Morphological dynamics of gully systems in the sub-humid Ethiopian Highlands: The Debre Mawi watershed

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Abstract. Gully expansion in the Ethiopian highlands dissects vital agricultural lands with the eroded materials adversely impacting downstream resources, for example as they accumulate in reservoirs. While gully expansion and rehabilitation have been more extensively researched in the semi-arid region of Ethiopia, few studies have been conducted in the (sub) humid region. For that reason, we assessed the severity of gully erosion by measuring the expansion of 13 selected permanent gullies in the sub-humid Debre Mawi watershed, 30 km south of Lake Tana, Ethiopia. In addition, the rate of expansion of the entire drainage network in the watershed was determined using 0.5 m resolution aerial imagery flown in 2005 and 2013. About 0.6 million tons (or 127 t ha^{-1} yr^{-1}) of soil was lost during this period due to actively expanding gullies. The net gully area in the entire watershed increased more than 4-fold from 4.5 ha in 2005 to 20.4 ha in 2013 (> 3% of the watershed area), indicating the growing severity of gully erosion and hence land degradation in the watershed.

Soil losses were caused by upslope migrating gully heads through a combination of gully head collapse and removal of the failed material by runoff. Collapse of gully banks and retreat of headcuts was most severe in locations where elevated groundwater tables saturated gully heads and banks, destabilizing the soils by decreasing the shear strength. Elevated groundwater tables were therefore the most important cause of gully

expansion. Additional factors that strongly relate to bank collapse were the height of the gully head and the size of the drainage area. Soil physical properties (e.g., texture and bulk density) only had minor effects.

Conservation practices that address factors controlling erosion are the most effective in protecting gully expansion. These consist of lowering water table and regrading the gully head and sidewalls to reduce the occurrence of gravity-induced mass failures. Planting suitable vegetation on the regraded gully slopes will in addition decrease the risk of bank failure by reducing pore-water pressures and reinforcing the soil. Finally, best management practices that decrease runoff from the catchment will reduce amount of gully related sediment loss.

Keywords: erosion, headcut, land degradation, sediment, East Africa, Ethiopia

1 Introduction

Gully erosion is likely the most serious form of land degradation (Poesen et al., 2003). Gullies form because they are an energy-efficient way for runoff to travel from uplands to valley bottoms (Gyssels and Poesen, 2003; Simon et al., 2011). Gullies can contribute more than 90% of catchment sediment yield (Tebebu et al., 2010; Simon et al., 2011; Zegeye et al., 2014). They have also been found to damage structures and transport routes (Nyssen et al., 2004b; Valentin et al., 2005).

Gullying is a threshold-dependent process controlled by a wide range of factors (Valentin et al., 2005), including rainfall and flowing water, soil properties, and drainage area. Capra et al. (2009) and Campo et al. (2013) found that most of the gully erosion took place during heavy rainfall events, i.e., storm events were one of the drivers for gully erosion. The mechanic actions of the flowing water can result in a rapid mass movement in the gullies by undercutting of the banks (See Fig. 1, Lanckriet et al., 2015). When these mechanic actions at the gully head exceed the cohesive strength of soil, erosion proceeds upslope through a headward cutting gully (Munoz-Robels et al., 2010). Interactions between such processes are important as hydraulic erosion promotes bank collapse, which then modifies subsequent hydraulic erosion (Thorne, 1990; Avni, 2005) (Avni, 2005, Thorne, 1990). Similarly, gully formation is initiated with the occurrence of convergent shallow subsurface flow that leads to seepage-induced erosion of surface soils, gully heads and sidewalls (Fig.1f; Vanmaercke et al., 2016; Tilahun et al., 2013a) and sliding (Fig.1d). Soil saturation by a rising water table decreases the soil shear strength (Poesen, 1993; Langendoen and Simon, 2008), and therefore destabilizes banks (Simon et al., 2000; Langendoen et al., 2013). Active gully networks are therefore predominantly found in the saturated valley-bottomlands (Tebebu et al., 2010; Steenhuis et al., 2014), and the deepest and the most spectacular gullies occur in the bottom of the watershed where in sub-humid monsoonal and wetter climates, the soil becomes saturated starting around the middle of the rain phase and then remain saturated until the end of the rain phase (Tebebu et al., 2014).

Soil properties and soil types also play a role in gully formation and expansion. For example, Vertisols, heavy clay soils with a high proportion of swelling clays (IUSS Working Group WRB, 2015), form deep wide cracks from the surface downward when they dry out (Fig. 1c) and are prone to the development of pipes (Fig. 1e) that can collapse and thereby turn into large rills or gullies (Valentin et al., 2005; Frankl et al., 2014). This may be one of the reasons that most severe gully areas are often associated with Vertisols (Valentin et al., 2005; Tebebu et al., 2014; Frankl et al., 2014). Similarly, in pasture bottom lands, piping often leads to development of permanent gullies (Jones, 1987; Zegeye et al., 2014). These pipes are part of gully networks and during the rain phase, the infiltrating rainfall discharges through the pipes, which increases the lower soil horizon's vulnerability to erosion.

The drainage area at the gully head is one of the parameters explaining linear, areal and volumetric gully headcut retreat (Vandekerckhove et al., 2003; Frankl et al., 2012, 2013; Vanmaercke et al., 2016). Runoff-contributing drainage area can be used as a surrogate for runoff, especially if it is assumed that the rainfall amount is equal for all drainage areas and that surface conditions and land use are also very similar (Oostwoud Wijdenes and Bryan, 2001). Frankl et al. (2012) reported for the semi-arid Tigray region in northern Ethiopia that among all environmental characteristics in a catchment, only the drainage area had a strong positive association with gully headcut retreat (hereafter, headcut retreat refers to the longitudinal gully growth and bank failure refers to cross-sectional gully growth). Similarly, when data from stable and unstable sub-catchments were combined, the main factors related to gully volume were drainage area of gully and stream heads (Muñoz-Robles et al., 2010). Nyssen et al. (2002) claimed that increasing the drainage area of the gully head enhances gully development. Additionally, long-term retreat rates often show negative-exponential trends with runoff-contributing area of the gully head, which could be explained by the declining runoff-contributing area of the gully head as it moves upslope (Begin et al., 1980).

Most gully erosion studies in Ethiopia have been carried out in the semi-arid Tigray region in northern Ethiopia (e.g., Billi and Dramis, 2003; Nyssen et al., 2006; Tamene et al., 2006; Nyssen et al., 2008; Frankl et al., 2011, 2012, 2013). In this region, rehabilitation of gully erosion has been relatively successful (soil loss has been decreased to a range of 1-6 t ha^{-1}) by using check dams and upland soil and water conservation (SWC) measures (Nyssen et al., 2004a, 2006, 2009). Using repeat photographs from 2006 to 2009, Frankl et al. (2011, 2013) found that about 25% of the assessed gully sections were stabilized as a result of siltation behind check dams. However, such physical structures have been ineffective in controlling gully erosion in the (sub) humid Ethiopian highlands, where gullies are formed in saturated Vertisol areas and where water often bypasses the check dams (Dagnew et al., 2015). Importantly, the amount of inter and surface flow in the humid region is different from that in the arid and semi-arid regions (Bayabil et al, 2010; Engda et al, 2011; Tilahun et al., 2013a,b; Steenhuis et al., 2014). Conservation structures that are effective in preventing gullying by overland flow in semi-arid regions (Nyssen et al., 2004a, 2006), may not be effective in the humid Ethiopian highlands regions where interflow elevates groundwater tables in the valley bottom that promote gully formation and expansion (Tebebu et al., 2010).

Thus, there is a clear need for a better understanding of gully erosion processes and factors in the sub-humid Ethiopian highlands in order to design effective gully control or rehabilitation measures. The objectives of this study were therefore: (1) to understand gully erosion processes in sub-humid Ethiopian highlands and identify factors controlling these processes for effective conservation practices, and (2) to provide quantitative estimates of the severity of gully erosion in the sub-humid Debre Mawi watershed.

2 Materials and Methods

2.1 Description of the Study Area

The study area, the Debre Mawi watershed, is located in the sub-humid highlands of northwest Ethiopia, 30 km south of Bahir Dar along the road to Adet between 11º20' and 11º22' N and 37º24' and 37º26' E. The watershed drains an area of 608 ha. The altitude ranges from 2194 to 2362 m a.s.l.; the elevations of the gullies considered in this study range from 2212 to 2272 m a.s.l. Rainfall is unimodal with an average value of 1240 mm yr^{-1}. The majority of the annual rainfall falls between June and the beginning of September and amounts to 900 mm yr^{-1}. The rainfall gauge station in the Debre Mawi watershed was constructed in 2008 by Adet Agricultural Research Center to record rainfall in rain phase only. The dry season lasts between 8 to 9 months. The mean daily temperature is 20°C.

The hydro-geomorphology of the Debre Mawi watershed is strongly controlled by the geological setting. The lava dykes in the watershed affect the hydrology upslope, forcing subsurface flow to the surface resulting in saturated source areas for surface runoff (Abiy, 2009). Soils are mainly Nitisols in the uplands, Vertisols in the bottom slopes, and Regosols on the steep hillslopes. 92% of the watershed is cultivated, 6% is rangeland and the remaining 2% is mainly covered by eucalyptus trees and shrubs, a small village and the road linking Bahir Dar with Adet. The small indigenous shrubs are predominantly found on the steep hillslopes.

