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Surface and subsurface flow effect on permanent gully formation and upland erosion near Lake Tana in the Northern Highlands of Ethiopia

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Abstract

Gully formation in the Ethiopian Highlands has been identified as a major source of sediment in water bodies, and results in severe land degradation. Loss of soil from gully erosion lowers crop yields, reduces grazing land availability, and is one of the major causes of reservoir siltation in the Nile Basin. This study was conducted in the 523 ha of Debre-Mawi watershed south of Bahir Dar, Ethiopia, where gullies are actively forming in the landscape. Historic gully development in a section of the Debre-Mawi watershed was estimated with semi structured farmer interviews, remotely sensed imagery, and estimates of current gully volumes. Gully formation was assessed by instrumenting the gully and surrounding area to measure water table levels and soil physical properties. Gully formation began in the 1980's following the removal of indigenous vegetation, leading to an increase in surface and subsurface runoff from the hillsides. A comparison of the gully area, estimated from a 0.58 m resolution quick bird image, with the current gully area mapped with a GPS, indicated that the total eroded area of the gully increased from 0.65 ha in 2005 to 1.0 ha in 2007 and 1.43 ha in 2008. The gully erosion rate between 2007 and 2008 was $530 \text{ t ha}^{-1} \text{ yr}^{-1}$ in the 17.4 ha area contributing to the gully, equivalent to over 4 cm soil loss over the contributing area. As a comparison, we also measured rill and inter-rill erosion rates in a nearby section of the watershed, gully erosion rates were approximately 20 times the measured rill and inter rill rates. Depths to the water table measured with piezometers showed that in the actively eroding sections of the gully the water table was above the gully bottom and, in stable gully sections the water table was below the gully bottom during the rainy season. The elevated water table facilitates the slumping of gully walls, which causes widening and up-migration on the hillside.

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1 Introduction

Soil erosion is one of the most challenging global environmental problems. Loss of soil has both on-site effects, such as loss of soil fertility and lowered water holding capacity, and off-site effects, such as siltation of reservoirs and lakes (Tamene and Vlek, 2007). Unfortunately, erosion is often far more severe in developing countries than in industrialized countries, often a result of the lack of financial, technical, and institutional capacity (Tamene and Vlek, 2008). In the Ethiopian Highlands, erosion has increasingly received greater attention since the 1980's following the development of the Soil and Conservation Research Program (Hurni, 1988; Moges and Holden, 2008). Researchers from Switzerland and Belgium in cooperation with Ethiopian researchers have made great advances in understanding upland erosion (Beshah, 2003; Bewket and Sterk, 2005; Herweg and Ludi, 1999; Hurni et al., 2005; Nyssen et al., 2004; Sheferaw and Holden, 1998), yet there has been little done, in practice, to promote soil conservation. For instance, Mituki et al. (2006) estimate that 36% of erosion in the Ethiopian Highlands is a result of inappropriate agricultural or agroforestry practices, but it is not clear what measures would ameliorate these losses.

While mechanisms for upland erosion are relatively well understood and acceptable soil loss rates have been established (Haile et al., 2006), the processes controlling gully erosion are poorly understood (Nyssen et al., 2006). Gully erosion is defined as the erosion process whereby runoff water accumulates in narrow channels and removes considerable amount of soil from this narrow channel over a short time period. A working definition of gullies in agricultural land is defined in terms of channels too deep to easily pass over with ordinary farm tillage equipment, typically anything deeper than 0.5 m (Poesen et al., 2003; Soil Science Society of America, 2010). Gullies can be active (actively eroding) or inactive (stabilized). An active gully (Poesen et al., 2002, 2003) can occur where the erosion is actively moving up in the landscape by head cut migration. Stabilized gullies have ceased widening and head cutting, and often begin to fill with sediment.

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While gully erosion is not a new phenomenon by any means, its importance has gained more attention lately. For instance, Carnicelli et al. (2009) examined gully formation since the late Holocene period in the Ethiopian Highlands and found that besides tectonic events, that gully formation is triggered by an increase in the stream transport capacity at the start of wet intervals, while gully stabilization and filling occurs during transitions towards drier climate phases where there is reduced water transport capacity. Several episodes of gully formation, stabilization, and re-filling have occurred prior to the spread of modern agriculture in the Highlands. Following the spread of agriculture to the highlands gully formation was found to be driven primarily by anthropogenic factors. For instance, Nyssen et al. (2006) found that gully development in the Highlands was related to a land use/land cover change such as planting of eucalyptus trees, cultivation of new land, or by the degradation of the vegetation cover on steep slopes. Yet it is still not clear if gully formation results directly from land management practices (tillage, crop type) or from a change in the hydrology of the landscape due to land management (e.g., higher water tables, lower evapotranspiration), or some combination of the two.

Two distinct cases of the interaction between gully formation and hydrology can be distinguished; one in which gully formation affects the hydrology and the other where the hydrology affects the gully erosion. The main effect of gully formation on the hydrology is that gully incision lowers the ground water levels by providing a shorter drainage path to the outlet for the same difference in elevation. Hydrological controls on gully formation are generally assumed to be dominated by the amount of surface runoff (Poesen et al., 2003; Carey, 2006; Mogis and Holden, 2009). The reasoning is that the smaller the stream power the smaller the gully erosion (Nyssen et al., 2006). Therefore, installation of upland soil and water conservation practices that reduce runoff (and increase infiltration) are expected to decrease gully formation (Nyssen et al., 2006; Wilson et al., 2008). A review of the role of subsurface flow on gully formation has recently been published by Fox and Wilson (2010), however, results are mainly based on laboratory experiments. Limited information exists on the effect of the subsurface flow

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processes on gully erosion under field conditions (Fox et al., 2007). In one field study in south eastern Nigeria gullies were found in the discharge areas of groundwater systems, and became very active during the peak recharge times of the rainy season because high pore-water pressures reduced the effective strength of the unconsolidated materials along the seepage faces (Okagbue and Uma, 1987). The seepage forces caused by the hydraulic gradient in the gully walls produce piping and tunneling that undermined the gully walls and activated their retreat (Fox et al., 2007).

