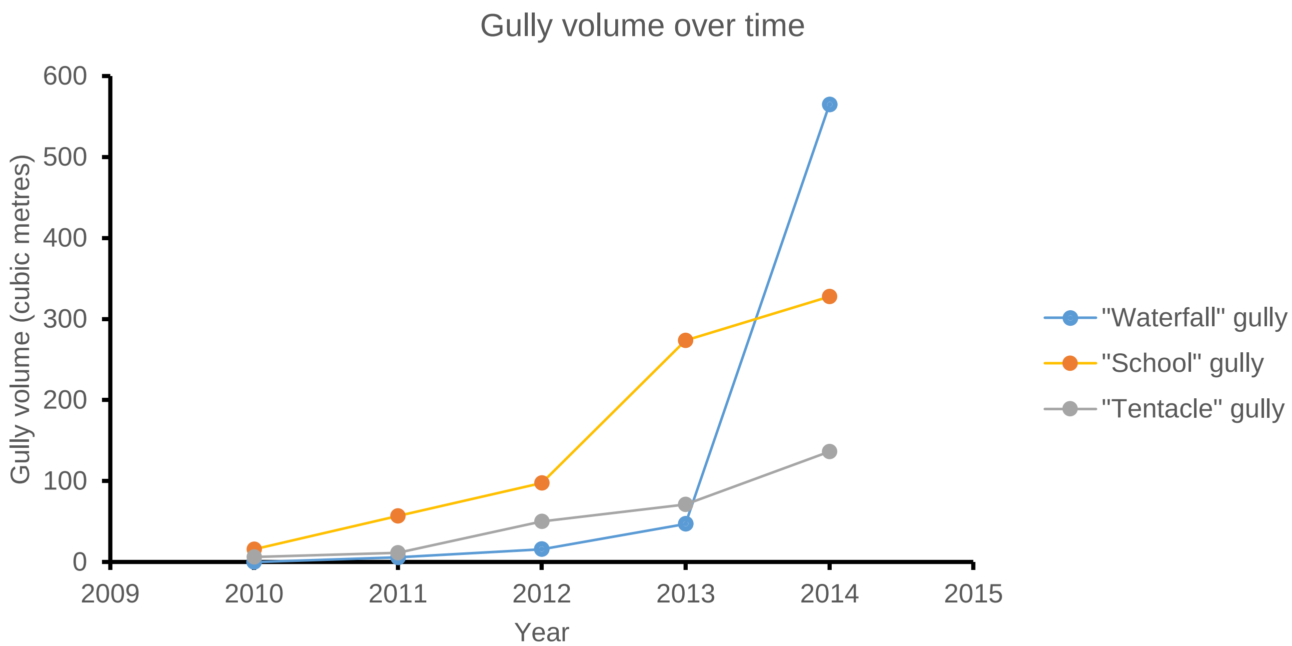


Figure 14: The Cumulative volumes for three researched gullies, from 2010 to 2014. The volumes have been derived from length measurements on aerial photographs (2010-2013) and through terrestrial photogrammetry (2014).

To see if there is a difference between the erosion *rate* before and after 2010, one must compare the erosion rate in tonnes per hectare per year. For the 2010-2014 period these rates have been calculated from the gully volumes in Figure 14. The ArcGIS procedure to delineate watersheds contributing to the researched gullies delivered satisfactory results for "Tentacle" gully (2.45 ha), but unsatisfactory results for "Waterfall" and "School" gully (both <1 ha). The resulting watersheds of the latter two were shown as a single diagonal line instead of an area. For these, the watersheds were determined manually, using the contour lines from the 3m-resolution DEM. The resulting sizes were 3.44 ha for "Waterfall" gully and 4.58 ha for "School" gully. Dividing the gully volumes by these areas and multiplying by the average bulk density for each respective gully resulted in the erosion rates for 2010-2014 (Figure 15). Figure 16 shows the average erosion rates for the three gullies.

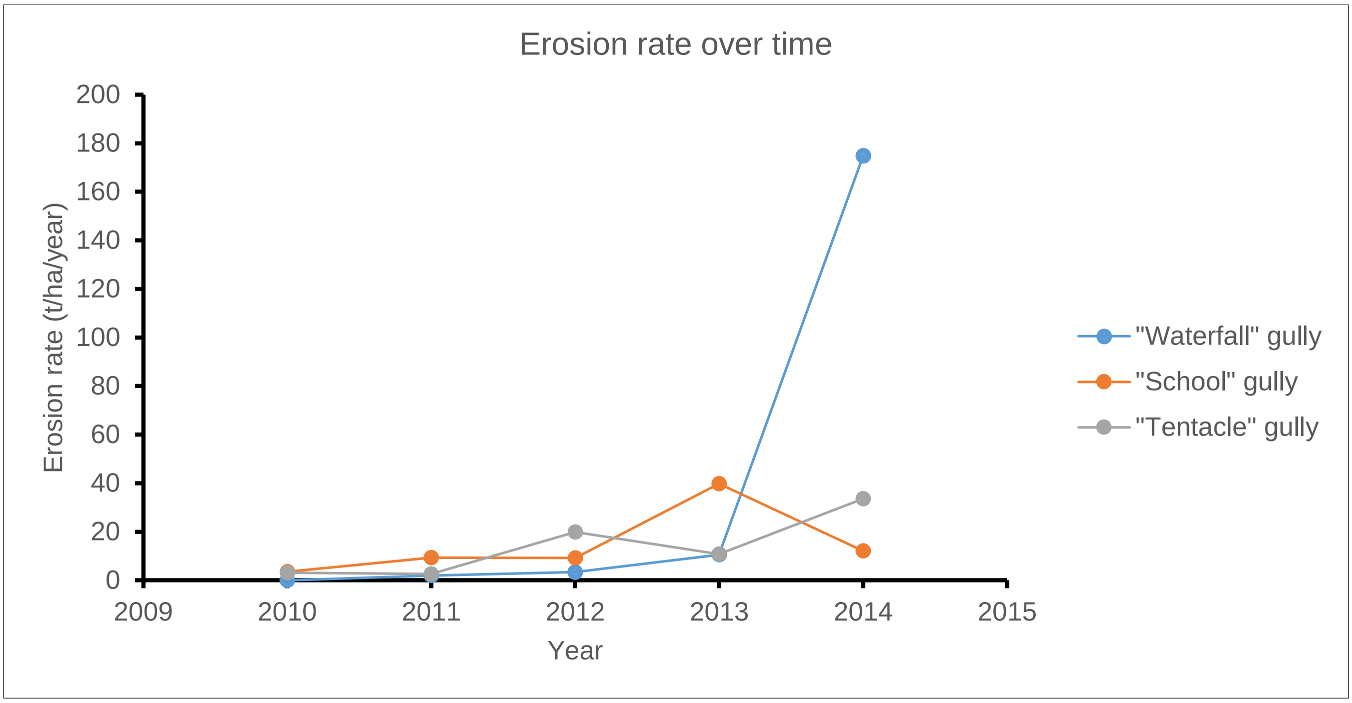


Figure 15: Erosion rates in tonnes per hectare per year for the period 2010-2014, per gully.

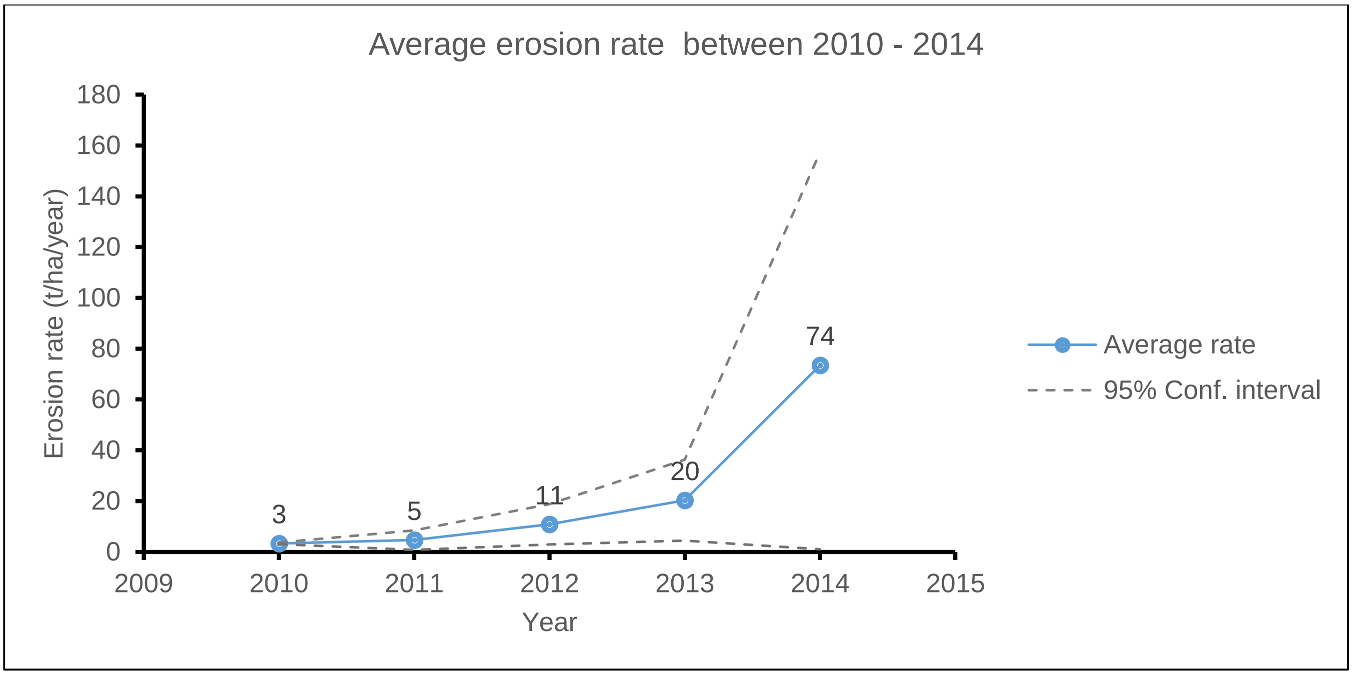


Figure 16: Average erosion rate for all three researched gullies over 2010 - 2014. The 95% confidence interval for the mean has been added.

Pore water pressure distribution

The Bahir Dar Regional Soil Laboratory (BDRSL) analysed the soil samples for soil moisture content six days after sampling. Figure 17 shows the differences between the soil moisture contents resulting from this analysis and those from the TDR. In 3 out of 4 cases, the TDR provided significantly ($p < 0.05$) higher values for the soil moisture content than the laboratory-analysed soil samples. The soil laboratory did not provide error margins for their results.