The soils on the steep slopes (20-30º) in the upper regions are too shallow to sustain crop growth, whereas the less sloping areas in the upper portion of the watershed are predominately cultivated with the major crops: teff (*Eragrostis abyssinica*), finger-millet (*Eleusine coracana*), maize (*Zea mays*) and wheat (*Triticum aestivum*). The mid-slopes of the watershed consist of cropland with mainly teff and some finger-millet and maize. Most fields in this area are cropped twice a year. In the main growing season (June – August), farmers primarily cultivate teff and barley (*Hordeum vulgare)*, and after these crops are harvested, they use the residual moisture to cultivate chickpeas (*Cicer arietinum*), grass pea (*Lathyrus sativus*) and wheat as secondary crops from September to December. The gently sloping areas (0-6°) contain the periodically saturated bottomlands, which are in pasture and significantly affected by active gully networks. Free grazing is prohibited on most of the grazing lands, particularly on the upper slopes and the valley-bottom areas where the gullies form. The community established bylaws in 2010 to sustain this enclosure, and the farmers started to use a cut-and-carry system to feed their livestock: biomass is now cut on this enclosed part of the watershed and then transported to farms for fodder. This cut-and-carry system is primarily aimed at gully rehabilitation but also used as a best practice to maximize biomass yields for animal feed, although enforcement of the rules is inconsistent.

Here, we focus on the gully processes in the bottomlands, and study both the medium-term (8 years, from 2005 to 2013) and short term (2 years, from 2013 to 2014) gully advancement in the watershed. Specifically, we conducted a comprehensive study of the dynamics of 13 gully headcuts (hereafter referred to as G1 through G13), and factors controlling these dynamics. Gullies G1 and G9 through G13 are located in the central part of the watershed, and gullies G2 through G8 are located at the bottom flat area of the watershed (Fig. 2). All gullies except G11 and part of G6 are situated on communal grazing lands that were enclosed recently.

2.2 Data collection and analysis

2.2.1 Measuring gully widening and headcut retreat during the 2013 and 2014 rain phases

During the 2013 and 2014 monsoon rain phases, we measured for 13 gullies: (1) the headcut retreat (longitudinal growth) and gully widening (or lateral retreat) 10-30 m downslope from the headcut, and (2) the gully expansion rates and associated amount of soil loss along the total gully length.

To measure the headcut retreat and widening of the 13 gullies, we divided the gully downslope of the headcut into 3 to 8 uniform segments. The average distance between two consecutive cross sections was 3.6 m and varied from 1 m to 10 m with a standard deviation of 2.7 m. This method of measuring the gully dimensions is relatively precise, simple and low-cost compared with other methods (Casalí et al., 2006, 2015). Gully cross-sectional geometry was surveyed by dividing the cross section into trapezoidal segments at abrupt changes in the ground profile, and measuring the width and depth of the gully at each segment (Fig. 3). Cross-sectional area (A) and surface area (S) and Volume (V) were then calculated:

$$A = \frac{1}{2}\sum_{i=1}^{n-1}\left|(w_i h_{i+1} - w_{i+1} h_i)\right| \qquad (1)$$

$$S = \sum_{j=1}^{N-1} L_j \left(\frac{W_j + W_{j+1}}{2}\right) \qquad (2)$$

$$V = \sum_{j=1}^{N-1} L_j \left(\frac{A_j + A_{j+1}}{2}\right) \qquad (3)$$

where n is the number of trapezoidal segment sides of height h and located a distance w from the left gully edge in a cross section (Fig. 3a), i is a trapezoidal segment index, W is cross section width, j is cross section index, N is number of cross sections, and L_j is length of the gully section between cross sections j and j+1.

Measurements were carried out repeatedly (about 8 times for large gullies to five times for small gullies mainly following large rainstorms and the period between surveys not exceeding two weeks) using a tape meter and benchmark pins installed 5 to 10 m from the gully edges. However, a few gullies expanded more than this distance and the affected pins were reinstalled 5 to 10 m upslope of the newly formed gully bank.

To estimate gully expansion and the amount of soil loss from the total gully reach, three gully topographic surveys (before and after the rain phases of 2013 and 2014) were conducted. The total soil loss volume over the monitoring period was then obtained by taking the difference in V_T after and before the 2013 and 2014 rain phase. The mass of the soil loss was calculated by multiplying the soil loss volume for each subsection (calculated using Eq. (3)) by the measured average bulk density of the soils (see Sect. 3).

The relationships between the change in gully headcut dimensions (lateral, headward and volumetric erosion) and the controlling factors (daily rainfall, cumulative rainfall, water table, drainage area, headcut height, and soil physical properties such as bulk density and soil texture) were analysed. Additionally, empirical relationships between the volumetric retreat (V) and the lateral (W) and longitudinal (L) retreat were developed.

2.2.2 Gully erosion dynamics from 2005 to 2013

To place the two-year gully expansion (Sect. 2.2.1) in a broader context, we measured, in addition, the gully dynamics over an 8-year period. Following the approach of Frankl et al. (2013), we determined the surficial land loss area due to gullying for the Debre Mawi watershed by digitizing all gully edges in Google Earth on aerial imagery flown on 6 Mar 2005 and 23 Mar 2013. This was not only done for the 13 gullies discussed above, but for all gullies found in the watershed (Table 1). The horizontal resolution of the imagery was 0.5 m.

Gullies were digitized by determining the location of each gully in the watershed using a hand-held GPS with a horizontal accuracy of about 3 m on August 2013, after which its coordinates were imported into Google Earth to situate all gullies on the aerial imagery. The gully edges were then digitized using Google Earth’s polygon mapping tool. Finally, the digitized polygons were converted to shape-file format using

ESRI's ArcGIS software, which was also used to calculate the surface area and the length of each gully. Since gully volume could not be obtained from aerial measurements, it was derived from the digitized gully surface area through a regression of the surface area and volume of the measurements of the 13 gullies with surface area in 2013 ranged from 260 to 14,050 m^2 (Table 2, Fig. S1a). The following regression equation was obtained.

$$V = 0.54\, S^{1.226} \qquad R^2 = 0.98 \tag{4}$$

where S is the gully surface area (m^2) obtained from Google Earth and V is the predicted volume (m^3) of the gully. The total gully volume for the entire watershed is then simply the sum of all individual gully volumes. The goodness of fit parameters (see Sect. 2.2.4) between measured volume and estimated (Eq. (4)) volume (Fig. S1b) are $R^2 = 0.98$, NSE = 0.99 and PBIAS = -0.8%. Obviously Eq. (4) is only valid in the sub-humid Debre Mawi watershed where the valley soils are deep and the depth is not restricted by bedrock. The area to volume relationship developed by Frankl et al. (2013) for gullies in the semi-arid Ethiopian highlands has a different form because of bedrock at shallow depth that limits the vertical growth.

2.2.3 Additional measurements to determine factors controlling gully expansion

Ground water elevation is believed to be one of the most important factors for gully formation and bank instability (Tebebu et al., 2010). Therefore, ground water depths were measured using a piezometer installed 5-10 m above each gully head (13 piezometers). Intrusion of silt and sand to the piezometer was prevented by wrapping filter fabric around the 40 cm-long screened bottom end. All piezometers were capped to prevent rainwater entry and were set in concrete to prevent any physical damage. Groundwater table elevations were read using a measuring tape twice a day: in the morning and in the evening.

Daily precipitation was measured at 5-minute intervals using an automatic tipping bucket, self-emptying rain gauge installed in the northern portion of the watershed. The drainage area (DA) above the gully heads was determined from topographic analysis in a geographical information system (GIS) using a digital elevation model (DEM) with 30 m horizontal resolution.

A total of 55 soil samples for bulk density (BD) and for textural analysis were collected from different soil layers along the profile of the sidewalls near the gully head (the number of layers varied from 3 to 5 depending on the gully depth). Samples for BD were collected with a 98-cm^3 (5 cm high) cylindrical core sampler. Soil samples were dried for 24 h at 105 °C, and bulk density was calculated by dividing the mass of the oven-dried soil by the volume of the core. The textural analysis was carried out using the hydrometer method after sieving (Day, 1965).

2.2.4 Statistical and uncertainty analysis

The statistical measures used to evaluate the goodness of fit of the empirical relationships were the coefficient of determination Eq. (5), the Nash-Sutcliffe efficiency Eq. (6) and percent bias Eq. (7):

$$R^2 = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2 (y_i - \bar{y})^2}} \tag{5}$$

$$NSE = 1 - \frac{\sum_i (y_i - x_i)^2}{\sqrt{\sum_i (y_i - \bar{y})^2}} \tag{6}$$

$$PBIAS = \frac{\sum_i (x_i - y_i)}{\sqrt{\sum_i y_i}} * 100 \tag{7}$$

where x_i and y_i are the predicted and the observed values respectively, and the overbar indicates their arithmetic mean value. The R^2 (ranges from 0 to 1) describes the degree of collinearity between predicted and measured data, and is sensitive to extreme values and insensitive to proportional differences. NSE is a normalized statistic that determines the relative magnitude of the residual variance (ranges $-\infty$ to 1). In general, based on Ritter and Muñoz-Carpena (2013), NSE > 0.65 is considered acceptable; NSE = 1 indicates a perfect fit, while an NSE < 0 suggests that the mean of the observed values is a better predictor than the evaluated model itself. PBIAS is the average tendency of predicted values with respect to their observed counterparts (ranges between -100 and +100). The optimal value of PBIAS is zero, with values close to zero indicating accurate model simulation.