The effect of subsurface flow process on gully formation and upland erosion in the Ethiopian Highlands has not received sufficient attention. Determination of which hydrological process (subsurface or surface) is the dominant cause of erosion, or the degree to which they are interrelated, is important for recommending effective erosion control management practices. In the research reported here we explore the interaction of hydrological factors on gully formation, and compare gully erosion rates to better understood rill and inter rill erosion rates in the Debre-Mawi watershed.

2 Material and methods

The study was performed in the 523 ha Debre-Mawi watershed located between 11° 20' 13" and 11° 21' 58" N and 37° 24' 07" and 37° 25' 55" E, 30 km south of Lake Tana, Bahir Dar, Ethiopia (Fig. 1). Elevations range from 1950 to 2309 m above sea level (a.s.l.) and slope varies from 6–35%. Average rainfall, falling mainly from June to September, is 1240 mm. Land use consists of rain fed agriculture in a mixed farming system with scattered indigenous tree species, including *Cordia* sp. The soils in the landscape are dominated by vertisols. Two sub-watersheds were selected for closer study within the Debre-Mawi watershed (Fig. 1).

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2.1 Watershed I: gully erosion site

2.1.1 Study site description

This sub watershed was selected to study gully formation. The contributing area to the gully (Fig. 1) has a total area of 17.4 ha, (1005 m long by 240 m wide at the upper end and 78 m at the outlet with an average width of 160 m). The topography was mapped with a differential GPS (GPS 1200 Leica Geo Systems) using 1034 points (Fig. 2a). Elevations range from 2184 to 2300 m a.s.l. The gully, with two branches, is clearly visible in the images Figs. 1 and 2a. The northern gully branch (left fork referred to as gully branch A) has a relatively shallow average depth of 55 cm, an average width of 20 cm or more at the bottom, and an average bank slope of 23°. The southern gully branch (referred to as gully branch B) is deeper with an average depth of 260 cm and a minimum width of 240 cm. Gully banks in the southern branch are steeper with an average slope of 35°. The northern and southern gully branch join at the mid-slope position of the hillslope (referred to as gully branch C) forming one larger, wider, and deeper gully. Below the junction of the two gullies, the depth decreases and the width expands, forming a local deltaic depositional zone. When the gully reaches the floodplain zone of the watershed (Figs. 1 and 2) it meets another large gully, which is advancing upslope as well. Our work focused on gullies A, B, and C.

A geologic map was constructed (Fig. 2b) from 30 geological test pits located mainly adjacent to the gully path and in the headwater area of the catchment. The watershed is underlain by shallow, highly weathered and fractured basalt. The fractures are highly interconnected with limited clay infillings. Surface exposures of basalt can be found on the hilltops (Fig. 2b) and in mid-slope areas on the hillsides. Weathered basalt (saprolite) can be seen in these areas as well as in the gully. An intrusive basaltic dyke is found in the centre of the southern gully branch (B) (Fig. 2b). This basaltic dyke has a general NE-SW trend, nearly perpendicular to the flow direction of the watershed. In the remaining watershed the basalt is covered with a black clay layer becoming thicker down slope. The black clay is generally underlain by brown silt loam that can be highly

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compacted, followed by a saprolithic layer.

The vegetation in the upper watershed (13% of the total area) is cropland with tef or small indigenous bushes and shrubs where the top soil is too thin to sustain crop growth. An artificial rock bund exists at the boundary between the upper and middle watershed (Fig. 2a). The middle, area of the watershed (60%) consists of crop fields principally cultivated with tef and some millet and maize. Most fields are double cropped. The lower watershed is saturated during the rainy season and covered with grass.

2.1.2 Measurements

The historic rate of gully development was assessed through the AGERTIM method (assessment of gully erosion rates through interviews and measurements, Nyssen et al., 2006) and by interpretation of air photos and satellite images. To determine the rate of gully formation the gully was visited with five key informants in four age groups (farmers of the age 20, 30, 40, and 50 years). The age of the various gully segments was estimated through different questions. The key informants located different segments of the existing gully and the location of the gully head over time and major changes that occurred during over the last three decades. The extent and location of the gully in its early stage was first reconstructed with the oldest informants. Information from the oldest key informant (approximately 50 yr old) was crosschecked with information provided by younger informants.

For 2005, the gully extent was estimated from a Quick Bird image (2005, 0.58 m resolution). Gully boundaries were determined before the rainy season in July 2008 (indicated as 2007 measurement) and after the rainy season on 1 October 2008 (the 2008 measurement) by walking the gully with a Garmin GPS with 2 m positioning accuracy. On 1 July and 1 October 2008, the volume and surface area of the entire gully system was estimated through measurements of width, depth, and length of several cross-sectional and length profiles.

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Twenty-four piezometers were installed at the beginning of the rainy season in 2008 both in the gully's contributing area and directly inside the gully. Piezometers were constructed from PVC pipes (approximately 5 cm diameter) with the bottom 30 cm screened. Intrusion of silt and sand was prevented by wrapping filter fabric around the screened end of the wells. Both ends of the piezometer were capped. Each piezometer was installed to a maximum depth of 4.2 m or until the saprolithic layer was reached. In the upper watershed, depths ranged from 55 to 185 cm with an average depth of 115 cm. In the mid-slope area the piezometer depth ranged from 185 to 400 cm with an average depth of 275 cm, while piezometers installed in lower gully area did not reach the saprolithic layer and depth ranged from 195 to 420 cm and were installed just below the ground water. The exact depth of each piezometer as well as its location is given in auxiliary material. Each piezometer location was geo-referenced using a GPS unit. Measurements of water table depths in the piezometers commenced on 5 August 2008 when the water table was elevated due to the onset of the rainy season.