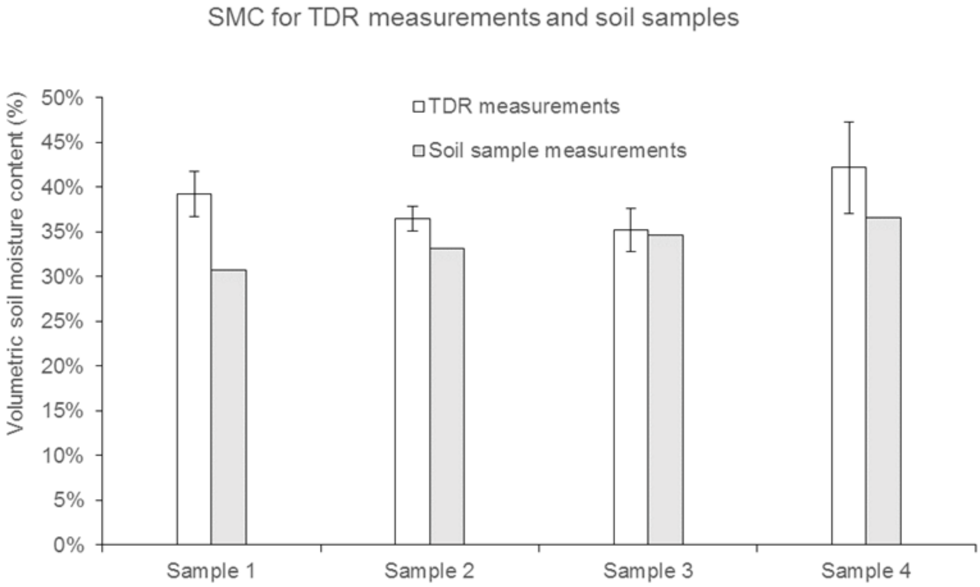


Figure 17: Comparison of soil moisture content values derived from TDR measurements and those determined after oven-drying soil samples. The error bar for the TDR measurements is the 95% confidence interval for the mean.

Interpolating the SMC samples from the TDR resulted in a distribution map of soil moisture in the 0-10 cm depth for each sampling date. The data has been classified, with each class representing 5% soil moisture. These values are taken directly from the TDR. In general, active infiltration took place at TDR readings above 45%, denoted by the two highest classes in the distribution maps below. The maps have been presented in isometric view, with the axes in each bottom right corner for orientation. The depicted gullies have the same size as those outlined in their respective sections earlier in this chapter, refer to their respective DEMs for scale.

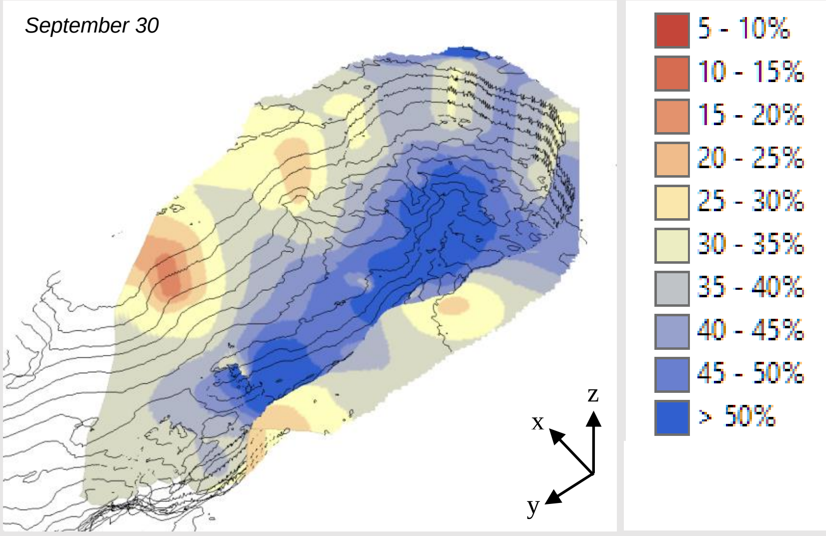


Figure 18: Soil moisture content map for "Waterfall" gully, interpolated from September 30 data samples.

The straight banks of the gully clearly show the drying pattern after the end of the rainy season. At the end of September, water is flowing from the exfiltration faces in the lowest 1m zone in the gully. There are dry spots, mainly along the edge of the gully, where there is some overhang. The measurements outside the gully edge, however, are above 20% SMC indicating that the soil outside the gully is wet. On the head-end of the gully, there is no overland flow visible. The gully head is at some places saturated for up to 2 meters from the gully bottom, where several pipes release their water.

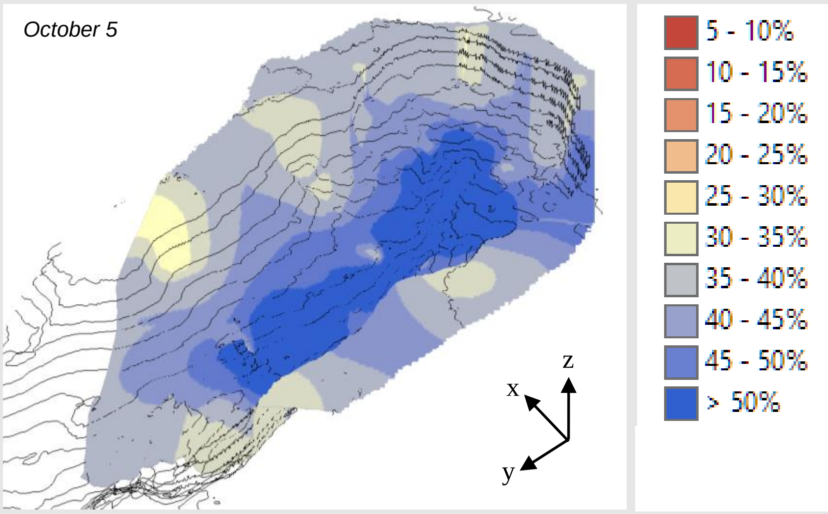


Figure 19: Soil moisture content map for "Waterfall" gully, interpolated from October 5 data samples.

After nightly rainfall, water has accumulated in the preferential flowpath (a ~5 cm depression at the head of the gully). Now, there are no more dry spots and the gully area is at its wettest. Several slight depressions have started ponding around the gully. Flow in the gully is still high, with exfiltration visible in the entire 1m band. The porous layers towards the exit of the gully are very unstable and have started to slump in two places. Where these slumps have taken place, water is flowing out in a stream.

The bottom of the gully is still an active stream, with water depth above the clay layer up to 8 cm.

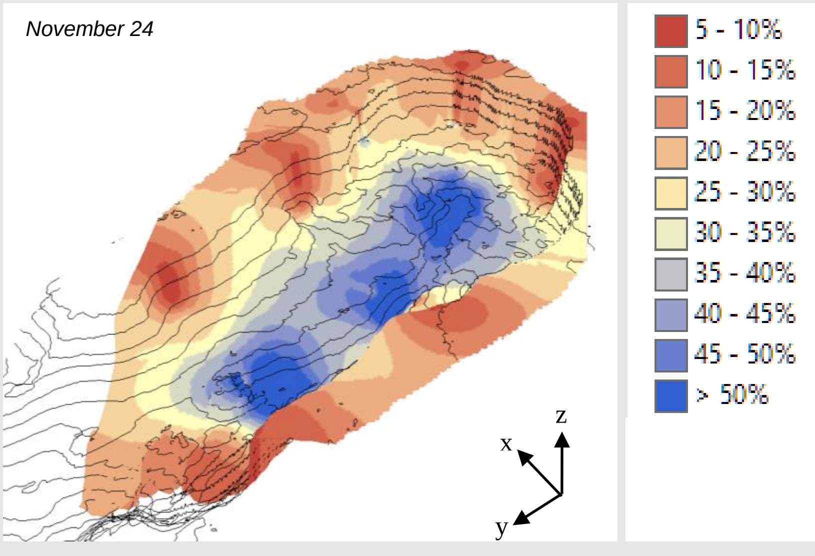


Figure 20: Soil moisture content map for "Waterfall" gully, interpolated from November 24 data samples.

The rains have stopped, as has the overland flow. There are no more signs of ponding around the gully, but the exfiltration from the soil pipes and the porous layers has continued: there is still water flowing in the gully.

Cracks have appeared in the gully walls, and at several places blocks of soil are overhanging because of this. With SMC values dropping below 10% above 1 m from the gully bottom, there is a clear distinction between the wet and dry zones in the gully.

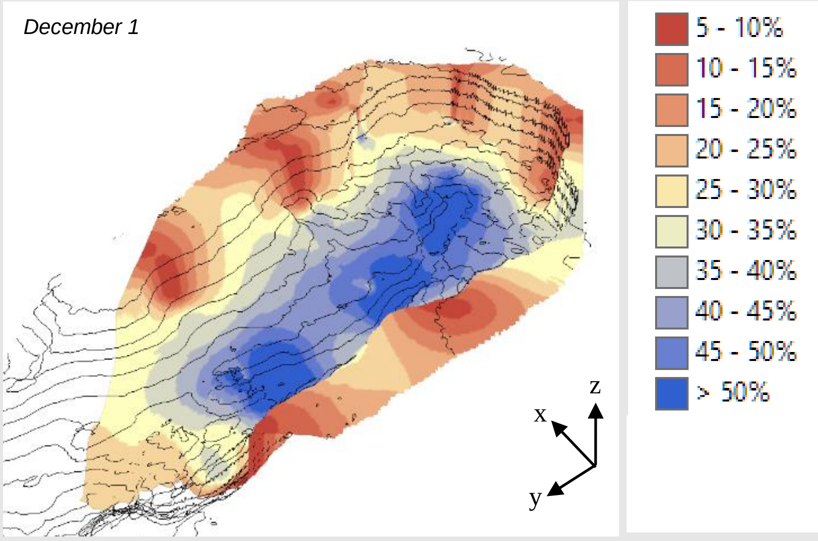
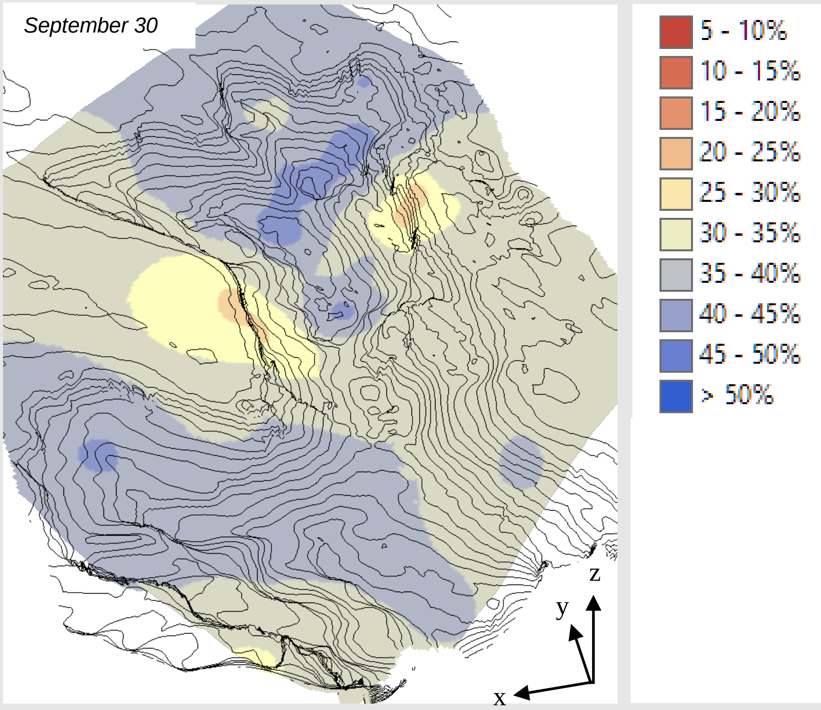