In order to determine the uncertainty of the calculated gully expansion metrics, the following errors were considered: (1) error generated from using the average bulk density to calculate the mass of soil loss, (2) measurement errors of length, width and cross-sectional area of the gully, and (3) the accuracy of the drainage area estimated from the DEM.

We obtained the measurements errors as follows. The bulk density measurement error was equated with the standard deviation of all bulk density samples (three to five samples were taken for up to five layers of each gully). The absolute measurement error of the gully length and width was assumed to be related to tape measurement and was estimated at 0.1 m. The absolute measurement error of the cross-sectional area was 1 m^2 based on previous experience.

The absolute drainage area (DA) measurement error was mainly attributed to the accuracy of the DEM that was used to delineate the drainage area. For this, we used the relationship of the relative errors ($\%re_{DA}$) in 14 sub-catchments studied by Oksanen and Sarjakoski (2005), which is $\%re_{DA} = 11.3 \exp(-0.0006\ DA)$. The absolute error is then $e_{DA} = 0.113\ DA \exp(-0.0006\ DA)$.

To calculate the uncertainty of the surface area (S), volume (V) and soil loss (SL) of the gullies we used the method presented by Ku (1966) on the propagation error (e) as

$$e(x \pm y) = \left[(e(x))^2 + (e(y))^2 \right]^{1/2} \quad (8)$$

$$e(xy) = |xy| * \left[(e(x)/x)^2 + (e(y)/y)^2 \right]^{1/2} \quad (9)$$

where *e(x)* and *e(y)* are the absolute errors of the variables *x* and *y* that stand for either length, width, area, volume or bulk density. The absolute error for headcut retreat measurement in each gully was obtained by first calculating the absolute error for each gully segment using Eqs. (8 and 9). Finally, we used Eq. (8) to calculate the combined error from all segments in each gully (Table 3). The absolute relative error in predicting gully volume for the 13 gullies was obtained by subtracting the measured volume from the predicted gully volume using Eq. (4) and then dividing for each gully by the measured value. Then we calculated the combined error for the combined volumes of the 13 gullies using Eq. (8). The error in volume (e_v) calculated from the digitized surface area for all gullies in the watershed was estimated based on the errors calculated from the 13 gullies investigated in more detail. This relationship is as follows, ev =0.25 $S^{1.02}$

3 Results

3.1 Gully expansion rates at the watershed scale (2005 – 2013)

The expansion of the gully network in the Debre Mawi watershed significantly impacted the landscape (Table 1, Fig. S2). Based on the digitized aerial images of 2005 and 2013 we found that the total length of the gully network increased from 8.7 km in 2005 to 26 km in 2013 (Table 1, Table S1). The surface area taken up by the gully expanded from 4.5 ± 0.17 ha in 2005 to 20.4 ± 0.4 ha (or 3% of the watershed) in

2013 or equivalent to 2 ha yr^{-1}. Using Eq. (4), this represents a soil loss of about 0.80 ± 0.013 million ton which is equivalent to 127 t ha^{-1} yr^{-1} (Tables 1 and 2).

3.2 Expansion rates of the thirteen gullies (2005-2014)

In this section we discuss the 13 gullies (G1-G13) monitored in more detail. They have a combined watershed area of 200 ± 9.4 ha (Table 3). Measurements were used from both aerial imagery (up to March 23, 2013) and manual measurement (2013-2014 rain phases) (Table 2). The surface area of the thirteen gullies was 0.7± 0.05 ha in 2005 and expanded to a total of 3.8 ± 0.26 ha in 2014. The corresponding soil loss from these gullies between 2005 and 2014 was estimated at 156 ±9 thousand tons (Table 2). This is equivalent to 78 t ha^{-1} yr^{-1} (ranging from 7 to 350 t ha^{-1} yr^{-1} with standard deviation of 90 t ha^{-1} yr^{-1} for the individual gullies). During the last two years of the study (2013-2014), the land area lost due to the expansion of the 13 gullies was 0.17 ± 0.014 ha (Table 3), which is about 10 thousand tons of soil (of which about 60% or 47 t ha^{-1} occurred in 2013) and is equivalent to 25 ± 0.8 t ha^{-1} yr^{-1}. The soil loss of the individual gullies ranged from 14 ± 3 ton (1.5 ± 0.3 t ha^{-1} yr^{-1}) for G12 to 5445 ± 804 ton (205 ± 52 t ha^{-1} yr^{-1}) for G6 (Table 2). In 2014, the longitudinal growth of most gullies (G1, G2, G3, G6, G7, G10, G12 and G13) was significantly reduced resulting in less annual soil loss (Table 3).

The recorded precipitation during the 2013 rain phase (44 days of rainfall) was 917 mm and 2014 (31 days of rainfall) was 1107 mm (Fig. 4c). The gully headcut retreat in 2013 ranged from 0.04 to 36 m, with a combined total of 103 m (Fig. 4a, Table 3); whereas the total retreat in 2014 ranged from 0 to 7 m, with a combined total of 19 m (Table 3). Over these two monsoon seasons (2013-2014), about 608 ± 33 m^2 of cultivated land was consumed by only the longitudinal headcut retreat of the 13 gullies. This is equivalent to 36% of the increase in total surface area (both longitudinal and lateral retreat of the entire gully) of the 13 gullies during 2013-2014, and about 1.5% of the total surface area of the 13 gullies since their formation up to 2014. During 2013-2014, the soil loss solely due to headcut migration equalled 2875 ± 248 ton (Table 3), which represented 30% of the total soil loss from the 13 gullies in the same period presented in Table 2.

The total 2-year soil loss caused by the linear headcut retreat of the individual gullies varied from 0.9 (G7) to 1260 ton (G5) (Fig. 4b, Table 3). During 2013, only six of the 13 gullies (G3, G4, G5, G6, G8 and G11) actively expanded with lateral retreat (widening) varying from 3 to 11 m and a headward retreat varying from 6 to 36 m, while the other gullies remained fairly stable. The headcuts of gullies G3 and G8 migrated the farthest, 36 m and 24 m respectively, but only during the 2013 rain phase. However, because of the relatively shallow headcut depth (1.4 m) and narrow width (2.6 m) of gully G3, its headcut migration contributed little (only 7%) to the total soil loss of the 13 gullies (Fig. 4b). As shown in Fig. 4b, the four largest gullies (G5, G6, G8, and G11) were responsible for about 94% of the total soil loss from the 13 gullies. The relationships between the lateral and longitudinal retreat and the associated volumetric soil losses are discussed in Sect. 4.

3.3 Factors controlling gully headcut retreat and their relationships with gully dimensions (2013)

The linear headcut retreat of the gullies varied by more than an order of magnitude and was not related to geographic location. This variation should, therefore, be explained by other factors, including: groundwater elevation, soil physical properties (texture, bulk density, and porosity), gully head height, and drainage area (Table 3).

The correlation between the observed change in linear gully headcut retreat (R_L) and the precipitation recorded during the day of the gully head retreat occurrence varied between -0.23 and 0.88. Some of the big gullies such as G5, G6 and G11 showed strong correlation ($R_{L, G5} = 0.88$, $p = 0.009$ and $R_{L, G6} = 0.84$, $p = 0.017$), whereas gullies with the greatest linear retreat ($L_{G3} = 36$ m and $L_{G8} = 24$ m; Fig. 4a) showed weak relationships ($R_{L, G3} = 0.27$, $p = 0.55$ and $R_{L, G8} = 0.34$, $p = 0.37$). The fairly low correlation coefficient is likely caused by the time delay between daily rainfall and saturation of the soil surrounding the gully (Tebebu et al., 2010, Tilahun et al., 2013b). Saturation of the gully banks is principally responsible for destabilizing the gully head (Tebebu et al (2010). Due to such slow saturation processes, the daily precipitation and gully head retreat on the same day are not correlated well. This does not mean that precipitation was not related to retreat since the largest retreat rates were observed on 13 Aug 2013 after the maximum recorded daily rainfall (94 mm) on 7 Aug 2013 with little or no rainfall within this period (Fig. 4a).

The combined linear retreat (daily and cumulative) of the 13 gully heads in 2013 was compared with three different rainfall amounts: daily rainfall recorded during the retreat events, cumulative rainfall between gully head retreat events, and the cumulative rainfall since the beginning of the rain phase. The combined linear headcut retreat showed a moderate relationship with daily rainfall (R_L = 0.76, p = 0.13), but fairly strong relationship with cumulative rainfall between retreat events (R_L = 0.91, p = 0.01). Note that the relationship with daily rainfall was relatively high due to the retreat that occurred on 13 Aug 2013 during the largest rainfall event as discussed above. When this rainfall was excluded from the analysis, the correlation was reduced to R_L = 0.035 (p = 0.95). The combined cumulative linear retreat was highly correlated with the cumulative rainfall since the beginning of the rain phase (R_L = 0.99, p = 0.0001). This clearly indicates that cumulative rainfall, and thus gradual wetting and saturation of the soil, is more important to headcut retreat than the wetting and surface runoff from daily rainfall or individual storms.