2.2 WATERSHED II: the upland erosion site

2.2.1 Study site description

The second watershed was used to study upland erosion (rill and inter-rill erosion) processes. The location of the upland site relative to the gully site, is given in Fig. 1. Soils consisted of clay and clay loam and land use/land cover was similar to the gully site.

For determining rill erosion, 15 fields were selected in the contributing area, representing a cumulative area of 3.56 ha. These fields were classified into three slope positions: upslope, mid-slope, and toe-slope. A series of cross-slope transects were established with an average distance of 10 m between two transects; positioned one above another to minimize interference between transects (Hudson, 1993). During the rainy season, each field was visited immediately after rainfall events in July and August when the greatest rainfall amounts occur. During these visits the length, width and

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depth of the rills were measured along two successive transects. The length of a rill was measured from its upslope starting point down to where the eroded soil was deposited. Widths were measured at several points along a rill and averaged over the rill length (Herweg, 1996). From these measurements, different magnitudes of rill erosion were determined, including rill volumes, rates of erosion, density of rills, area impacted by the rills, and the percentage of area covered by the rills in relation to the total area of surveyed fields (Herweg, 1996; Hagmann, 1996; Bewket and Sterk, 2003). The percentage crop canopy coverage was estimated whenever rill measurements were taken.

3 Results

3.1 Long term evolution of gully development in Debre-Mawi

Debre-Mawi watershed has many active, permanent gullies. We selected one of the more active gullies (Fig. 1) with a contributing area of 17.4 ha. According to farmer interviews, the gully began actively incising in 1980, which corresponds to the time when the watershed was first settled and the indigenous vegetation on the hillsides was cleared and converted to agricultural land. According to the respondents, in the early 1980's, the valley bottom of the study area was marshy, and grasses were grown all year long. There were three springs located in the valley bottom in the 1980's (Springs 1, 2 and 3, Fig. 3). Respondents agreed on the incision location and confirmed that the locations of the incisions were related to three springs in the valley. According to the oldest respondent the most bottom spring, SPRING 1, had flow all year long and was used to fill a pond. According to the farmer, the time when the pond began to dry up coincided with the incision of the gully in the valley bottom. According to the local informants, after the fall of the Derg regime in 1990 and 1991, the marshy area around the second spring (SPRING 2) changed into a branched gully with a northern and a southern gully branch as soon as settlers returned from the Debre-Mawi town. The

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third spring (SPRING 3), located near the head cut areas of the southern gully branch is still actively eroding into the hillside as indicated by newly developed, ephemeral side branches (Fig. 3).

The Debre-Mawi gully is very active in a few areas as indicated by the red triangles in Fig. 3. Below we discuss the gullying mechanisms for each of the gully sections. We will show that in all cases of active gullying the water table is above the gully bottom.

Figure 4 shows the depth of the water table for several piezometers near the gully. Piezometers P23 and P24 are located in the valley bottom, P13 and P1 in the southern gully branch (branch B) and P16 in the northern gully branch (branch A). After the rainy season water levels in the piezometers declined slowly with the exception of P24, which declined very rapidly. This piezometer is located near the newly formed head cutting zone in gully branch B and shows a faster drop in the water table than the other piezometers.

3.2 Valley bottom gully (branch C)

The depths (Fig. 5a) and the corresponding widths (Fig. 5b) of the gully in the valley bottom (branch C) are estimated before (2007) and after (2008) the rainy season as a function of the distance from the valley bottom. The average water table depth for the piezometers closest to the gully bottom (from bottom to top P24, P23, P22 and P26 and P17) are shown and indicate that the valley bottom is saturated close to the surface while further upstream the water table falls below the gully bottom. During the 2008 rainy season the gully was actively incising, further head cutting past the 187 m mark (from the gully bottom, Fig. 5a) and widened up to 20 m in top width (Fig. 5b) where the water table was near the surface (approximately 4 m above the gully bottom, Fig. 5a). Under static conditions the pore water pressure near the head cut point is 4 m, which is sufficient to cause slumping of the gully walls (Fig. 6).

The piezometers P24 and P26 at 244 and 272 meters from the junction show that while the water table is near the surface the gully has not incised yet (Fig. 5a). If our current theories on gully formation and advance are right, then, over the next few rainy

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seasons, it is likely that the gully head will rapidly incise and migrate uphill in these saturated soils. At sites 323 and 372 m from the bottom, the water table is below the bottom of the P17 piezometer and thus below the bottom of the gully. Here the gully is stable despite its 3 m depth.

3.3 North gully (branch A)

The active gully erosion process in the northern gully (branch A) is driven by similar ground water dynamics as found in the valley bottom (Fig. 7). The change in gully depth and bottom and top width during the 2008 rainy season is depicted in Figs. 7a, and b. The water table height above the gully bottom was obtained by subtracting the water table depth from the gully depth. Positive numbers indicate that the water table is above the bottom of the gully and negative numbers indicate it is below the gully bottom. Although the relationship is not as dramatic as Fig. 5, the general trend is quite similar. Where the water table is approximately 2 m below the gully bottom (at the 130 m from the junction of branches A and C) the gully is stable. However, at the sites 201 and 231 m above the junction the water table is 75 cm above the gully bottom. In this area the gully dimensions increase most dramatically (Fig. 7b).