Figure 21: Soil moisture content map for "Waterfall" gully, interpolated from December 1 data samples.

The exfiltration zone has shrunk to 0.8 m from the gully bottom, but the main pipes are still active. In the porous zones, water does not reach the surface anymore but trickles down until the gully bottom and exfiltrates above the clay.

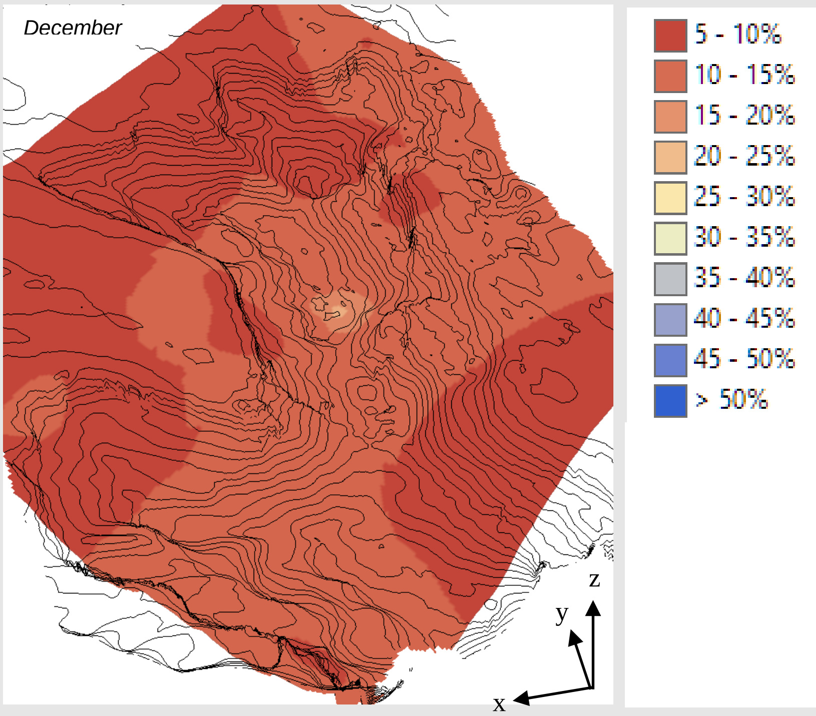
The gully head has retreated another 0.5 m because cracked portions of the wall have collapsed and are now lying on the gully bottom. The vegetation, although sparse) is still green. There are no significant changes from December 1 until December 15 (the last date of sampling).

“Tentacle” gully



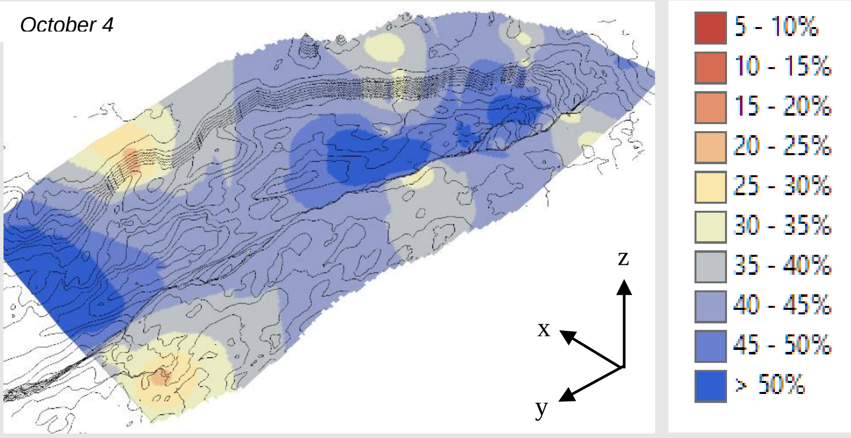
Nearing the end of the rainy season, there is some ponding at the gully bottoms but no running water. Diffuse exfiltration occurs at the overhanging gully heads, but are barely visible in the interpolated map shown left. Overall, there is no strong soil moisture pattern visible, although the wettest spots are close the gully bottom. The porous slopes in the main trunk were extremely sticky.

The gully head at the top right had a slight depression leading up to it, where overland flow could be observed on days after rainfall (<1 litre/minute).



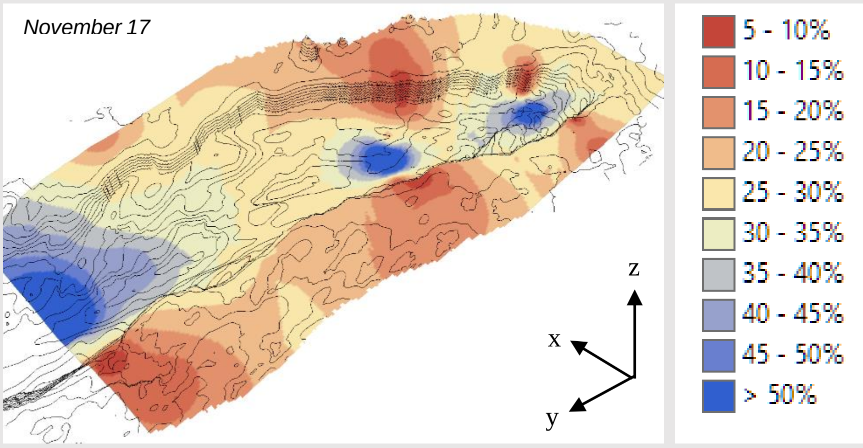
Through October and November, the gully dried quite uniformly. This shows in the final situation, where SMC was under 15% throughout the gully. Ponding stopped halfway through October. Few cracks appeared, confined to the gully head-end.

“School” gully

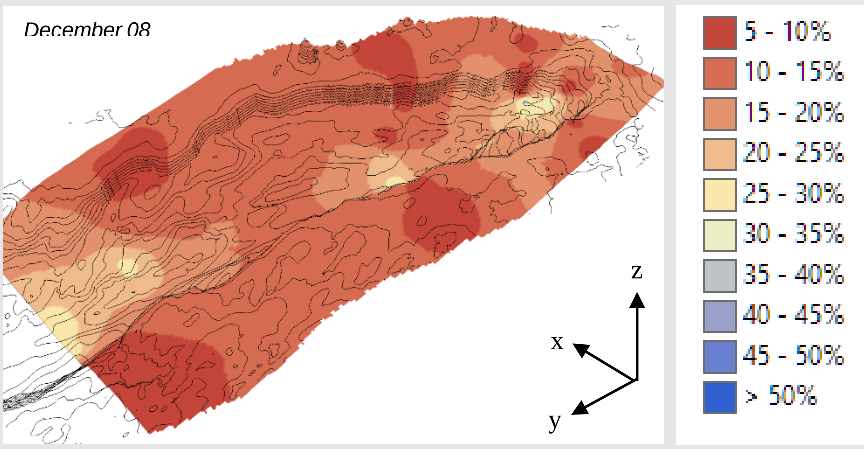


October 4 yielded the wettest measurements. A trickle was flowing in from an upstream, stabilized gully. It accumulated with water flowing from the exfiltration zone (concentrated within 3 m from the gully head). The extensive vegetation on the porous layers >10 m from the gully head was at its highest, and diffuse exfiltration could be seen throughout the gully.

The driest areas were those on the gully banks. There was ponding around the gully, but all upstream of the gully head.



Over time, the edges of the gully dried fastest. By November, all water on the bottom of the gully (which still had standing water) was provided by subsurface flow, now only present in the gully head proper. School children had littered and treaded on the porous side slopes of the gully by this time, compacting it.



December 8 was the last measurement with yielded a value over 35% moisture, whereas the rest of the gully had dried by this time. The wet spot (barely visible on the image) was taken at the bottom of the gully head.

Sections of the gully walls had collapsed into the gully, mostly on the school-side (above in image). A final measurement was done at December 15, where the wet spot had dried as well. It showed no different pattern than the December 8 situation pictured here.

Figure 22 presents the total amount of soil moisture and its trend throughout time, to give a better overview of the SMC distribution maps presented above. Absolute values were different for each gully due to size, so all values were compared to the values for the first sampling date for that gully, which was assigned a reference value of 100. The overall trend is similar for all gullies: first, the values increase for all gullies, before falling when the dry season progresses. The soil moisture peak trails the last rain day. Time off and lack of transport to the study area caused the 30-day data gap.