The drainage area for the studied gullies varied from 0.7 (± 0.1) to 68 (± 7) ha with an average value of 15.4 ha and standard deviation of 18.9 ha (Table 3). In order to understand whether drainage area is related with both linear and volumetric retreat of the gully in 2013, simple linear regression models Eqs. (10 and 11) and power law relationships Eqs. (12 and 13) between drainage area (DA, in ha) and cumulative headcut retreat length (L, in m) and increase in gully volume (V, in m^3) were developed. Since rainfall in 2014 was less erosive and small gullies did not retreat, we did not use regression relationships for the 2014 rain phase.

$$L = 0.3DA + 3.15, (R^2 = 0.28, p = 0.06) \qquad (10)$$

$$V = 11.7DA - 13.2, (R^2 = 0.67, p = 0.0007) \quad (11)$$

Fitting a power law relationship between both the linear (L) and volumetric (V) gully retreat and drainage area yielded:

$$L = 0.21(DA)^{1.047}, (R^2 = 0.33) \quad (12)$$

$$V = 2.32(DA)^{1.26}, (R^2 = 0.48) \quad (13)$$

The predicted L and V using Eqs. (10 and 11) were compared linearly with the measured L and V. The goodness of fit parameters for the length L and volume V were R_L^2 = 0.28 (p = 0.06), NSE_L = 0.11 and $PBIAS_L$ = 52%, and R_V^2 = 0.69 ($p << 0.01$), NSE_V = 0.47 and $PBIAS_V$ = 49%, respectively. Similarly, the predicted L and V using a power type regression equations (Eqs. 12 and 13) were compared with the measured L and V. The goodness of fit parameters were R_L^2 = 0.33, NSE_L = -0.36 and $PBIAS_L$ = 98%, and R_V^2 = 0.48, NSE_V = 0.48, and $PBIAS_V$ = 49%. For both the linear and power type fitting the R^2 and NSE of the volumetric gully retreat were larger than those for the gully linear retreat.

Figure 5 shows the water table rose above the gully bottom for all 13 gullies during the rain phase, which indicates mostly saturated gully head and bank soils. In this study, the water table measurements were carried out twice a day (i.e., in the morning and evening).The groundwater table fluctuated between these readings (Fig. 5), but the variation was not significant (p = 0.98). The water table decreased between morning and evening readings on average by 0.7 cm with a standard deviation of 4.0 cm. The greatest fluctuations were observed at G2 (Fig. 5). The power type regression model between the minimum water table depth during the rain phase (ranging from 0.02 m at G3 to 1.5 m at G1) and the linear retreat and volumetric expansion of the 13 gullies had fairly high coefficients of determination with length, R^2_L= 0.62 and volume, R^2_V = 0.60 (Table 4).

By fitting a simple linear regression, the volumetric gully expansion was significantly related with the height of the gully headcut (R^2_V = 0.49, p = 0.007). However, the linear retreat of the gully was not explained by the headcut height (R^2_L = 0.0004, p = 0.9). The reason is likely the fact that gully G3, which had large linear retreat but small headcut height affected the analysis. When this gully is excluded from the analysis, the R^2_L for the linear and power relationship between the gully linear retreat and gully head height increased from 0.0004 to 0.26 (p = 0.09) and from 0.21 to 0.52, respectively. In this case, the gully height fairly well explained the linear retreat. Note, gully heads of lower height are relatively more stable than those with greater heights as the factor of safety for stability is, approximately, inversely proportional to gully head height. An equivalent increase in gully head stability can be obtained by regrading the gully head to a lower slope.

The major soil texture for all gully banks was clay-sized (53 to 67% with standard deviation of 4.5%), and an average bulk density of 1.2 ± 0.3 g cm^{-3} (Table 3). The gully head retreat rates were only weakly correlated with the texture (Table 4), probably because of the limited variation in soil texture. Linear regression and power type regression of clay content with the volumetric and linear headcut retreat were therefore not significant (Table 4).

4 Discussion

4.1 Effects of gully erosion on agricultural lands

Gully expansion affects the economic feasibility of soil conservation measures in reducing the amount of land available to farm. In 2013, the net gully area in the Debre Mawi watershed was 3% of the watershed area. If additional strips of 1 m width on each side of the gully area is not cultivated, the total area taken up by gullies becomes 5% of the total watershed area.

Most gullies in the watershed were not stable and impaired more than 16 hectares of agricultural land from 2005 to 2013. Gully expansion in the Debre Mawi watershed is not evenly distributed because the upper slopes of the watershed (about 50% of the watershed area) reduces gully formation mainly because it does not saturate (Tilahun et al., 2013b, Steenhuis et al., 2014; Tebebu et al., 2015). Gully expansion therefore affects mostly the bottomlands where soils become saturated around the beginning of July (Tilahun et al., 2013b). A loss of 2 ha of productive farmland per year is considerable for any farmer, but even more significant in a region with smallholder farmers. As farmers' land holding in the Ethiopian highlands is about one hectare of land per household (Sonneveld and Keyzer, 2003), the land loss observed between 2005 and 2013 could have provided farmland for 16 farming households in the watershed.

The rate of soil erosion (2005 - 2014) due to gully expansion in the sub-humid Debre Mawi watershed (127 t ha^{-1} yr^{-1}) is more than five times as much as the upland erosion reported by Tebebu et al. (2010) and Zegeye et al. (2010) in this watershed(Tebebu et al., 2010, Zegeye et al., 2010). The soil loss relative to the change in gully surface area is about 4000 t ha^{-1} yr^{-1} or 400 kg m^{-2} yr^{-1}, which is more than 2-fold the rate reported by Daba et al. (2003) for semi-arid eastern Ethiopia over a 30-year period. One of the reasons for the difference is that the gullies in the sub-humid Debre Mawi watershed are much deeper than in the semi-arid area studied by Daba et al. (2003). Another reason is that the soils are more often saturated in a humid climate than in semi-arid areas. Upland soil and water conservation practices are not effective for areas with gullies because sediment concentration in the runoff increased greatly, effectively negating any positive effect of upstream practices (Zegeye et al., 2015).

4.2 The relationship between gully headcut dimensions and their controlling factors

Table 5 lists the goodness-of-fit parameters Eqs. (5–7) of the power-law and linear regression relations between the change in gully volumetric headcut erosion (V), the top width retreat or lateral expansion (W) and the linear headward migration of the headcut (L). Both the power and linear regression analyses (Table 5) show that the volumetric gully expansion (V) was strongly related to top width retreat ($p < 0.01$), whereas no significant relation was found between V and L ($p = 0.36$). Similar results were obtained using a power law relationship (Table 5). Additionally, as shown in Table 1, the relative change between 2005 and 2013 in net gully area (350%) is more than 2-fold the relative change in length (199%). This indicates that sideways or lateral gully retreat is a more important mechanism of soil loss and gully expansion than linear migration of gully headcuts. Note that the R^2 value can sometimes be misleading, as indicated by the other goodness-of-fit parameters assessed. For example, the V-L power-law relationship for all 13 gullies has an $R^2 = 0.83$, which indicates a good fit between gully volume and linear gully extension. However, based on NSE and PBIAS (Table 5), the relationship between gully volumetric expansion predicted by the V-L equation ($V=18.3L^{0.91}$) and the observed volumetric expansion is not in the acceptable range (NSE = -0.004, PBIAS = -32.4). This indicates that assessing the quality of fits between gully expansion parameters cannot solely be done based on R^2, and that good fits also require other measures like NSE and PBIAS to be in the acceptable range.

Both the linear Eqs. (10 and 11) and power Eqs. (12 and 13) type regression relationships indicated that drainage area predicted the volumetric gully erosion (V) better than the linear headward migration (L) of the gully headcut. This suggests that the larger the drainage area, the greater the lateral expansion is by collapsing gully banks, and hence the greater the sediment production is. Studies in the semi-arid Ethiopian highlands with relatively shallow soils over bedrock have indicated that drainage area (which was not significantly related in the Debre Mawi catchment with deep soils) was a major controlling factor of gully head retreat (Poesen et al., 2003; Frankl et al., 2012).

Similar relationships were also developed by Vandekerckhove et al. (2003) for semi-arid southeast Spain ($V = 0.069\ DA^{0.38}$, $R^2 = 0.51$) and Frankl et al. (2012) for the semi-arid Tigray region in northern Ethiopia ($V = 0.53\ DA^{0.31}$, $R^2 = 0.27$). Note that in the Debre Mawi watershed, gully volume expansion is stronger related to drainage area than in southeast Spain and the Tigray region, as the power law exponent is about four times greater in the Debre Mawi watershed: the larger the exponent, the greater the increase in V per unit increase in drainage area (Frankl et al., 2013). The ratio of the volumetric expansion relations for Debre Mawi and the Tigray Region is 4.4 $DA^{0.95}$, which shows a near linear increase in this ratio with drainage area. For a gully draining 10 ha of land in the Debre Mawi watershed, the volumetric expansion is on average almost 40 times greater than that of a gully draining the same area in the semi-arid Tigray Region studied by Frankl et al. (2012). The greater retreat rates in Debre Mawi are caused by the rainfall amounts during the rain phase exceeding potential evaporation with excess water saturating the valley bottoms (see Sect. 3.3). In addition, the Vertisols soils are up to 10 m deep overlaying the bedrock. This combined with high ground water tables indicates the potential for erosion is greater in the Debre Mawi watershed compared with the drier semi-arid regions of Tigray and southeast Spain where soils are also thinner. These findings are in accordance with Frankl et al. (2013) that the establishment of relationships like Eqs. (12 and 13), are necessarily region-specific and only representative for similar environmental settings with respect to climate, topography, lithology, soil and vegetation.