3.4 South gully (branch B)

Widening in the southern gully branch is influenced by the presence of saprolite close to soil surface. The basalt and saprolite outcrop (referred to as dyke in figures) are shown in Fig. 8a. Figure 8b shows that the most active gully formation occurred at 263 m from the junction with branch B just uphill from the dyke where the water table was approximately 3 m above the gully bottom (Fig. 8b). At this site, the saprolite outcrop acts as a dam for lateral ground water flow, and ground water remains perched above the gully bottom. Downhill from the dyke at the site 115 m from the junction is the water table below the gully bottom, likely a result of the little flow contribution from upslope (Fig. 8a). Note also that there was no widening or deepening of the gully at

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this location (Fig. 8b). Unlike gully branch A and valley bottom gully (branch C) where the water table stays above the gully bottom causing a collapse of the walls, there is no widening in the gully in the section 300 to 400 m from the junction with branch A (Fig. 8a and b) despite the elevated water table (1–2 m above the gully bottom). Here the water is ponded on the saprolite layer and seeps through the saprolite to the gully. Thus the rock keeps the bank stable and prevents collapse.

3.5 Estimating gully erosion rates

Erosion rates for the main gully (branch C) and two gully branches (A and B) are given in Table 1. The increase in the erosion rate of the main gully between 2007 and 2008 can be explained by recent widening and deepening of the gully at the lower end (Fig. 2). Estimations of the gully extent in 2005 from the Quick Bird image and 2008 before and after the rainy season showed that from 2005 to 2007, the gully system increased from 0.65 ha to 1.0 ha, a 43% increase in area. During 2008, it increased by 60% to cover 1.43 ha at the end of the rainy season in 2008.

Once gully size was determined, the rates of erosion were then calculated by determining the change in dimension (width, depth, length) of the different gully segments. The eroded volume of each gully segment was calculated using the cross sectional dimensions and the distance between cross sections.

$$V = \sum_{i=1}^n L_i A_i \quad (1)$$

Where L_i is the length of considered gully segment (m) and A_i is the representative cross sectional area of the gully segment (m^2). Long-term gully erosion rates ($\text{t ha}^{-1} \text{yr}^{-1}$) (R_L) were calculated using the estimated current volume (V) of the gully, the average bulk density (Bd) of soils occurring in the contributing area, the time span of gully development in years (T) and the watershed area in hectares (A).

$$R_L = \frac{VBd}{TA} \quad (2)$$

The soil bulk density was estimated at six locations and depths throughout the contributing area of the gully using a cylindrical core sampler with a volume of 98 cm³.

Based on these estimates the average gully erosion rate from the period from 1981 to 2008 was equivalent to 31 t ha⁻¹ per year in the contributing watershed. The gully erosion rate has accelerated significantly since 2006. After the 2008 rainy season the erosion rate was estimated at 530 t ha⁻¹ (Table 1), which is equivalent to nearly 4 cm of soil from the contributing watershed. These values are extreme for the region compared to the results from other studies (e.g., Daba et al., 2003; Nyssen et al., 2006), but little work has explored erosion rates from active gullies.

4 Upland erosion

We compare the gully erosion estimates calculated above, to measurement of rill and inter-rill made on adjacent fields. The average upland erosion measured from the 15 agricultural fields was 27 t ha⁻¹ during the 2008 rainy season. The erosion plots located at toe slope areas had significantly greater soil loss (34 t ha⁻¹) and a greater area impacted by rills (884 m²) than either the plots in the mid or upper slope areas (Table 2). Higher erosion rates from toe slope areas are not uncommon, as these areas tend to receive greater flow from upslope areas, and saturate more frequently, resulting in greater runoff losses, and hence more erosion (Easton et al., 2010). Erosion rates (8–34 t ha⁻¹) from all slope locations were several orders of magnitude lower than the gully erosion rates (128–402 t ha⁻¹) in 2008. The average soil loss for each observation date is shown for the various crops in Table 3. The tef plots had the greatest density of rills and generally the greatest erosion rates (Table 3), which correspond with the reduced crop coverage following planting (Table 3). Later in the growing season, once plant cover was established tef actually had greater sediment depositions rates than the other crops. In late August, the rills degrade resulting in what amounts to negative soil loss. The erosion is greatest at the end of June when the soil is loose and dry and easily erodible (Bewket and Sterk, 2003). After the onset of the rainy season, the soils

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wet up and plant cover is established, and erosion rates decrease across all crop types (Table 3).

5 Discussion

Poesen et al. (2003) list gully erosion rates for 60 different locations around the globe. The gully erosion rates range from a low of 0.1 ton ha⁻¹ yr⁻¹ in New South Wales, Australia to a maximum of 65 ton ha⁻¹ yr⁻¹ in Spain. The percentage of gully soil loss as a percentage of total soil loss from a watershed range from 10% in Belgium to 94% in Losotho. Thus, the historic gully erosion rates (30.7 t ha⁻¹ yr⁻¹) estimated in the Debre-Mawi watershed, which represents 64% of the total soil loss (if we assume that the rill and inter rill erosion rates measured in 2008 are representative of historic averages) (Table 1), falls in the midrange of the values listed by Poesen et al. (2003). The gully erosion rates for 2007–2008 of 530 t ha⁻¹ yr⁻¹ represent 97% of the total soil loss, which is far greater than any of the observed gully erosion rates collected by Poesen et al. (2003).

For both the upland erosion and the gully erosion there is a clear relationship between moisture content and the rate of erosion. In the gully, where the water table is close to the gully bottom, gully erosion occurs by the sliding of the gully walls (both at the head cutting end and from the sides) into the bottom of the gully. Slumping occurs, because the pore water pressure above the gully bottom pushes the soil out when soils are saturated and the pore water pressure is greater than the soil strength. Thus the elevated water table causes the rapid upslope migration of the gully head (Fig. 3). When the water table is below the gully bottom the soil is unsaturated and maintains some degree of cohesive strength. If the gully widens when the soil is unsaturated, it is caused by overland flow entering the gully, but this occurs at much lower rates than when the soil is saturated (Fig. 7).