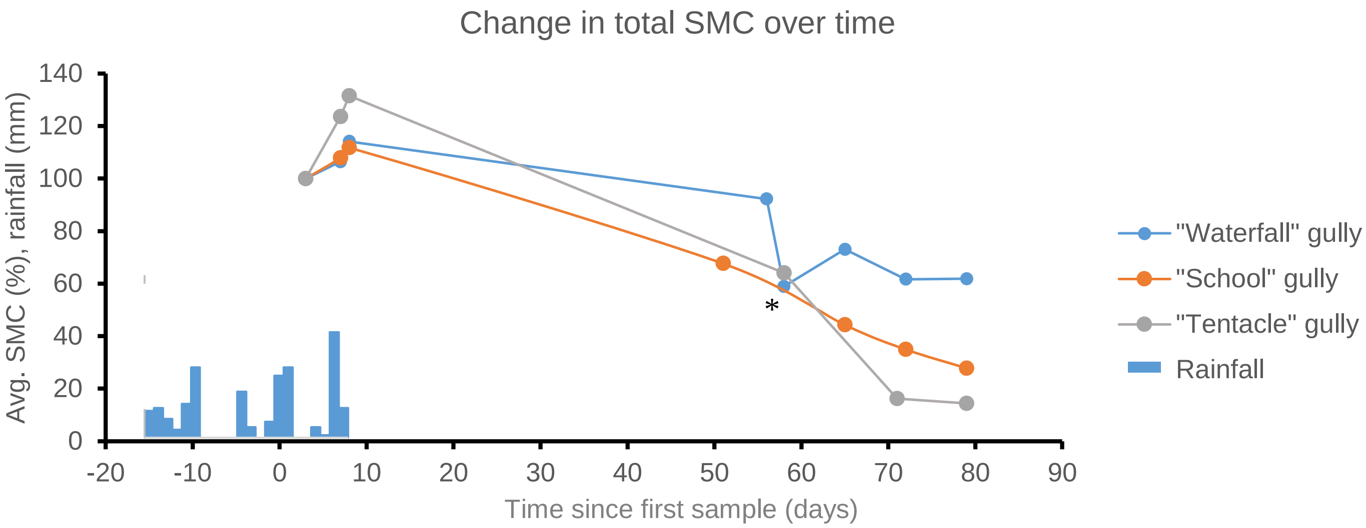


Figure 22: Change in total soil moisture content during the study period, per gully, and rainfall. The values at the first sampling date for each gully serve as reference point (100%). The asterisk indicates a sample date for "Waterfall" gully that has some missing values. Day 0 is the first sampling date, September 27, 2014.

As for the trends in the individual gullies, the "Waterfall" gully has the most stable SMC totals. Together with "School" gully, its moisture peak is not as pronounced as "Tentacle" gully's. In addition, its decline is the slowest of the three gullies. Missing data for a set of sampling points has caused the outlier at day 58: the values for the completed points at that day do fit in the overall downwards trend. The "Tentacle" gully has shown the most pronounced trend: it first shows the highest total SMC value, before its decline. The decline is the fastest out of the three gullies and drops to the lowest level. The "School" gully has a very linear downwards trend, more so than the other two gullies.
The rainfall in the two weeks before, and week after the first sampling date totalled 201 mm. After 4 October, no significant rainfall had been registered in the area, signalling the end of the 2014 rainy season.

Presence and cause of piping and seepage

Since the soil moisture can arrive from both surface runoff and subsurface flow, a checklist was completed to check for signs of subsurface flows. Table 1 (next page) presents the results for all gullies and for both survey data in the beginning of September and halfway through December, correlating with the end of the rainy season and 10 weeks into the dry season. The results from both surveys are almost identical, with only one case (indicated by an asterisk) where less evidence could be found 10 weeks from the end of the rainy season. Not only were the numbers of evidence identical, so was the specific evidence. This means the evidence found on September 7 was in all cases bar one the same as on December 15. The detailed checklists have been added to the Annex (Evidence for Piping) and contain descriptions of the evidence types, as well as remarks and photographs, where relevant. In both cases the survey could be completed as outlined in the methodology.

Table 1: Number of signs of subsurface flow observed as part of all signs as listed by Hagerty (1991), for each gully at two sampling dates. A decrease between two sampling dates has been marked by an asterisk.

Gully name	Evidence type	Evidence present Sep 7	Evidence present Dec 15
“Waterfall” gully	Primary direct	1/2	1/2
	Primary indirect	2/2	2/2
	Secondary indirect	1/2	1/2
	Tertiary indirect	2/4	2/4
“School” gully	Primary direct	1/2	1/2
	Primary indirect	2/4	2/4
	Secondary indirect	1/2	1/2
	Tertiary indirect	2/4	1/4*
“Tentacle” gully	Primary direct	1/2	1/2
	Primary indirect	2/2	2/2
	Secondary indirect	0/2	0/2
	Tertiary indirect	1/4	1/4

Sampling in the three gullies was done at the end of November, when the upper layers of the soil were already dry. The resulting cracks and dried clay made inserting sample rings difficult. Since the clay layers below the phreatic zone were still wet in the “Waterfall” and “Tentacle” gully, sampling was easier for those. Since the clay layer lay exposed, the samples were taken on from the surface. In “Tentacle” gully, however, loose material from the side slopes had covered the impermeable layer, which had also already dried up by the sampling date. The digging involved, combined with the very compacted, stone-fragmented layer meant that the sample ring could not be extracted without losing some material.

Employees of the Regional Soil Laboratory were responsible for determining the bulk density. The laboratory did not analyse the samples before 7 days from the sampling date, due to time constraints on their side. In the mean-time, the samples were stored in the open air, although they were capped. Results were presented on a measurement report, which have been presented in Figure 23. The laboratory did not provide error margins for their measurements.

In two out of three gullies, the layer below the water-carrying (phreatic) layer had a higher density, at 9.3% and 13.6% for the “Waterfall” and “School” gullies, respectively. The “Tentacle” gully reversed this pattern and has a slight decrease in bulk density, at 3.6%. It also has the highest absolute bulk density values.

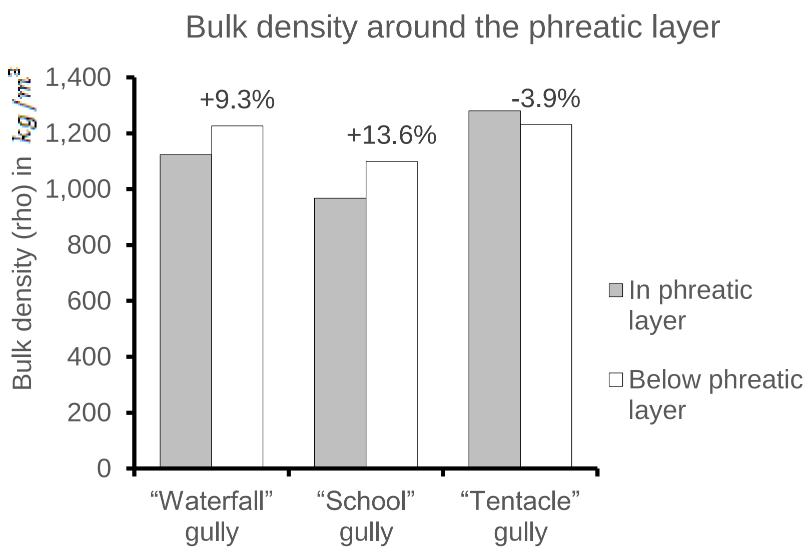


Figure 23: Comparison of the soil bulk density in and below the water-carrying layer, for all three gullies. The percentage difference from samples inside, to below the phreatic layer has been indicated.

Presence and impact of SWC measures

Both *fanja yuu* and stone bunds have been implemented extensively in the area's watershed. They have been digitally mapped and projected on a 3m DEM (derived from 30m DEM) in Figure 24. In total, 160 km of barriers have been constructed, the majority since 2010. In general, observations showed that the most all agricultural (cropping) fields have a form of contour barrier implemented. The barriers are restricted to sloped cultured lands and have been built along the contour lines. Most stone and soil bunds have some form of planting: either grass or shrubs. Observations on the bunds in the area surrounding the gully system showed the remarkable width of the bunds. The majority of observed bunds were 0.5 to 1 m wider than had been advised, according to a local extension worker, despite small plot sizes. The area of the main gully system (marked orange in Figure 24) coincides with uncultured grassland used as pasture until it was closed for grazing in 2013. Observations showed an insignificant number of infiltration pits dug mainly in the greater study area's South-East.

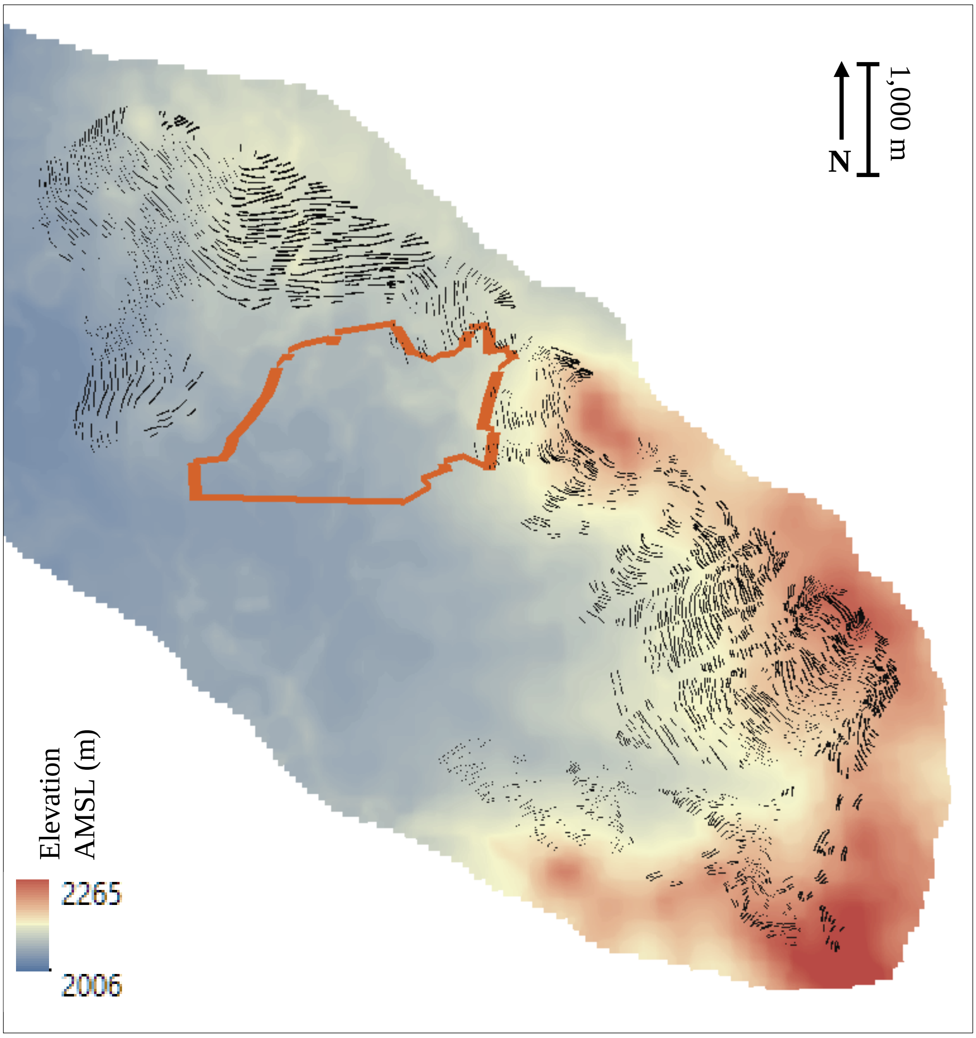


Figure 24: A 3 m resolution DEM of the greater study area. The area affected by gully formation has been outlined in orange. Constructed stone bunds and *fanya juu* have been indicated in black.