4.3 Viable gully erosion control measures for the sub-humid Ethiopian highlands

Gully erosion can rapidly change landscapes as can be seen for instance for G6, G8 and G11 in Fig. 6. Gully G6 has expanded laterally into cultivated land through erosion of the right bank (west bank), whereas lateral erosion of the left bank, located on grass land, was rather limited. This decreased gully expansion on the grassed bank may be due to the effect of the grasses either in terms of increasing the topsoil shear strength (De Baets et al, 2008) or drying out the soil through evapotranspiration (Pollen and Simon, 2005) and thereby reducing soil saturation. Also, grasses could modify overland flow and infiltration patterns, and therefore affect subsurface drainage. Gully G11 was surrounded by cultivated land on both sides, and hence expanded laterally through erosion of both left (south) and right (north) banks. In 2012 the land adjacent to the left bank was planted with eucalyptus trees to halt erosion. In 2013, erosion of this left (south) bank was significantly reduced, and gully development then occurred through extension in north-eastern direction and lateral expansion in northern direction instead (see Fig. 6). The lesson learned from these two gullies

(G6 and G11) is that vegetation may reduce gully expansion by increasing soil shear strength through their roots, slowing down the storm runoff and trapping sediments which was also observed by among others Gyssels and Poesen (2003) and De Baets et al. (2006). Therefore, planting suitable species on the gully face and around the boundary may reduce or slow down bank failure and water-induced erosion especially for fairly deep gullies. In contrast to the above explanation, although both banks of G8 were surrounded by grasses (Fig.6), the gully head migrated uphill by about 25 m in two months. The reasons for this could be: 1) both banks were steep and deep enough for gravity-induced bank failure, and 2) the surrounding soil was highly saturated (Table 3) and bank layers near the bottom were more erodible than the overlying layer, causing a preferential retreat that undercut the bank and consequent cantilever failures (Figure S3).

Our monitoring data also contained valuable information regarding the effectiveness of soil and water conservation measures such as soil bunds that were extensively installed across the upper portion of the catchment since 2012. Dagnew et al. (2015) in the same watershed reported that soil bunds reduced runoff by 60%, sediment concentration by 36% and sediment load by 80%, which resulted in a significant reduction of runoff volume and sediment loads in the first two years of implementation. However, a reduction of downslope sediment concentration was not significant due to the presence of large gullies near the watershed outlet. Further, the SWC measures (soil bunds), aimed to reduce the development of rills and gullies in the area, were implemented on saturated Vertisol areas, and have rather led to gully initiation and development (see Fig. 1f; Steenhuis et al., 2014, Dagnew et al., 2015). These soil and water conservation measures appear to be ineffective on these locations as they cannot reduce or stop upslope gully headcut migration, which requires alternative, structural measures. Similarly, diversion waterways have been tested in the watershed to arrest gully heads, but have produced new gully branches (Zegeye, et al., 2014). Our data therefore supports the findings of Dagnew et al. (2015), which indicate that the extensive implementation of soil and water conservation measures on periodically saturated Vertisols areas may have exacerbated, rather than mitigated gully formation and expansion.

In the bottomlands of the watershed with Vertisols dominant, gully formation was severe due to alternate swelling and shrinking of expanding clays resulting in deep cracks in the dry season (Fig. 1c). As was previously observed by Frankl et al. (2012), the shrink-swell behaviour of Vertisols eventually developed into pipes (Fig. 1d) and contributed to gully development. Though pipes contribute to gully formation, we observed in this study that they are also important to drain excess subsurface water near the gully banks, thereby potentially mitigating gully expansion. For example, soil pipes in the heads of gullies G7 and G13 drained the elevated ground water table resulting in only minor headcut retreat (Table 3). This implies that gully expansion rates could be reduced by controlling the water table and therefore the pore-water pressures in the gully head (Zegeye et al., 2016). For example, drop pipes are a common practice in the United States (Field Office Technical Guide standard 587; NRCS, 2015) to control groundwater and surface water level to halt erosion of gully heads up to 15 m in height, but can be very costly (>$50,000 each). Moreover, most of the Debre Mawi watershed gullies are deep gullies (up to 7 m) that are therefore susceptible to gravity-induced bank collapse. Regrading the gully head and bank slopes decreases their weight and reduces the probability of bank failure (Langendoen et al., 2014, Zegeye et al., 2016).

In the semi-arid Tigray region of northern Ethiopia, Frankl et al. (2012) recommended the application of a subsurface geo-membrane (vertical dam) at the gully head to increase groundwater levels and subsequently decrease soil cracking and soil piping. However, this may not be effective in the (sub) humid region of Ethiopian highlands as we have shown that elevated groundwater tables increases the rate of gully expansion (Table 4, Fig. 1f). Therefore, gully mitigation measures in the sub-humid Ethiopian highlands and similar climate types should target to reduce soil water content.

5 Conclusions

Field observations in the Debre Mawi watershed indicate that permanent valley-bottom gully drainage networks and in particular gully widening and headcut retreat are important erosion processes severely impacting the productive farmlands.

Gully mapping and monitoring indicated that the continued gully incision, lateral expansion and headward extension are governed by the collapse of the gully head and sidewalls, and the subsequent removal of the failed materials by flowing water (Figs. 1 and 6). About 5% of the watershed area has been impaired by the expanding gully network. The gully expansion rate at the watershed scale between 2005 and 2013 was 127 t ha^{-1} yr^{-1} (Table 1). The headcut migration of the 13 gullies during the 2013 rain phase varied significantly from 0.04 to 36 m yr^{-1} (Table 3 and Fig.4).

Understanding the controlling factors of gully head migration and lateral expansion of gullies is crucial to design appropriate gully control measures. Retreat rates depended most strongly on groundwater table elevation (Table 4). The elevated water tables saturate the soils surrounding the gullies thereby reducing the soil erosion resistance. Elevated groundwater table may also lead to seepage-induced erosion. Additionally, the gully head depth and the drainage area, which is representative of surface runoff magnitude, were other factors controlling gully erosion in the Debre Mawi watershed (Table 4). Therefore, conservation practices that address these parameters may be most effective.

The lateral retreat for deep gullies contributes the most to the volumetric gully erosion in the Debre Mawi watershed (Table 5). Therefore, regrading the gully head and bank slopes could reduce the occurrence of gravity-induced bank collapse for deep gullies. Studies need to be designed to evaluate the effects of controlling groundwater movement, for example by subsurface drainage, on the stability of Vertisols. Vegetation may play a vital role in reducing soil water and increasing soil shear strength. The planting of an assemblage of suitable, native plant species (both herbaceous and woody) are tested in the watershed.

Author contributions

A. Zegeye, E. Langendoen, T. Steenhuis and S. Tilahun designed the experiments. A. Zegeye carried them out. A. Zegeye, E. Langendoen, F. Zimale and D. Dagnew analysed and interpreted the data. A. Zegeye, E. Langendoen, T. Steenhuis, C. Stoof, C. Guzman, B. Yitaferu and S. Tilahun supervised the research and cooperated on writing (editing, commenting, developing, formatting etc.) the manuscript.

Data availability

The supplementary data (excel, movie) for this manuscript are available online in: TIB AV-Portal Data Repository. doi: http://dx.doi.org/10.5446/18056

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Supplementary material

Table S1a: Measured length and area of the gullies in the Debre Mawi watershed obtained from Google image in 2005. The volume was calculated with equation Eq. (4) in the manuscript: Vp = 0.54 A1.1226, where Vp is predicted volume and A is area of a gully. The soil loss was calculated as Vp times average bulk density (1.2 g cm-3).

Table S1b: Measured length and area of 245 gullies in the Debre Mawi watershed obtained from Google image in 2013, arranged in ascending order of their surface area in five columns. The total calculations in each column is given at the end of the table and the total magnitude of 245 gullies is presented at Table 1 in the manuscript. The volume was calculated with equation Eq. (4) in the manuscript: $V_p = 0.54\ A^{1.1226}$, where V_p is predicted volume and A is area of a gully which was obtained from the regression relation between measured volume and area of the 13 gullies (Figure S1a). The soil loss (SL) was calculated as V_p times average bulk density (1.2 g cm^{-3}).

Figure S1**.** a) The measured volume versus gully surface area for the13 gullies. The regression equation obtained in this relationship was used to estimate the volumes of all gullies in the Deebre mawi watershed presented at Table 1 in the manuscript, Table S1, in the supplementary table, whose surface areas were digitized from Google in 2005 and 2013, (b) the predicted volume obtained using the equation obtained in (a) or Eq. (4) in the manuscript, versus measured volume of the 13 gullies

Figure S2: The relationship between gully formation locations and topographic wetness index (TWI), and gully expansion rate between (a) 2005 and (b) 2013 in the Debre Mawi watershed, Ethiopia. Lines represent gully edges digitized from aerial imagery.