It is of interest to examine why the active gully in Debre-Mawi continues to expand. According to a formal and informal survey carried out in the watershed, gullying be-

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gan in the early 1980's following the removal of indigenous vegetation, leading to an increase of surface and subsurface runoff from the hillside to the valley bottoms. This increased flow then increased saturation at the bottom of the slope and formed a small disturbance (either natural or perhaps from grazing animals) and a small gully forms.

Once these initial gullies form they migrate rapidly upslope. Thus our results agree in part with those of Mogus and Holden (2008) who indicated that gully formation is human induced. When forests are replaced by agricultural land, the evaporative term in the water balance becomes smaller, making the soils wetter and sometimes saturated. These saturated soils lack cohesive strength and thus a gully can more easily form.

Many studies on gully erosion have report that gullying initiation can be worsened by a dry period (Nyssen et al., 2006). Often during a dry period, particularly in crack prone soil such as the vertisols common to the Highlands, preferential flow paths can form when these soils dry and crack. Preferential flow paths result in a positive pore pressure in unsaturated soils (Collison and Simon, 2001). Thus, locations that were saturated during wet periods dry out and crack during dry periods, often to considerable depth. When rainfall resumes water infiltrates in these cracks and can cause a positive pore water pressure that can initiate gully formation. Once the gully is established and the ground water is drained the soil becomes unsaturated, regains its strength in the surrounding areas, and the gully stabilizes. Gully formation stops when the gully has back cut to a location where the slope steepness is great enough to prevent a water table from becoming elevated above the gully bottom for extend periods.

6 Conclusions

Comparing the gully and upland erosion rates in the Debre-Mawi watershed, indicates that the soil loss rate of the gully system is approximately 20 times higher than to the erosion rates for the rill and inter rill system. While significantly lower than gully erosion, rill erosion is still nearly four times greater the generally accepted soil loss rate for the region and thus cannot be ignored in terms of agricultural productivity and soil fertility.

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However, if reservoir siltation and water quality of Lake Tana and the Blue Nile are the primary impetus for soil conservation, gully erosion has far greater consequences.

In terms of gully erosion control mechanisms, the most effective would appear to be dewatering of the soil in the areas directly connected to the gully system. This can be accomplished with drain tiles which, in theory, are practical. However, installation of drain tiles under Ethiopian conditions may be infeasible due to the relatively high costs and lack of mechanized equipment for installation. A management practice that is relatively low cost and easily implemented in the Highlands would be to plant eucalyptus trees on locations where the original forest was removed, which would increase evapotranspiration and lower the water table (Lane et al., 2004). Once started, gully formation can be stopped (or reduced) by stabilizing the gully as soon as it is incised. This requires continuous attention of the farmers and soil and water specialists.

Supplementary material related to this article is available online at:

[http://www.hydrol-earth-syst-sci-discuss.net/7/5235/2010/](http://www.hydrol-earth-syst-sci-discuss.net/7/5235/2010/hessd-7-5235-2010-supplement.pdf)

[hessd-7-5235-2010-supplement.pdf](http://www.hydrol-earth-syst-sci-discuss.net/7/5235/2010/hessd-7-5235-2010-supplement.pdf).

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Table 1. Gully erosion losses calculated with Eqs. (1) and (2) distributed uniformly over the contributing area.

Gully location	Soil loss		
	1980–2007 (t ha ⁻¹ yr ⁻¹)	2007–2008 (t ha ⁻¹ yr ⁻¹)	2007–2008 (cm yr ⁻¹)
Branches	17.5	128	1
Main stem	13.2	402	3
Total	30.7	530	4

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Table 2. Soil loss, area affected, rill density, and slope percent for the three different slope positions. Means with different letter within a column are significantly different based on a paired t-test at $\alpha=0.05$.

Slope position	Soil loss (t/ha)	Soil erosion effects		Erosion factors
		Area of actual damage (m ² /ha)	Rill density (m/ha)	
Down slope	34 ^{a*}	884 ^a	4946 ^a	14 ^a
Mid-slope	23 ^b	662 ^b	2860 ^b	10 ^b
Upslope	8 ^c	256 ^c	1029 ^c	9 ^b

Means followed by different letters (a,b,c) with in columns are significantly different at $\alpha=0.05$

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Table 3. Soil loss, percent plant cover on days of observation, and the 5 d antecedent precipitation for upland erosion measurements.

Month	Observation date	Rain fall (mm/5 d)	Rate of soil loss (t/ha)				Crop coverage (%)			
			maize	wheat	millet	tef	mz	wh	mt	tef
July	11 Jul 2008	51	4.9	0.9	6.9	7.3	26	3	10	0
	18 Jul 2008	75	8.3	0.6	−1.4	6.8	36	10	25	1
	22 Jul 2008	69	1.4	4.9	−2.0	4.2	40	25	30	5
	29 Jul 2008	55	0.1	0.5	0.8	2.2	46	53	55	15
August	1 Aug 2008	57	−1.0	0.6	−0.5	2.4	50	55	55	17
	12 Aug 2008	34	−3.0	−0.7	−3.8	−7.0	60	70	70	40
	27 Aug 2008	52	−1.1	−0.7		−0.6	75	85	90	75