Water level change since Reservoir construction

With the limited physical possibilities to determine the ground water, the water level in the wells of seven farmers were measured and the farmers answered questions about trends on December 18 (

Table 3). The wells were hand-dug and used a large earthen vase, with the bottom removed, as a cap. All farmers were located on the North side of the gully, within the area of the accompanying extension worker. The level was measured to the edge of the wells, which was elevated ca. 0.5 m above the surrounding area. The estimations for highest level, however, use the soil surface as reference.

At three farms the water would reach the surface at its highest point. There were few wells that had been in operation before 2010. From those that were, half (2/4) farmers reported a change in water levels: both had increased. From these, one farmer proposed a cause for the rising water levels: the extensive implementation of soil and water conservation measures since 2010.

Table 3: Ground water levels and changes therein since 2010, with proposed reasons for any change. Data based on measurements and farmer interviews.

Well ID	Distance from gully system (m)	Ground water level in December (m from surface)	Highest ground water level (m from surface)	Changes observed since 2010	Proposed reason behind change
a	259	-14.08	-8	Well has not dried completely in the dry season, as was the case before 2010	Implementation of SWC measures
b	11	-1.55	0	N/A (well was constructed in 2013)	N/A
c	138	-3.20	0	None	N/A
d	23	-3.20	-2	N/A (no owner)	N/A
e	77	-2.00	0	N/A (well was constructed in 2013	N/A
f	192	-3.72	-1.8	1.5 m rise in year-round level	Farmer does not know
g	270	-4.35	-3	None	N/A

.

Determining land use change

Overall, the dominant land use was cropland, with 97%, 89% and 88% for the “Waterfall”, “School”, and “Tentacle” gullies, respectively. The remainder of land was taken up by grassland used as pasture, except for 0.23 ha of grassland that serves mainly as a school yard. Some plots contain a building constructed, but built-up area constituted less than 1% of the watershed, so it has been excluded from this study. Nevertheless, the number of building has risen in two of the watersheds: in “Waterfall”, from 5 to 7, and in “School” gully watershed from 6 to 9. There was little to no change in the land use in the studied period. Only “Tentacle Gully” showed a 1% increase in cropland and subsequently a 1% decrease in pasture. The aerial imagery for 2010 survey dated from April 2012; the imagery for 2014 from January 2015.

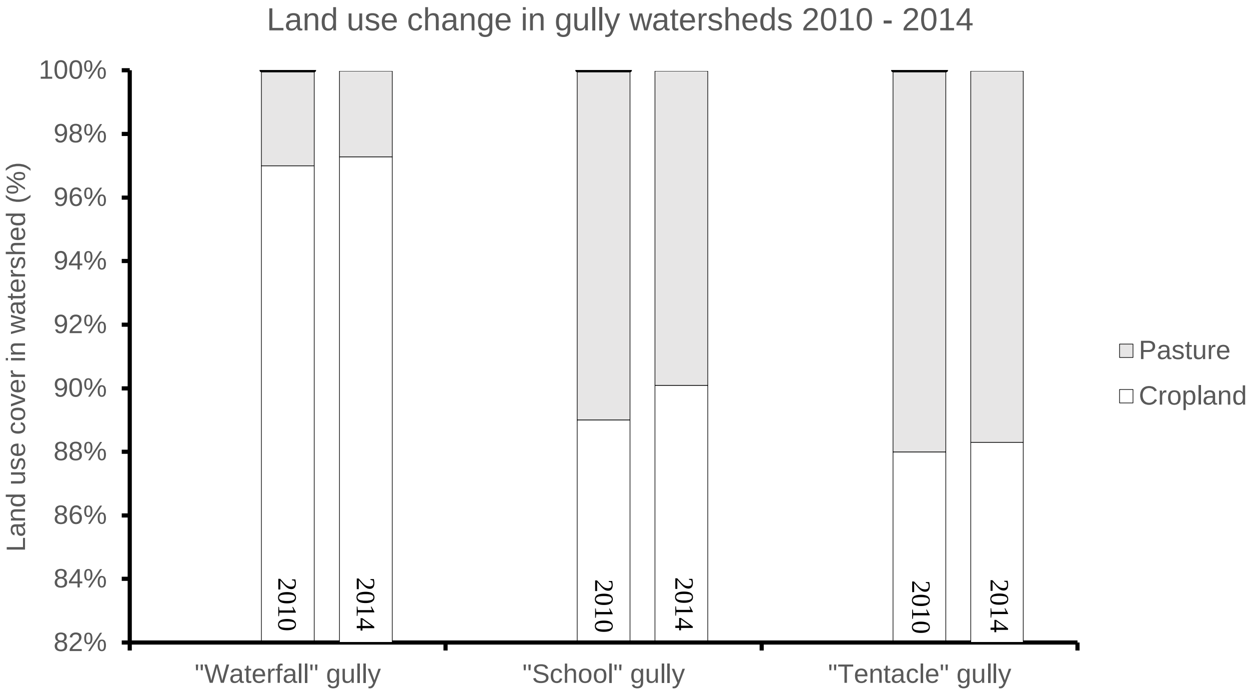


Figure 25: Changes have been low or absent in land use cover of each watershed for the studied gullies, over the period 2010 - 2014.

4. Discussion

This chapter discusses the results that have been obtained during the data collection phase. It aims to relate findings to literature and to place findings in perspective. In addition, it includes the limitations of the study. To keep with the overall structure of the thesis, the chapter is structured per research question.

Strengths and limitations of the methodology

Aspects of the methods used during this study influenced its results. These will be discussed here, according to the order of the research questions.

All gully 3d models have been based on photographs taken towards the end of the wet season. It should be noted that the end of the precipitation did not coincide with the end of erosion. Several chunks broke off weeks after the rains had stopped. This was due to cracking of the gully banks, and impacted the width of the gully more so than the length. These chunks were deposited at the gully bottom, and will probably be washed away during the next rainy season. Therefore, they did not influence the volume calculations - but to better represent gully dynamics it would have been better to postpone gathering imagery until further into the dry season.

The use of terrestrial photogrammetry to survey the gully volume that has been added in 2014 had two consequences for the results. The first relates to the impact of the 3d workflow. The model resulting from the photo alignment is in true 3d, but does not allow for advanced analysis: for example, volume calculations are not possible on objects that are not completely enclosed. Therefore, the analysis has been done in ArcScene. However, 3d models in ArcScene can only be edited and analysed as what is in essence a 2.5d model. The main difference is that a x,y-coordinate can only have one associated z-value (elevation). Issues arise when dealing with overhangs: for any x,y-point with two elevations, the algorithm creating the DSM will only use the one with the highest elevation. This makes any overhangs into vertical walls (Figure 26) and ignores hollowed spaces. The contour lines approach each other so closely they form jagged edges. Since adjacent pixels have such differing elevation values, the colouring on the DSM has artefacts on the vertical walls. Since all soil moisture distribution maps use the simplified elevation data from the DSM, it simplifies the dynamics of the gully. All three gully heads had an overhang with the main exfiltration zone in a cave-in under surface overhang, caused by slumping of the over-saturated soil. The dense grassroots held the topsoil in place, while the soil below eroded, creating the overhang. This is not visible on the soil moisture distribution maps. The core of the issue is the lack of 3d tools in the ArcGIS package. Interpolated layers (such as those created from soil moisture sampling points) can only be displayed in 3d by ‘draping’ them over a layer with unique x/y/z values for each pixel, such as a raster DEM. The original, detailed 3d model cannot provide elevation data for another layer, nor can features (such as sample points) be placed on the 3d-model surface directly.

This is an example of a wider issue with working in 3d. Creating 3d objects is becoming more and more accessible: editing and displaying 3d data is following at a slower pace. Since common document formats (e.g. Word and PDF files) do not properly integrate moving images such as gifs or videos, detailed 3d models are shown as a still image from one or two viewpoints – meaning information obscured by objects or perspective is not shown. Pending better support for moving images, perhaps the better way to display 3d information is digitally, through video clips or 3d viewers.

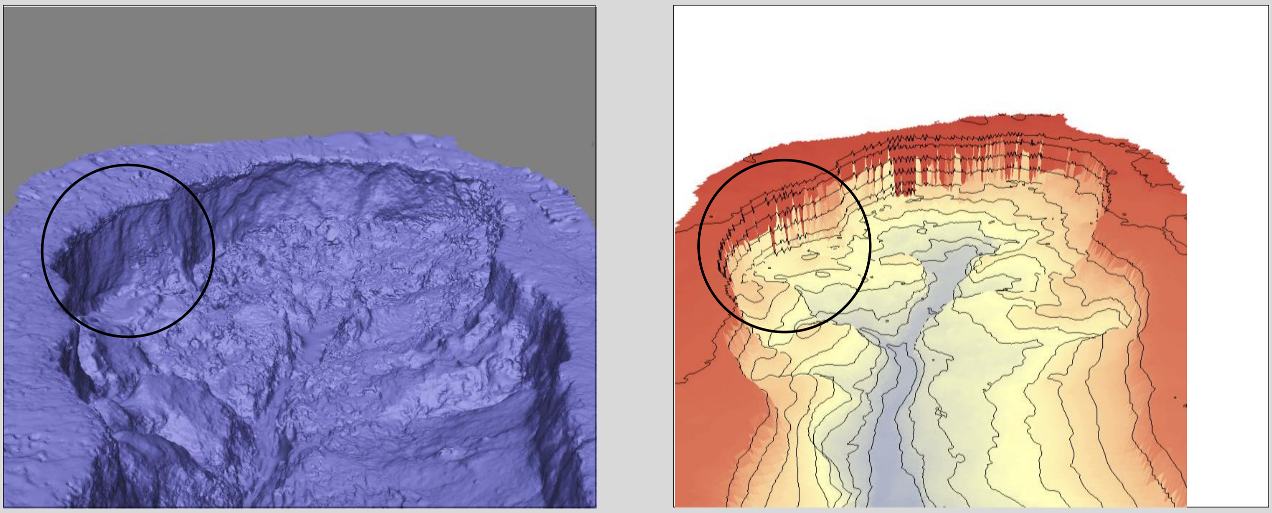


Figure 26: Comparison between the original 3d-model of the "Waterfall" gully (in Agisoft Photoscan Pro, left), and the derived DSM (in ArcScene, right). Note how the overhang in the 3d-model is reduced to a near-vertical wall, leading to artefacts in the colouring.