Figure S3: The picture shows that bank layers near the bottom were more erodible than the overlying layer, causing a preferential retreat that undercut the bank and consequent cantilever failures. The picture was taken at the headcut of gully G8 by the author in July 2013.

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Tables

Table 1. The combined length, area and volume of the total gully network in the 608 ha Debre Mawi watershed obtained from satellite imagery in 2005 and 2013. The “soil loss” in the last column represents the total soil loss from the gully network preceding the date of measurements and is calculated as the gully volume in column 4 times the bulk density. Errors were estimated using Eqs. (8 and 9).

Year	Gully length	Gully area	Gully volume	Soil loss
	km	ha	10^3 m^3	10^3 t
2005	8.7	4.5	140	168
Estimate error in 2005		0.17	3.5	5
2013	26.0	20.4	654	784
Estimated error in 2013		0.4	0.87	13
Increase from 2005-2013	17.3	15.9	514	616
Relative change, % 2005-2013	199	350	366	366

Table 2. Increase in surface area and corresponding soil loss of the 13 gullies in the Debre Mawi watershed in the period between 2005 and 2014. Surface area up to March 2013 was obtained by digitizing the gully edges on aerial imagery and the next two rain phases by manual measurement.

Gully name	Gully surface area (m^2) From aerial image				Manual measurement		Bulk density ($g\ cm^{-3}$)		2005 - 2014						2013-2014			
	6/3/05	4/5/11	3/4/12	23/3/13	18/9/13	18/10/14	measured	Error	Change in area	Error (m^2)	Change in	error (m^3)	Soil loss (t)	Error (t)	Change in volume (m^3)	Error (m^3)	Soil loss (t)	Error (t)
G1	140	265	390	420	440	440	1.26	0.02	300	42	709	84	894	107	52	9	66	11
G2	785	2700	3330	3560	3573	3575	1.19	0.02	2790	395	10354	817	12321	1005	63	11	75	13
G3	210	530	600	1430	1460	1460	1.14	0.05	1250	177	3712	360	4232	447	103	18	117	21
G4	230	400	450	750	780	785	1.17	0.11	555	78	1488	157	1740	244	104	18	122	24
G5	2820	10700	11500	13700	13960	14050	1.16	0.04	11230	1588	56511	3383	65553	4618	2000	346	2320	411
G6	1720	6770	8100	9110	9580	9960	1.22	0.18	8240	1165	38076	2467	46453	7492	4463	773	5445	1239
G7	110	365	365	385	390	390	1.15	0.05	280	40	639	78	735	95	13	2	15	3
G8	365	2140	2860	3740	3850	3890	1.19	0.09	3525	498	12856	1038	15299	1674	640	111	762	143
G9	40	730	1050	1120	1150	1180	1.19	0.09	1140	161	3102	328	3691	485	195.3	34	232	44
G10	50	190	400	455	460	460	1.25	0.11	410	58	928	116	1160	180	13	2	17	3
G11	152	600	750	890	1020	1070	1.23	0.07	918	130	2540	263	3124	363	565	98	695	126
G12	50	170	240	255	255	260	1.22	0.06	210	30	428	58	522	75	12	2	14	3
G13	199	240	345	365	370	370	1.14	0.05	171	24	405	47	462	58	13	2	14	3
Total	6800	25800	30380	36180	37288	37890	1.19	0.30	31019	2091	131748	4432	156186	9053	8236	861	9894	1321

Table 3. List of soil and gully topographic factors for the 13 gully heads in the Debre Mawi watershed, and observed gully head erosion during the 2013 and 2014 rain phases (between July and September). BD is bulk density and DA is drainage area.

Gully name	Min. water table depth (m)	Clay content (%)	Mean bulk density (g cm^{-3})		head cut depth (m)	Drainage area (ha)		Linear headcut retreat(m)		Area retreat (m^2) 2013-2014		Volumetric retreat (m^3) 2013-2014		Soil loss (t) 2013-2014	
			measured	error		measured	error	2013	2014	measured	error	measured	error	measured	error
G1	1.50	58	1.26	0.02	3.9	12.8	1.44	0.4	0	3.3	0.46	9	1.5	11	2.0
G2	1.22	53	1.19	0.02	2.2	13	1.46	2.2	0.5	10.9	1.32	32	5.3	38.5	6.4
G3	0.02	55	1.14	0.05	1.4	41.6	4.59	36	0	22.5	3.17	146	25.3	167	29.7
G4	0.59	59	1.17	0.11	2	1.7	0.19	7	5	15.7	1.57	61	7.9	72	11.3
G5	0.05	60	1.16	0.04	4.8	68	7.38	10	3	101.5	10.16	1087	167	1260	199.4
G6	0.08	67	1.22	0.18	4.6	13.3	1.49	12	0	182.0	25.66	413	71.5	504	114.7
G7	1.36	59	1.15	0.05	1.4	0.7	0.08	0.2	0	0.7	0.09	1	0.1	0.9	0.2
G8	0.07	56	1.19	0.09	3.3	17.4	1.95	24.4	7	108.9	12.10	237	34.5	281	46.1
G9	1.20	59	1.19	0.09	3.4	6.8	0.77	3.8	1.65	21.2	2.46	73	9.5	87	13.2
G10	1.44	55	1.25	0.11	2.5	6.5	0.73	0.7	0	2.7	0.38	6	1.0	7.5	1.5
G11	0.45	66	1.23	0.07	4.2	9.2	1.03	6.2	1.4	123.4	14.17	356	55.6	437	72.2
G12	1.38	66	1.22	0.06	1.9	4.1	0.46	0.07	0	5.0	0.71	3	0.6	4	0.7
G13	1.25	60	1.14	0.05	1.3	4.8	0.54	0.04	0.8	10.1	1.18	3	0.5	2.8	0.6
Total /Ave	**0.82**	**59.5**	**1.19**	**0.30**	**2.84**	**200**	**9.4**	**103**	**19**	**608**	**33.6**	**2427**	**195**	**2873**	**248**

Table 4. Power type and linear regression equations of the longitudinal headcut retreat, L, and the volumetric gully expansion, V, with the controlling factors, X, listed in the first column: L or V = aX^b. The goodness of the fit is represented by the coefficient of determination, R^2.

Controlling factors (X)	$L = aX^b$			For linear regression equation of L with (X)		$V = aX^b$			For linear regression equation of V with (X)	
	a	b	R^2	R^2	p-value	a	b	R^2	R^2	p-value
Water table	0.73	1.11	0.62	0.64	0.001	12.7	1.09	0.60	0.49	0.009
Drainage area	0.21	1.047	0.33	0.28	0.06	2.32	1.26	0.47	0.67	0.0007
Headcut depth	0.25	2.16	0.21	0.0004	0.9	1.57	3.24	0.47	0.49	0.007
Clay content	110.7	-1.05	0.023	0.05	0.46	0.000	4.04	0.018	0.08	0.35
Bulk density	5.73	-6.2	0.008	0.13	0.23	26.8	1.28	0.0004	0.02	0.67

Table 5. Relations of the volumetric gully headcut erosion (V) with the headward migration length (L) and the lateral erosion (W) during the 2013 rain phase for the 13 gullies in the Debre Mawi watershed. The observed gully volumes were fitted as functions of L or W using power-law and linear regression models. V–W or V–L refers to V as a function of W or L, respectively.

Relationship	Power law relationship ($V = a\,x^{b}$)			Predicted versus measured		
	a	b	R^2	R^2	NSE	PBIAS
V–W	0.65	2.15	0.63	0.63	0.89	-21
V–L	18.3	0.91	0.83	0.83	-0.004	-32.4

	Linear regression ($V = mx + n$)				Predicted versus measured		
	m	n	R^2	p	R^2	NSE	PBIAS
V–W	33	-115	0.87	6.2E-06	0.89	0.88	11
V–L	6.9	112	0.07	0.36	0.08	0.08	0

x represents W or L; a, b, m, and n are constants.

Figure captions

Fig. 1. Examples of gully expansion controlled by: (a, b) bank geometry (height and slope), (c) tension cracks, (d) land slide, (e) soil pipes and (f) saturated vertisols (gully development on conservation ditches, narrow ditch upstream of gully headcut) in the sub-humid Debre Mawi (a,b,d, and f), Mota (c) and Geregera (e) watersheds (pictures taken in 2013).

Fig. 2. Location of the Debre Mawi watershed within the Blue Nile River basin, Ethiopia (top figures). The watershed map (bottom) shows the contour lines, elevation, stream lines, and the 13 studied gullies (indicated by the labels beginning with the letter G). Projected Coordinate System: WGS_1984_UTM_Zone_37N

Fig. 3. (a) Cross section segmentation methodology to determine the cross-sectional area of the gullies. (b) Measured profiles of a cross-section located on gully G6 during the 2013 rain phase, showing the lateral and downward expansion of the gully.

Fig. 4. The observed expansion of the 13 study gullies in the Debre Mawi watershed (see Fig. 2 for gully location): (a) cumulative headcut retreat and rainfall during the 2013 rain phase, (b) increase in gully surface area and volume during the 2013 and 2014 rain phases, and (c) increase in the combined gully surface area and the total summer rainfall (RF) between 2011 and 2014.

Fig. 5. Comparison of minimum groundwater table depth, gully headcut depth and the average groundwater fluctuation between morning and night for the 13 study gullies in the Debre Mawi watershed, Ethiopia for the 2013 rain phase.