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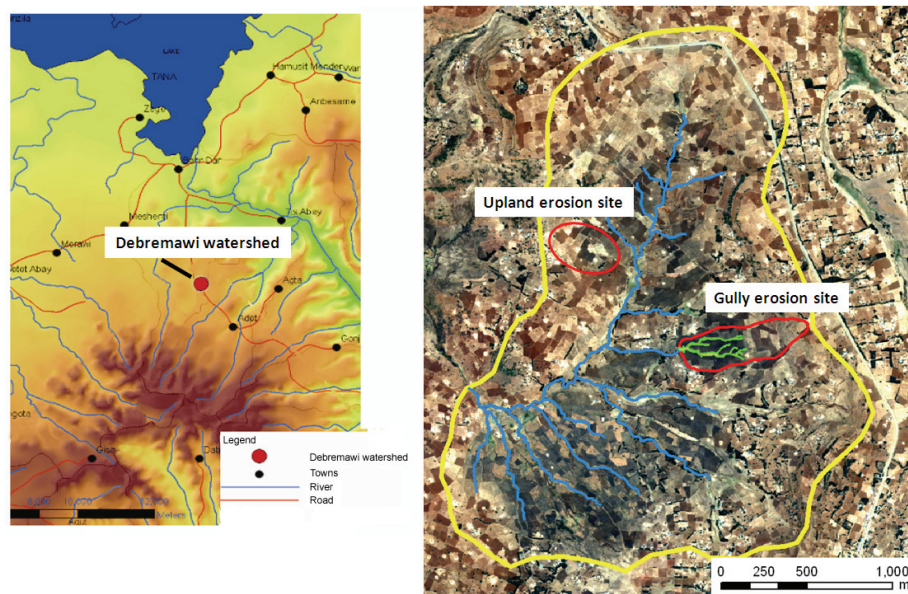


Fig. 1. Location of the Debre-Mawi watershed in the Lake Tana basin, Ethiopia, and a detailed map of the gully erosion and upland erosion sites.

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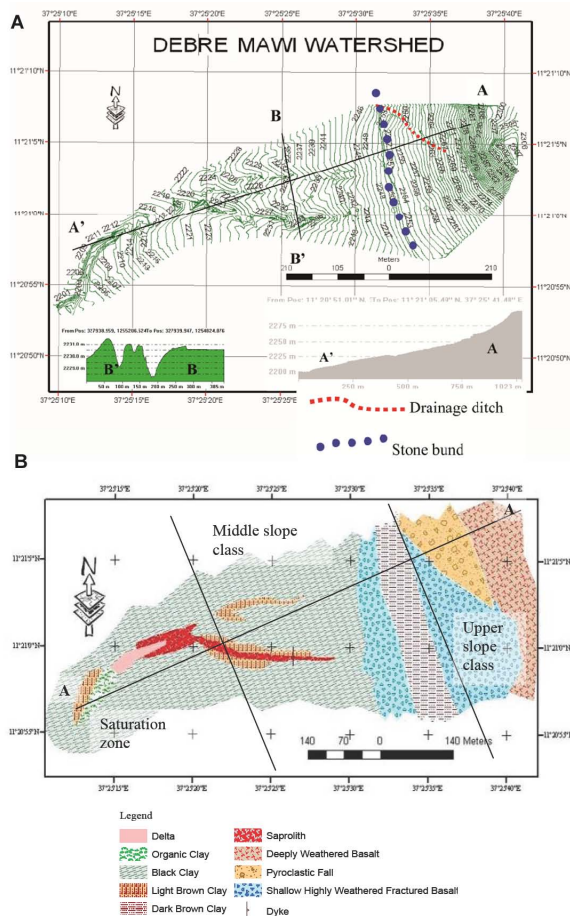


Fig. 2. Contour map of the gully erosion site with gully profile transect (A) and soil map of the gully erosion site (B).

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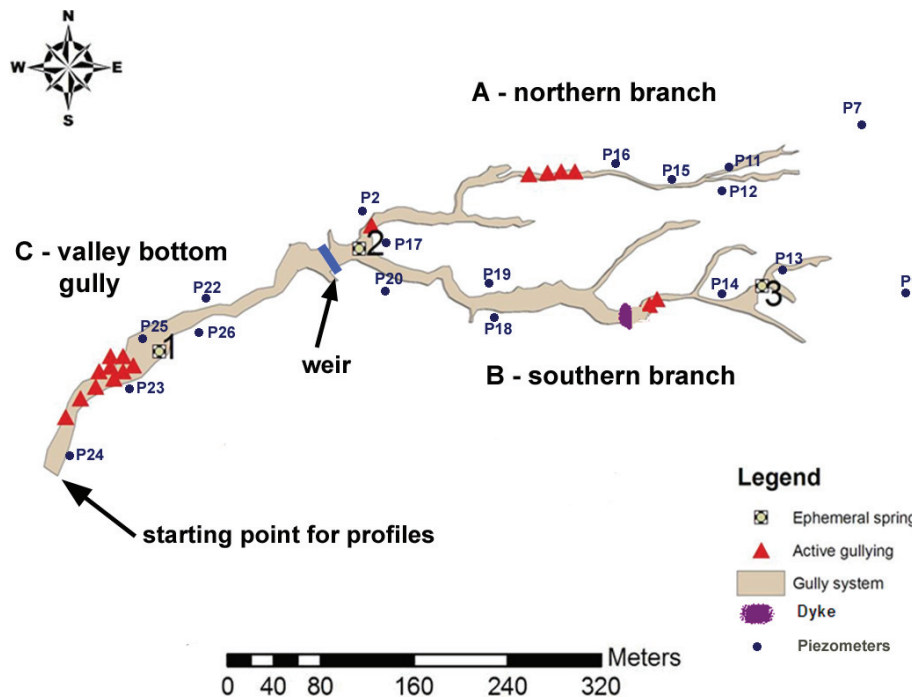


Fig. 3. The Debre-Mawi gully generated by handheld GPS tracking. Active erosion areas are indicated by triangles. Ephemeral springs and piezometer locations are shown as well.