The second consequence of using photogrammetry for volume calculations relates to the accuracy of the results. The resulting 3d model present a digital surface model (DSM) of the gullies, and not a digital elevation model (DEM). Any substantial amount of vegetation is represented as a part of the surface (small patches or single plants are filtered from the results). A similar problem occurs in LiDAR technology, where laser pulses also bounce on vegetation canopies, presenting it as the surface (Raber *et al*., 2012). In LiDAR, however, more options for accurate correction are available, as LiDAR devices have so-called ‘multiple-return’ pulses. In these, transmitted pulses can bounce of multiple layers: the tree canopy trunk, branches, stems, and leaves; the understory trunk, branches and leaves; and at last the actual terrain surface. These multiple-returns allow for a variety of vegetation point removal techniques aimed at revealing the true ground surface (Raber *et al*., 2012; Plaut *et al.*, 1999; Hodgson *et al.,* 2002).
Hypothetically, the vegetation detections options are also viable for the high-density point clouds generated through photogrammetry, by exporting these to LiDAR data analysis and editing software such as those published by LAStools. Detection of vegetation points, especially for imagery containing a near-infrared (NIR) band, can reach 90% (Maltezos and Ioannidis, 2015). However, since NIR-filters are rare on consumer cameras, using only the visible colour spectrum would lower accuracy as only shades of green can be used to assign points to a vegetation class. Furthermore, no ground pulses as in LiDAR are available to trace the ground surface underneath the removed vegetation, only interpolation from surrounding surface points. If vegetation is too high or covers most of the surface, this will not work or will not be accurate (Isenburg, 2014). Therefore, this method should be applied to bare or recently developed landscape features, where vegetation has not yet had time to develop.
Relating this issue to the studied area, it has lowered the accuracy for the “Waterfall” and especially the “School” gully. The “Waterfall” gully had a patch of bushy vegetation near its exit: since it was quite dense, the Photoscan software treated it as a bump on the soil surface (Figure 27). This has added approximately 2 m^3 to the gully volume. In “School” gully, vegetation covered most of the west bank up to 0.5-meter height, over an area of approximately 15 m^2. Therefore, the gully volume has been overstated by approximately 7.5 m^3. Due to this low impact, no further effort to correct the DTM has been undertaken.

These drawbacks beside, the models were very detailed and accurate, especially since manual calibration is simple and time-effective. Gathering video material for the gullies took approximately 15 minutes per gully, and an additional 10 minutes was spent on measuring distances between reference points for calibration of the scaling. This greatly limits the time necessary to spend in the field compared to traditional methods. Data processing in Agisoft Photoscan Pro however can be more time consuming. The transfer of the resulting 3d models between software is complicated as documentation is sparse.

Figure 27: Looking from the gully head to gully exit, and example of the representation of vegetation in a 3d model. The bushes (circled) in "Waterfall" gully are part of the surface.

Historic erosion rates cited in literature served as a baseline for to compare the found rates to. Although both the study by Tebebu *et al.* (2012) that was used and this study have not had extensive soil analysis done to compare the soils, the factors mentioned in section *Comparing soil erosion rates* and the similarity between the erosion features photographed in the paper, and those observed in the study area, justify the use of the cited historical erosion rate. The 2012 study does not indicate the error margin on the erosion rate figure. The error margins for this study, displayed in Figure 16 (chapter Results), have been based on the spread in bulk density measured in the different horizons of the gully. It does not take into account the error in delineating the watershed, nor the error in measuring the gully volumes. As seen in the figure, the error margin for average bulk density alone is enough to negate any statistically significant difference. The error margin is large relative to the small differences in the absolute values of the density, as the samples were only measured twice, and in the procedure of establishing bulk density variations occur. These variations include different amounts of residue left in the sampling rings, and most importantly the difference in the amount of soil in the sample rings. Sampled soil was either very hard (dried) or very sticky (most clay) and after retrieving the embedded sample rings they were not uniformly filled and small air spaces around the edges of the sample rings will have led to differences in samples even as they were taken close together in the same soil layer.

In addition, establishing the watershed for a feature such as a gully is not exact: the watersheds are small in comparison to the low detail of the DEM. Despite this, the 2012 study cites an exact 17.4 ha watershed size without notes on the method that was used to get such an accurate number. Despite this, the 2012 study cites an exact 17.4 ha watershed size without notes on the method that was used to get such an accurate number. Taking into account the importance of the watershed size in establishing erosion rates per hectare, finding the statistical significance of the difference in erosion rates between this study and the 2012 study was not possible.

The first step in researching the process behind the gully erosion was to check for the presence of subsurface flow using checklist of subsurface flow signs, taken from Hagerty (1991). Although the secondary and tertiary signs of subsurface flow can be open to interpretation, the direct signs are clearly defined and accompanied by clear pictures. Since these were found, there is no doubt that subsurface flow was present according to this method. In addition, the practical method complements the data of the more theoretical approach of indirect soil moisture measurement with the TDR

On this topic of soil moisture, the lack of piezometers made a direct measurement of pore pressures impossible. The indirect method of measuring soil moisture content through TDRs and comparing it to a soil moisture retention curve from literature has two potential weaknesses. First, related to the Time-Domain Reflectometer (TDR). The results of the reading are very local, but give the impression of accuracy due to its precise (one-tenth of a percent) results. It is therefore important to take the samples in the same spot, every sampling date. However, the studied gullies were active gullies: banks slumped during the research period and material deposited in the gully bottom had moved after heavy rainfall. That meant subsequent samples were sometimes taken in different patches of soil, mostly in newly exposed parts of the gully wall directly behind a slumped piece. A related issue is the sampling of dried soil: the dried, hard vertisols made sampling below approximately 10% SMC cumbersome. Often, cracks would appear around the TDR prongs, resulting in very low (1-3%) readings. Therefore, the

accuracy of readings below 5% should only be interpreted as very dry, cracked soil and not as an absolute SMC value. Such problems did not occur at soil moisture levels near saturation, which is what this study focuses on. Overall, the results are still deemed accurate: the readings for samples on opposite sides of a gully, often very similar in terms of soil texture and hydrology, were very similar in results as well. Furthermore, the raw data shows very few outliers going against an established drying trend for that sampling point. Both arguments show that although the TDR data is local, and that the locality might change slightly over time, this does not take away from the patterns that were established.
The second potential weakness lies in the conversion from the TDR readings to actual soil moisture content. Results show significant differences between the soil moisture content measured with the soil samples and with the TDR in 3 of 4 samples. The soil moisture distribution maps were however created using unadjusted TDR readings. Two considerations led to this choice. The laboratory readings did not provide error margins, even though error must have been introduced during the removal of the soil samples and the repeated weighing. Adding to this, the hard soil from which the samples were taken meant that some sample rings were not fully filled or had crumbles that had caved in during the hammering of the ring. Therefore, the volume in the ring was probably closer to 90 cc than 100 cc. This could have artificially lowered the SMC percentage for the laboratory-analysed samples. It would have been better to take the samples during a wetter period, when the sampling process was easier and the rings would have been filled more evenly. The second consideration is the unequal difference between the different methods in the different samples. The increase is not clear and uniform enough justify an adjustment for the TDR values.
The implication of this choice is that the TDR numbers could be slightly lower (0-5% points) than displayed, but it is unclear how much exactly.
In a wider perspective, combining bulk density measurements with direct infiltration measurement methods, such as a double ring infiltrometer or permeameter, could add value to future similar research. In hindsight, there was enough water available to do these measurements, as opposed to what was reasoned when deciding on the methodology. Then there is the recurring lack of error margins: due to the cost the soil laboratory analysed only one sample per layer per gully. Therefore, little can be said on the significance of the differences. However, the soil samples were taken with care and the weighting and drying procedure was done with care, so the outcomes have been judged as accurate.
Progressing from formation processes to potential root causes, the final cause that has been investigated was land use change. The imagery was highly detailed and land use was easily identifiable. The results are dependent on the accuracy with which the watersheds were identified. As mentioned earlier in this discussion, this might not have been completely accurate. In case the watersheds were overestimated, the proportion of pasture would have increased; in case of underestimation, the proportion of cropland would have increased. There would be no impacts on the land use change: the land surrounding the watersheds is uniformly in use as cropland
As for the comparison of these results with land use change before 2010, an analysis of aerial imagery for the period before would have been the most effective, as had been done for 2010 - 2014. This was not possible because there was no imagery dated before 2011 for the study area that was sufficiently detailed to do such an analysis. Instead, the research by Yeshaneh *et al.* (2013) served as the source. A potential weakness is that the gullies' watersheds form of only a part of the study's Koga catchment. There are no indications however, that there were major ongoing land use changes in the Koga catchment in 2010 and the literature did not provide clues that a more detailed research for a subset of the catchment would yield different results. Therefore, the literature research is deemed sufficiently reliable and accurate to use its findings for the study area.

Comparing soil erosion rates

It is clear from observations and from the presented data that gully volume has increased over time, drastically in some cases. However, the results do not show a significant ($p > 0.05$) increase in the growth factor during the researched 2010-2014 time period. From a visual observation of the graphs, there does seem to be an increase, especially during the last 2 years: however, data collection has been too short to prove a significant trend. Two factors probably played a role in the extension workers' reports stating the threat of gully erosion has increased since 2010. First, during the past few years, gullies have encroached on farmers' fields and a school yard, making the gully erosion more visible and therefore increasing the urgency for farmers and extension workers. Secondly, what could be called a form of reversed "exponential growth bias" could have played a role. This bias is used in economics, especially personal finances, to describe the common tendency to underestimate the effect of compound interest, a form of exponential growth, on a starting capital. This reasoning can also be applied the other way around, when observing the added gully volume for 2014. Based on the large eroded volume, it seems that growth 'must' have increased from earlier years. However, the mechanisms and their magnitude of these mechanisms could still be the same, simply acting upon a larger initial gully area.