Fig. 6. Examples of gully expansion in the Debre Mawi watershed: (Top photo) expansion of gullies G8 and G11 during the 2013 rain phase, the trees which were upstream of the two gullies felled down in to the gullies; (Bottom image) expansion of gullies G6 and G11 between 2005 and 2013.

Figures

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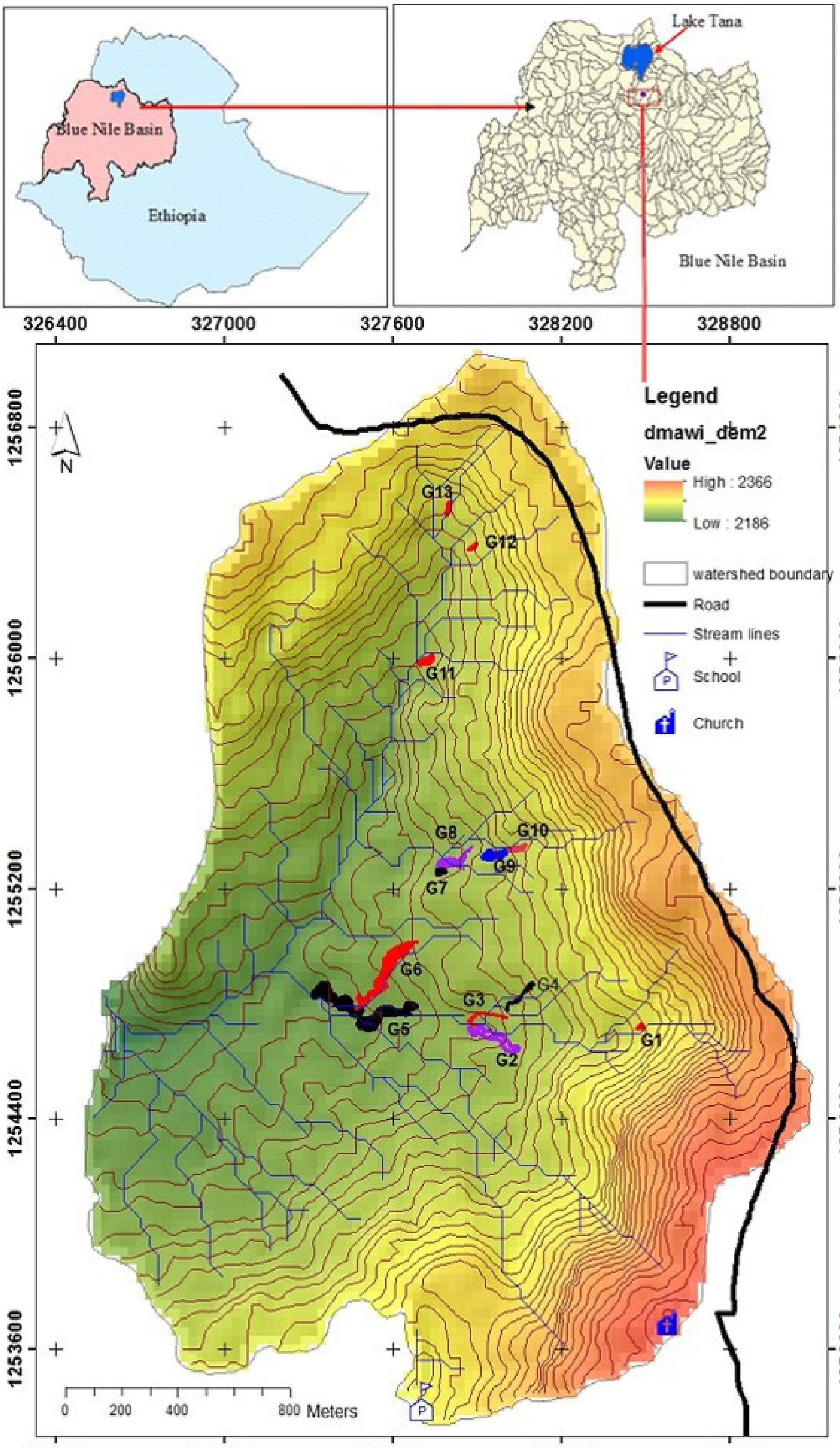

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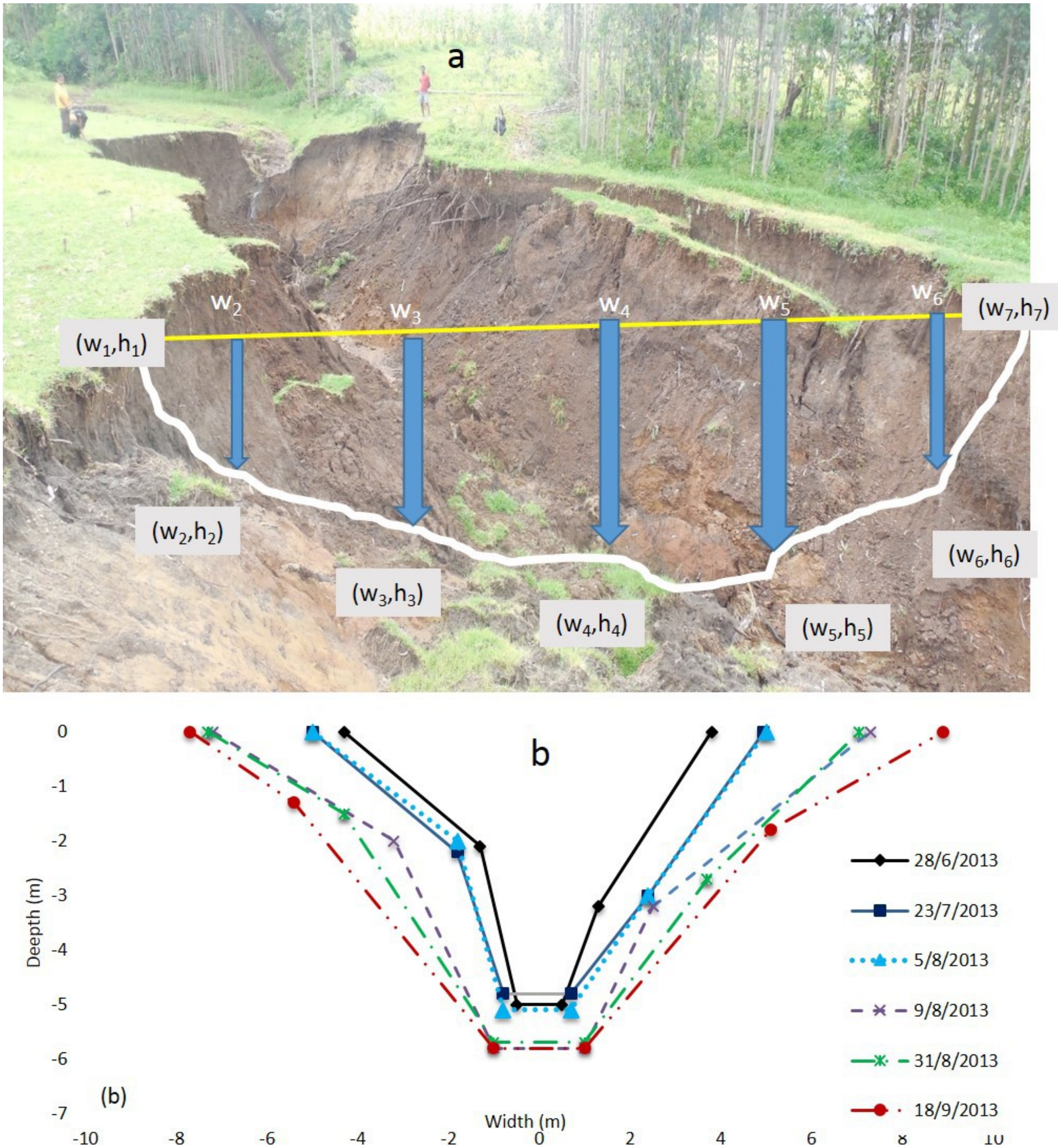