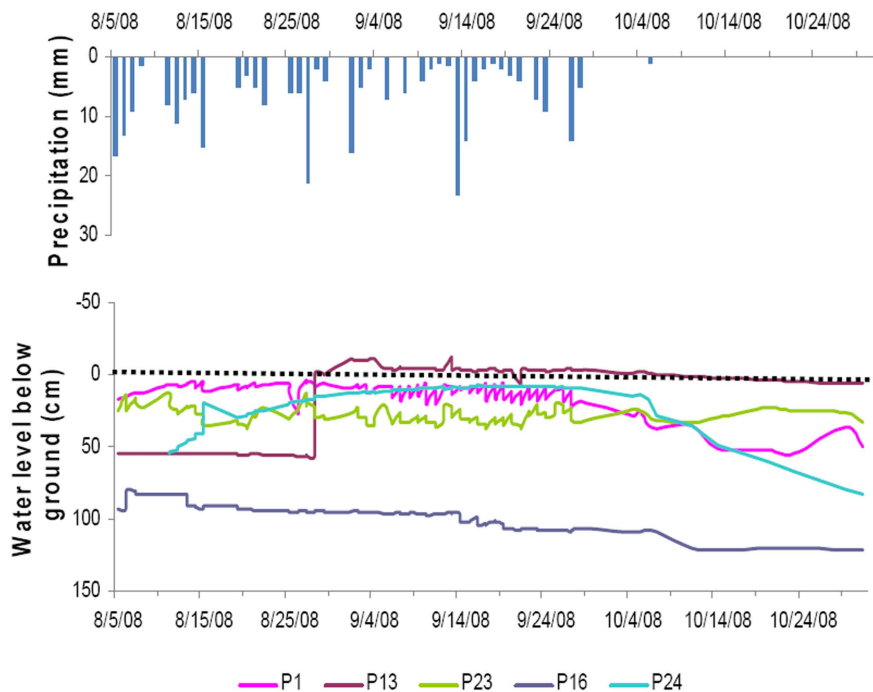


Fig. 4. Water table elevations for selected wells in and around the active gully section. Precipitation during the period is also shown.

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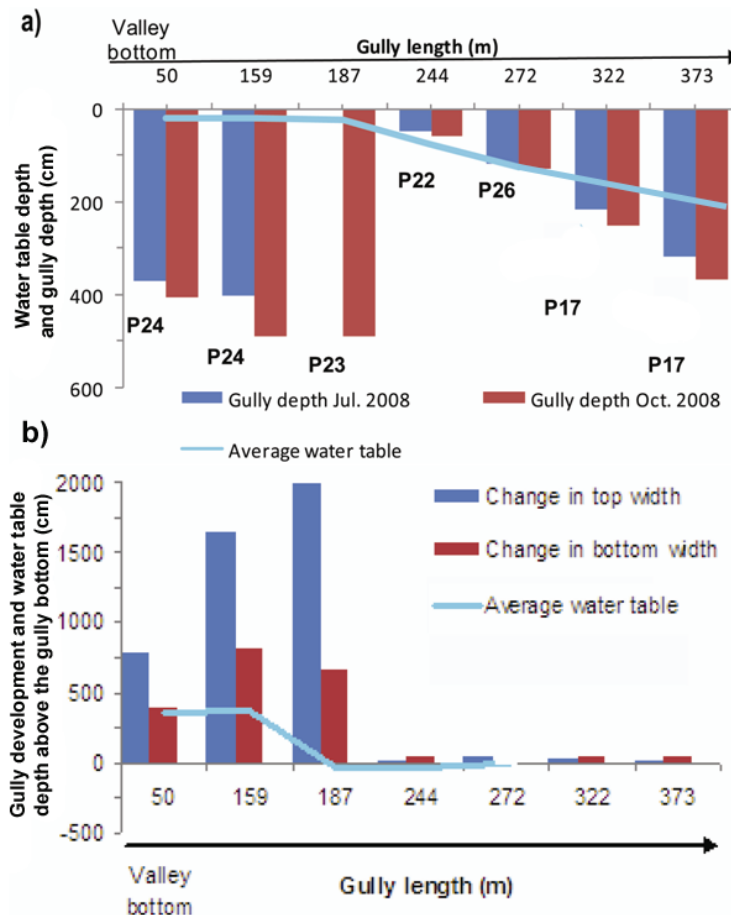


Fig. 5. Gully dimensions before and after the 2008 rainy season for the main stem **(a)** and depths and average ground water table change in top and bottom width and depth of the gully **(b)**.

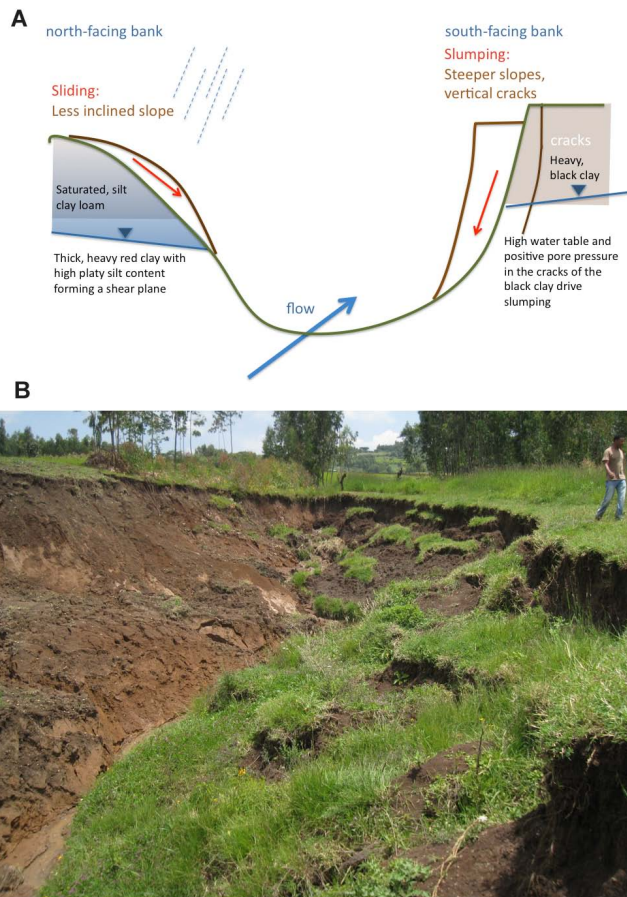


Fig. 6. Schematic of gully processes **(A)** and example of gully bank failures **(B)**.