The impact of the data point in 2014 for "Waterfall" gully becomes clear when looking at the average erosion rate for all three gullies over the research period has been shown in Figure 16. As for erosion rates before the studied period, Tebebu *et al.* (2012) presented historical erosion rates. These figures were chosen over more frequently cited review studies (e.g. Poesen *et al.*, 2003), for their origin in a close-by catchment (less than 50 km) and similar hydrogeology. It measured gully branches in a downslope area (6-10% slope) with a dominant Vertisol and grass vegetation. For the 1981 – 2007 period, they cite an erosion

rate of 17.5 t/ha/year for the measured gully branches. This figure only includes erosion in the branches, not in the main gully stem – which would have doubled the rates. The lower figures were used because this study has also focused on branches only (parts of the gully at an angle with and feeding into the larger main gully). These rates were compiled based on historical aerial imagery and farmer interviews through the AGERTIM method. The historical erosion rate has been surpassed by the erosion rate in the study area since 2013, and was nearly triple for the 2014 rainy season.
All values cited fall within or reasonably close to the range of 0.01 – 65 t/ha/year found by Poesen et al. (2013) for 60 globally distributed locations.

Determining gully formation processes

After establishing the development of erosion over time, the results provide clues on the mechanics of gully erosion in the study area. Specifically, the methodology had been designed to give insight into the role of subsurface flows. The first step in researching the process behind the gully erosion was to check for the presence of subsurface flow using checklist of subsurface flow signs, taken from Hagerty (1991). Since at least one direct primary indicator of subsurface flow was present in each gully during at both sampling dates, the presence of subsurface flow in the study area is clear.
The dominance of subsurface flow as erosion process is supported by the clues that Figure 22 (caption: change in total soil moisture content over time) provide. The soil moisture peak lags the rainfall peaks, and recedes more slowly than would have been the case in a catchment dominated by surface runoff. Unfortunately, the data gap in October makes it impossible to see if values would rise further and what the recession limb would look like in the initial phase. Despite this, if the soil moisture content is taken as a hydrograph of gully flow, the pattern fits the description of shallow subsurface flow as described by Guebert and Gardner (2001), visualized in Figure 28 (marked 3). They observe that this flow might exit the soil near the base of a hillslope (Figure 28, marked 5), as has been observed in the study area.

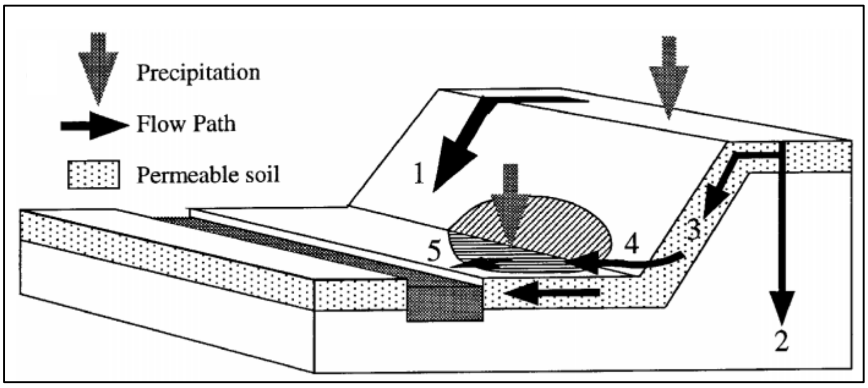


Figure 28: Examples of hill slope flow processes: 1. infiltration-excess overland flow, 2. ground water recharge, 3. shallow subsurface flow, 4. return flow, and 5. saturation overland flow on a hillslope. Modified from Guebert and Gardner (2001).

Beside the methodological limitations of the TDR that have been discussed, a **third** potential weakness lies in determining the threshold value for soil saturation. The SMC percentages from the TDR readings need to be related to a soil water retention curve to determine the pore pressure. However, soil water retention or pF curves are highly dependent on soil characteristics (Matula *et al.*, 2012). There was no equipment available for determining the pF curve; nor had the soil samples been analysed for the factors, such as soil organic matter, necessary to model the pF curve. So to place the observation of active exfiltration above 45% in context, it is necessary to compare it with an existing pF curve for a similar soil. Mile and Mitkova (2012) present pf curves for Vertisols, depending on the soil horizon. Their threshold value for soil saturation is 46% (Mile and Mitkova, 2012: p. 110). SMC higher than this would denote a positive pore pressure. The threshold value was the one established for the transition layer from topsoil to substrate, the layer showing of the signs of subsurface flow in the study area. The study was done for a Macedonian vertisol, but the sand/silt/clay fractions (p. 105) are similar to those found in the study area (Figure 7, Chapter Results). This coincides with observations of active exfiltration in this transition zone at places with a value of >45%. Therefore, the 45-50% and 50% classes in the soil distribution maps in the Results section are indicative of zones of active exfiltration.
The results on the cause of the positive pore pressures were more ambiguous. From Figure 29, it becomes clear that the water table nears the surface close to the gully area. In general, the highest ground water level get closer to the surface when descending into the gully system (Figure 29). The correlation between distance from the gully system and the water level is significant ($p<0.05$). One sampling point suggests an outlier (well ID “a”, annotated with an asterisk in Figure 29). This well was located circa 400 m from the other wells, which were quite clustered. From this well, the terrain slope to the gully system was at a SSW direction, as opposed to the SE direction of the other six wells. Therefore, the trend line in Figure 29 does not

take the data point for well "A" into account. Doing otherwise would not change the conclusions, but it would increase the slope of the trend line.

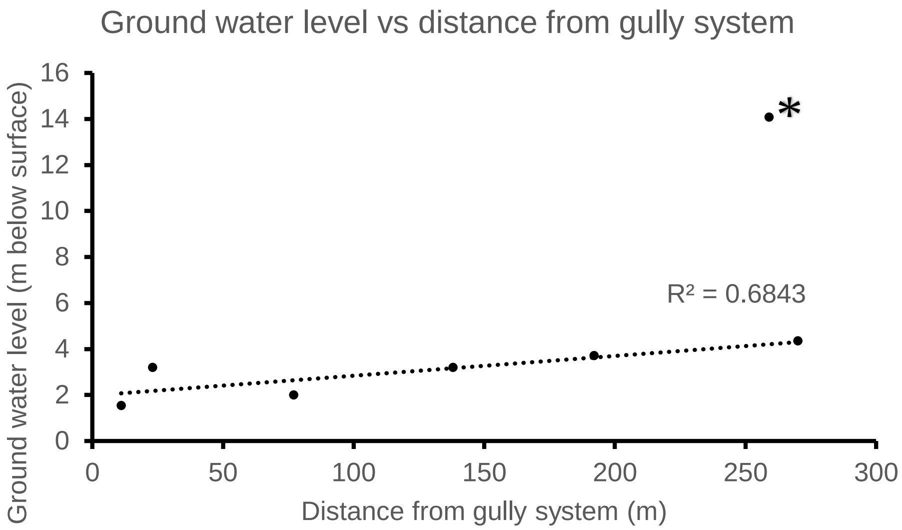


Figure 29: The relation between the ground water level measured in water wells in December, and their distance to the edge of the main gully system. The asterisk at (275,14) denotes an outlier for well "a", which has not been taken into account when creating the trend line.

This fits with the observations of standing water in and around the gullies, as described in the results – the gully system lies in the foothills of the catchment. Research has suggested a perched water table following from a contrast in soil texture as cause for positive pore pressures (Tebebu *et al.,* 2013; Wilson and Fox, 2010; Faulkner, 2006). Differences as small as 10% in bulk density between soil layers could be the cause of this. The reasoning is that increased bulk density decreases the amount of macropores in the soil, lowering the hydraulic conductivity (Iversen *et al.,* 2001). The data for bulk density in the studied gullies supports this in 2 out of 3 gullies: for the "Tentacle" gully however, the pattern reversed. Here, the bulk density was slightly higher in the phreatic layer than in the layer below. This contradicted observations as well: this gully was bound by a very solid, gravely soil that was hard to penetrate with a sample ring, even when using a hammer. It was very distinct from the sticky but porous black clay that the phreatic layer consisted of – near the gully bottom, water could be observed exiting the clay layer and streaming on top of the gravely soil. The results can be explained by an exception on the link between higher bulk density and lower hydraulic conductivity. Dec *et al.* (2008) studied a similar case, where samples with a higher bulk density did not show a lower hydraulic conductivity. They concluded that the influence of continuity in the pore system led to this result, and that continuity is not only dependent on bulk density but also on aggregate formation and disturbance. The continuity of the pores could not be determined in the study area, but from observation it is plausible that the porous clay has more continuous pores than the compacted layer underneath, despite its slightly higher bulk density. Indeed, differences in macro porosity between soil layers may be a stronger determinant of subsurface flow, as opposed to differences in bulk density as has been proposed by Fox and Wilson in their 2010 review, especially in soils prone to cracking, such as Vertisols.

Finding root causes of erosion

The final research questions dealt with the possible root causes of erosion. The first was the construction of a reservoir, finished in December 2010. Major issues with the administration of the Koga Project Office in Merawi meant that no historical data was available for groundwater levels surrounding the reservoir before and after the construction of the reservoirs. The head of the Project Office blamed the lack of trained workers to monitor the levels in the piezometer that had been installed surrounding the reservoir. Upon asking if it were possible to visit the piezometers ourselves to measure the current water levels, it became clear that the coordinates of the piezometers were lost. Possible leads on these coordinates at Bahir Dar University did not yield any results. Seeing the potential rise of groundwater level following the construction of a reservoir and its potential impact on the surroundings, this seems like an oversight from the Project Office. However, the reservoir is 4.35 km downstream of the gully system, and with a 51 m lower elevation it would seem unlikely there would be significant impact from the reservoir. None of the interviewed farmers mentioned the impact on the reservoir by themselves. When influence of the reservoir was suggested to the farmers, none were convinced this was the case. These interviews of course only selected a small portion of farmers, all on the West-side of the gully system, which was in the direction of the reservoir. These farmers also used very crude measurement methods to determine the water levels (a rope with knots). Besides the inherent difficulties in monitoring water levels throughout the years with such tools, the farmers often had difficulties accurately estimating distances and lengths.

These results fit with the notion asserted in literature that water level changes are mostly present directly around and directly downstream of a reservoir (Winter *et al.*, 1998: pp. 68-69).