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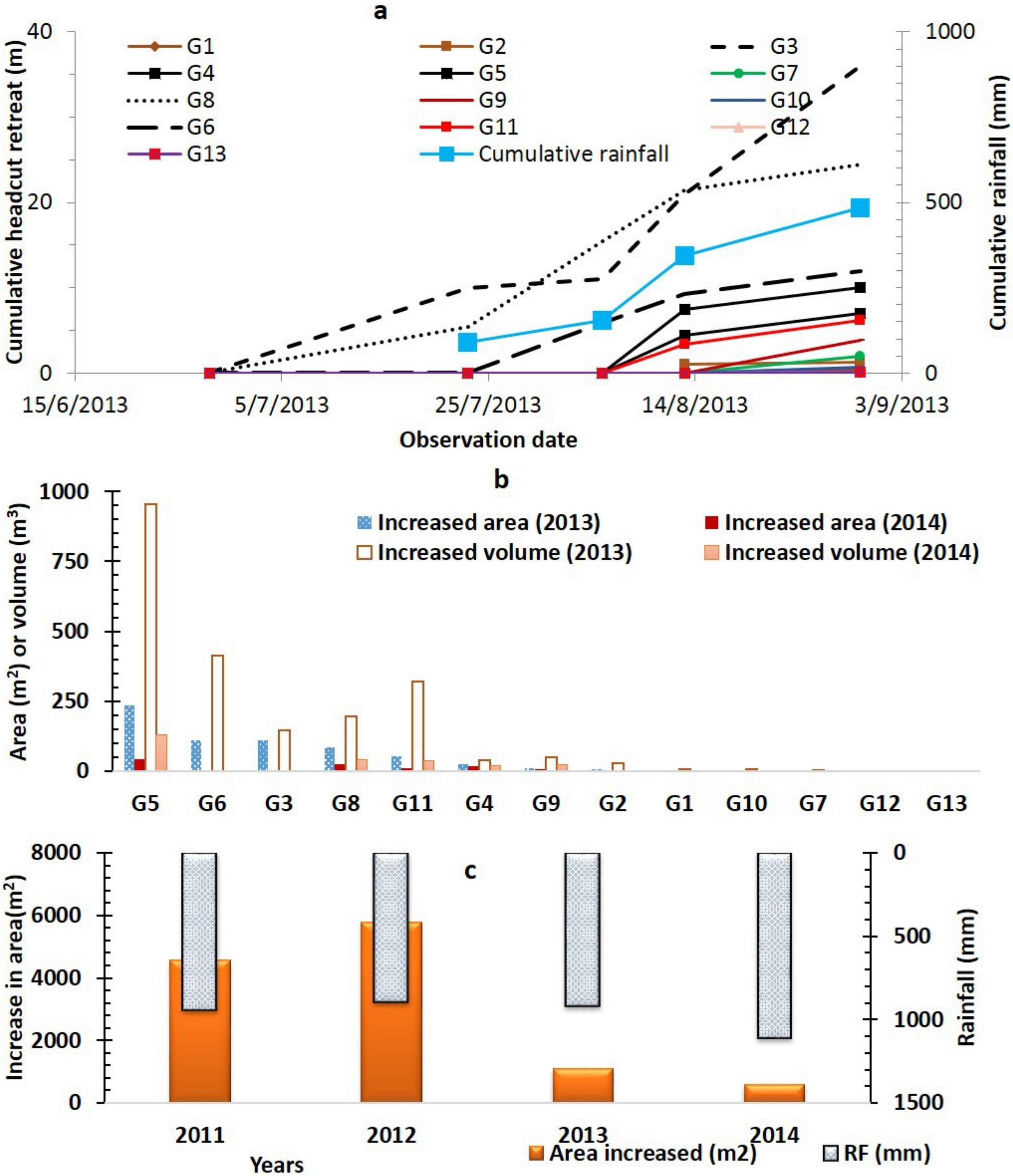

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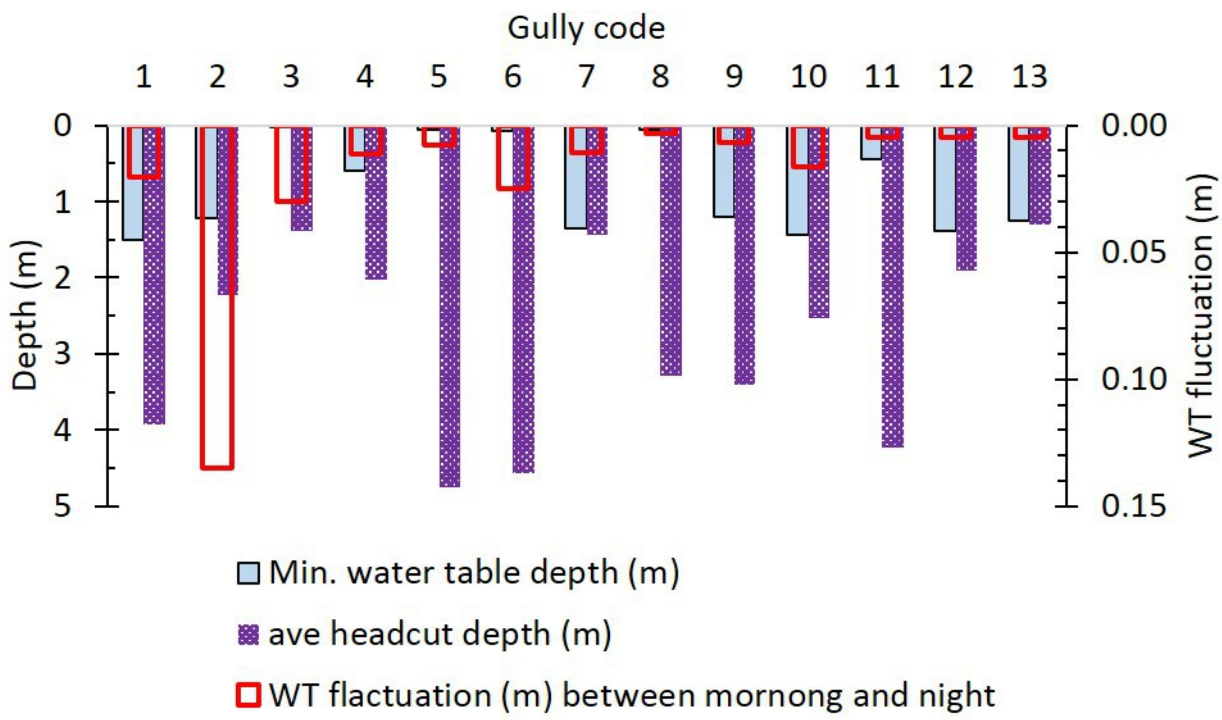

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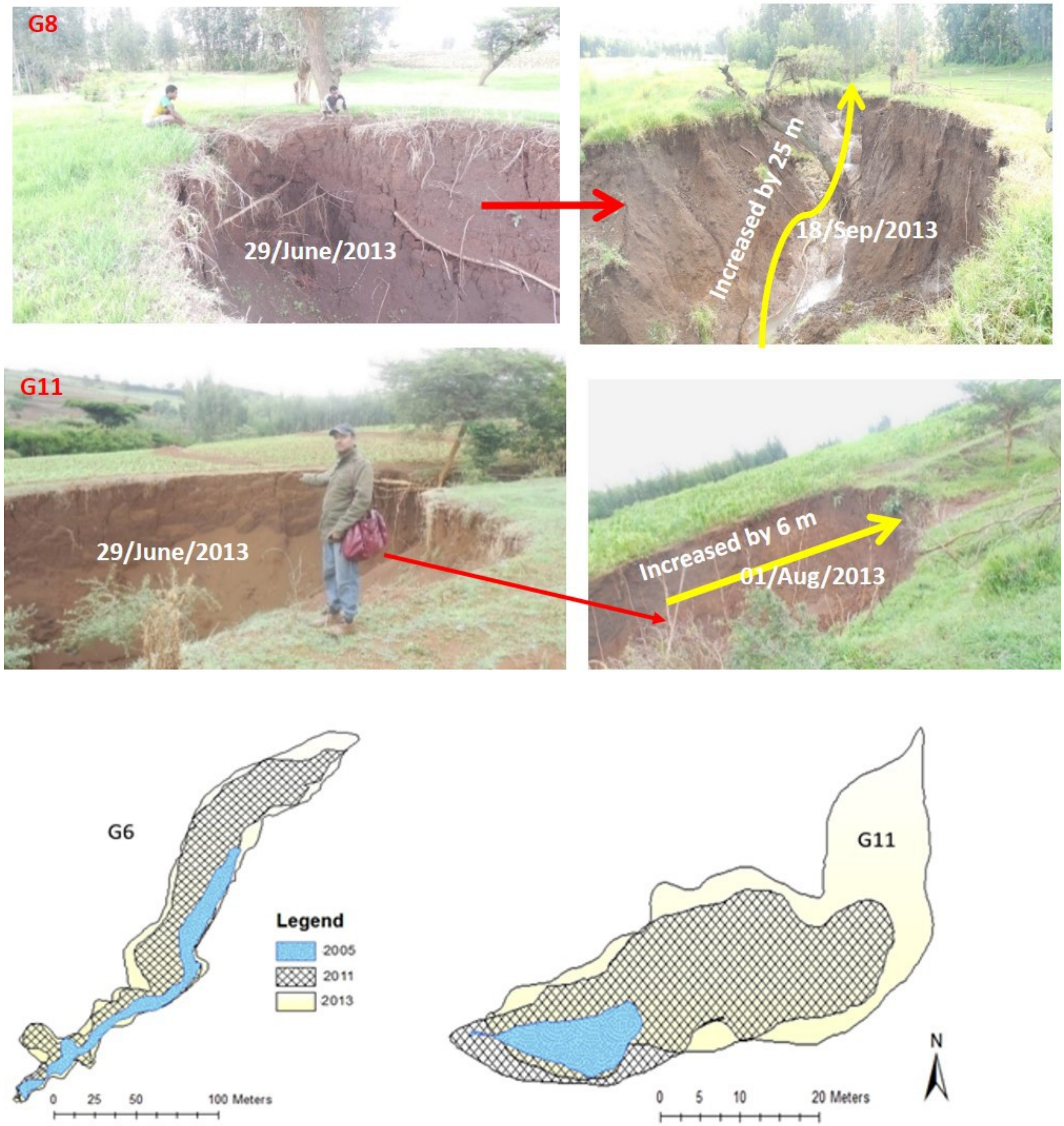

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