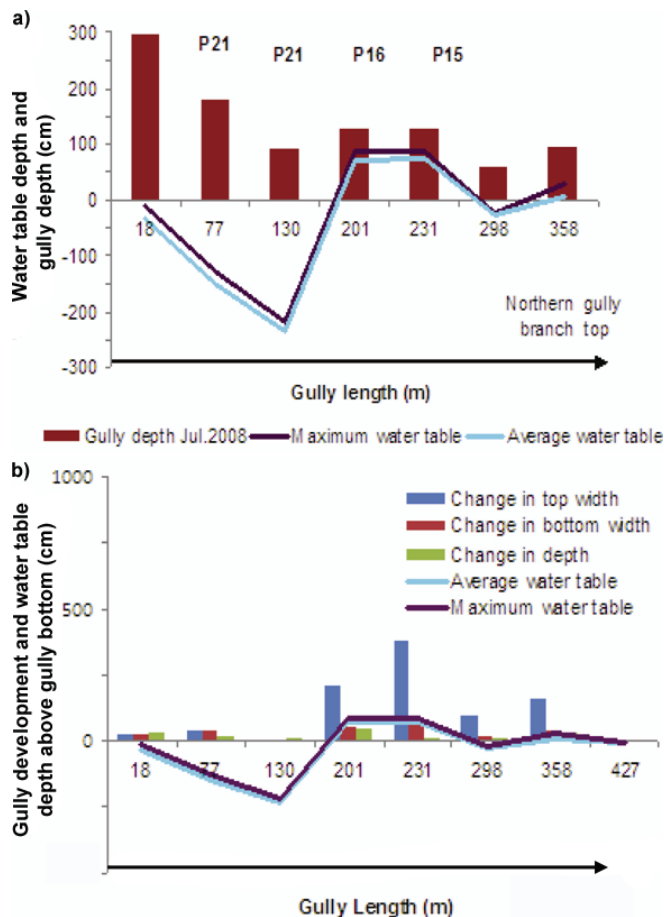


Fig. 7. Gully dimensions before and after the 2008 rainy season for the northern gully, branch A (a) and depths and average ground water table and change in top and bottom width and depth of the gully (b).

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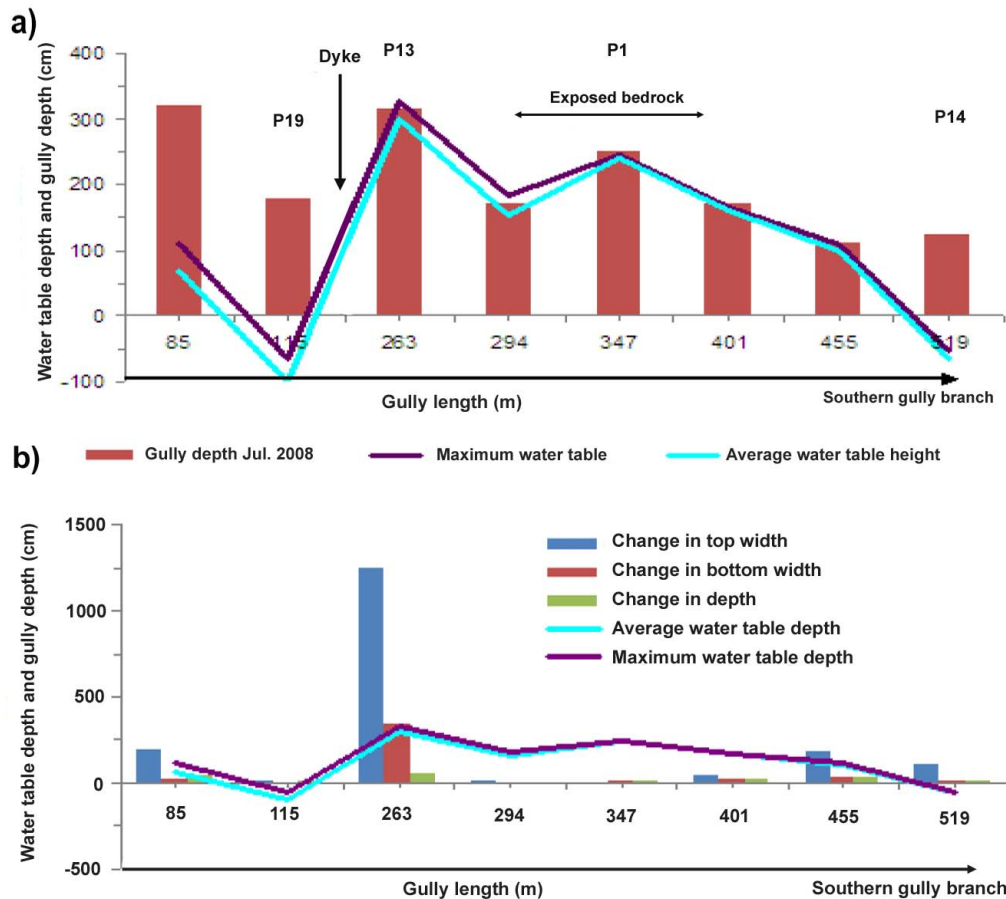


Fig. 8. Gully dimensions before and after the 2008 rainy season for the southern gully, branch B **(a)** and depths and average ground water table and change in top and bottom width and depth of the gully **(b)**.

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