The second possible root cause was the implementation of land and water conservation measures. The finding that only contour barrier type of SWC measure has been implemented in the study area contradicts the more diverse set of measures that had been found in the greater Koga Catchment by Mengstie (2009). This was caused by two factors. First, the study area was only a relatively homogenous subset of the Koga catchment, which excluded for example steep slopes where other SWC measures have been taken. Secondly, measures that are only visible during parts of the year could not be included. This refers to no tillage and mulching practices that had not been applied at before harvest and are not visible on aerial imagery. Continuing with the barrier type measures, digitization of the contour lines barriers could be done accurately as they were clearly visible on aerial imagery. The imagery dated from 2014, so any new measures implemented since then have not been included. Also, the method did not allow for the classification of the type of barrier, nor for characteristics, such as width and height, other than length. This means that any difference between barrier types in their effects on the hydrology could not be analysed. The mapping exercise does show that the barriers cover virtually every field on the hills of the watershed, and that they end at the edge of the gully system. To get more insight into the hydrology surrounding these different barrier types, a separate but parallel study was planned but had to be cancelled. Therefore, to look at the impact of these measures on the area's hydrology, these measures need to be grouped. Both *fanya juu* and stone bunds are forms of contour barriers. The main effect of this type of anti-erosion measure on the area's hydrology is increased infiltration as barriers stop or slow run-off (Schwilch *et al.*, 2012: p.43). Hengstdijk *et al.* (2004) suggested a 50% increase in infiltration in a modelling study. This will lead to increased soil moisture behind the barriers, and increased percolation, if subsurface soil porosity permits. These effects have been reported for 5 out of 7 case studies (Schwilch et al., 2012: p.51). The results from the farmer interviews pointed at the same effect in the study area: the sole farmer suggesting a cause for increased water levels suggested the cause lay with the implementation of the contour barriers.

The final possible root cause that has been investigated was land use change. The imagery was highly detailed and land use was easily identifiable. The results are dependent on the accuracy with which the watersheds were identified. As mentioned earlier in the limitations of methodology, this might not have been completely accurate. In case the watersheds were overestimated, the proportion of pasture would have increased; in case of underestimation, the proportion of cropland would have increased. There would be no impacts on the land use change: the land surrounding the watersheds is uniformly in use as cropland. The roughly equal proportion of pasture in all watersheds is due to the proximity of the gully heads to the boundary between cropland and pasture – all gullies started in pasture, close to this boundary, with the majority of their watershed in the cropland (where the soil water conservation measures have been constructed). It is possible that the construction of the reservoir meant a loss of grazing area there and directly downstream, and a movement of cattle to the study area. There, it could have led to an increased grazing intensity, even if overall pasture area there has not changed. If so, overgrazing could have lowered the threshold for gully establishment. Before the 2014 rainy season, the pasture had been closed for grazing, a measure that had been properly enforced according to a local extension worker. Seeing as there was no grazing during the study period, this was deemed true. The goal was to reduce erosion. Observations showed that the grass layer had grown to about 15 cm, and was very dense and uniformly covering the ground surface. However, the closing has not impacted gully growth rate. The increase in gully area and impact has come not from the establishment of new gully heads, but rather from gully expansion. As has been argued in this thesis, expansion is mainly driven by soil saturation and not so much vegetation cover.

How does this compare with land use change before 2010? An analysis of aerial imagery for the period before would have been the most effective method in determining the land use change, as had been done for 2010 - 2014. This was not possible because there was no imagery dated before 2011 for the study area that was sufficiently detailed to do such an analysis. Yeshaneh *et al.* (2013) studied land use change in the Koga catchment, to which the gully area belongs. They concluded that between 1979 and 2010, cropland has decreased by 10%, while pasture has increased by 67%. Still, pasture makes up the minority of agricultural land in the Koga catchment. Overall, agricultural land over the time period has increased by less than 1%. By 2010, there was no unused land in the Koga catchment.

An interesting note in the study is the rise in woody vegetation since 1986, which the authors contribute to the planting of Eucalypt trees on plot boundaries and for tree nurseries. Although there are no tree nurseries in the gullies watersheds, trees are present on most plot boundaries (none were found within the boundaries of the gully system). It was not possible to verify their increase between 2010 and 2014 since the imagery was taken at different moments of the season, making the canopy sizes impossible to compare. However, it is reasonable to expect that the overall trend of increasing the planting of trees on plot boundaries and contour barriers has also applied to the gully watersheds. Effects of the planted trees on the hydrology are improved infiltration of rainwater and increased uptake of soil moisture (Hengsdijk *et al.*, 2004). According to Lane *et al.* (2004), the net effect of these eucalypt trees is a lowering of the water table.

5. Conclusion

This study aimed to find the root cause of gully formation over the last decade in the low-lands of the Minizr sub-catchment, in North-Western Ethiopia. To do so, we have researched and discussed the soil and size characteristics of the gullies; how terrestrial photogrammetry can help in establishing these; the mechanism of the erosion; how the soil erosion rate has changed after 2010; and the influence of the construction of a reservoir, land use change and the implementation of SWC measures on this mechanic?

The merit of this study has been threefold. First, it shows the applicability of a fast, accessible and accurate way to digitally represent gullies and other landscape features through the use of video footage and photogrammetry. Secondly, it lends validation to claims by farmers and extension workers that the gully erosion issue has become more urgent since 2010. Finally, it shows the dominant processes in gully formation in the area, allowing for a justified selection of measures to halt further gully growth and rehabilitate existing gullies.

Gully erosion rates in 2013-2014 have increased, in cases showing a two- or three-fold increase, up to 74 ton/ha/year, far above soil replenishment rates and very high on a global scale. What is more important to policy makers and indeed local population, is the increased impact of the erosion as gully heads currently encroaching on roads and school yards.

The erosion in the study area is driven mainly by subsurface flows. Water infiltrates on the slopes surrounding the gully system as the water table approaches the surface near the gully system. The high soil moisture content in and following the rainy season has been shown to be analogous to positive pore pressures leading to piping and bank collapse, as the water pressure negates the cohesive strength of the clay aggregates. The positive pore pressures, extending from 6 weeks until at least 3 months into the dry season, stem from differences in the permeability of layers, but these differences could not be explained exclusively by differences in bulk density, but rather by differences between the continuous pore structures in the water-carrying layer and disconnected pore structures in the layer underneath. The gully growth has not slowed by closing the pasture, a measure aimed at reducing gully erosion. Therefore at least for existing gully heads subsurface erosion must be the dominant driver.

No evidence points towards influence of the reservoir, in use since 2011, on erosion rates in the study area. It was hypothesized that the reservoir could have led to heightened ground water table in the study area, causing soil saturation and therefore lowering the soil stability. This would make the soil increasingly prone to erosion. However, this study did not find changes in the water table nor testimonies from farmers to support this. An important finding, though, was the lack of monitoring of groundwater levels near the reservoir. Piezometers around the reservoir have been installed but have not been monitored; neither were their locations available to the Koga Project Office. Because of this oversight, changes in water level change closer to the reservoir might have been missed. These could influence agricultural practices in these areas.

The same holds true for land use changes. The gully system consisted of pasture, surrounded by cropland. The land use in the watersheds of the gully area has been stable since 2010, and a literature study on land use change before that did not find reasons to suppose the land use had changed significantly in the 1985 – 2010 period. Clsoing of grazing land in the gully area has led to increase grass cover. This measure cannot be expected to fully reverse the gully expansion issue as it does not relate to the formation process of the gullies, although more time is needed to see if it has effect on the establishment of new gully heads in the study area.

More than 160 km of contour barriers have been implemented in the study area since 2010, including on most farm plots in the gullies' watersheds. These measures have been implemented in an effort to decrease runoff and the following surface erosion. A side-effect of these measures is an increase in the infiltration rate by up to 50%. This would increase the subsurface flow towards the gully system.

Therefore, the only researched factor shown to have changed the dynamics responsible for the erosion process in the study area, is the implementation of soil and water conservation measures since 2010 on slopes surrounding the gully system. It is plausible that these SWC measures have been the root cause of increased subsurface flows towards the gully system. This has rendered the soil in the gully system more susceptible to erosion.

6. Recommendations

These conclusions lead to two recommendations for the organization dealing with sustainable land management in the study Minizr sub-catchment. An extension worker who regularly joined field work suggested filling the gullies with soil and installing check dams. Neither should be implemented as a first step, as the new soil will be washed away and check dams will be easily bypassed along the sides and through piping. Tebebu *et al.* (2013) advised constructing a drainage system in a comparable situation, to control the subsurface flows. Further study should look into the engineering and financial aspects of such a drainage system: suggested starting points include Muirhead and others' 1996 study on subsurface drainage in an irrigated vertisol with a perched water table, and Asamenew and others' 1989 study used by the FAO on the economic evaluation of improved Vertisol drainage for food crop production in the Ethiopian highlands.

A recommendation perhaps more related to the larger Koga catchment than to the study area proper, the Koga Project Office should start monitoring ground water levels surrounding the Koga Reservoir by tracing the installed piezometers and enlisting data collectors to check and register the levels as was planned at construction. This will provide more insight into the reservoir's influence on the area's hydrology.

7. References

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8. Appendix

Evidence for piping

Table 4: Evidence types for identifying piping/sapping in the field, with description and examples. Compiled based on data from Hagerty (1991).

Evidence type	Description	Examples
Direct	Direct observation of water and soil grains outflow from an exfiltration face	1. holes in the exfiltration face 2. soil particles can be caught with cupped hands
Primary Indirect	Features or conditions that are caused solely or predominantly by the piping/sapping mechanism	1. Fan-shaped deposit of particles from cavity in bank/shore 2. "Blind" gully or rill: water has flowed out of the soil face and not overland flow.
Secondary Indirect	Features associated with piping/sapping but that are somewhat removed from the exfiltration zone per se or that indicate persistent seepage outflow without conclusively indicating that piping has occurred.	1. Stained zones in a stream bank or shoreline and holes where soil pipes have collapsed remote from the seepage exit point in the bank or shore. 2. Presence of holes in the floodplain adjacent to a stream or in a terrace above a streamline (often in a depression)
Tertiary Indirect	Features or conditions associated with a process ancillary to piping/sapping or that may have been created by another mechanism or progress.	1. Collapse of upper bank or shore zones 2. Cantilevered soil layers 3. Lateral spreading and rapid flow of loose pervious soil layers 4. Nearly vertical faces in a bank or shore (scarps characterized by small cusps).