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Gully head retreat rates in the semi-arid Highlands of Northern Ethiopia

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Abstract

Due to overgrazing and agricultural intensification, gully erosion severely affects sub-Saharan countries; however, insufficient quantitative studies exist for this part of the world. This paper presents data on gully head retreat rates in Northern Ethiopia and relates these rates to gully and environmental characteristics. The monitoring of headcuts over one rainy season (2010) revealed that present-day retreat rates are low, with average annual linear (R_l), areal (R_a) and volumetric (V_e) retreat rates of 0.34 m y^{-1} , $1.70 \text{ m}^2 \text{ y}^{-1}$ and $5.2 \text{ m}^3 \text{ y}^{-1}$, respectively. These results express the positive effects of recent soil and water conservation practices on gully stabilization. Significantly higher values of R_l (up to 1.93 m y^{-1}) occurred in the Vertisol areas affected by soil piping. When considering the medium- to long-term time scale (1–47 years) using archival terrestrial (and aerial) photographs, headcut retreat rates proved to be significantly higher than those in the short-term. The averages for R_l , R_a and V_e are 3.8 m y^{-1} , $31.5 \text{ m}^2 \text{ y}^{-1}$ and $47.7 \text{ m}^3 \text{ y}^{-1}$, respectively. Retreat rates are up to 10 times higher after road construction. On the medium- to long-term time scale, headcut retreat rates were positively related to the catchment area (A). A power relationship that best describes the relation between V_e and A is $V_e = 0.53 A^{0.31}$ ($r^2 = 0.27$, $n = 18$). Compared to other areas worldwide, regressive erosion has been rapid in Ethiopia as a result of the degraded and steep landscape combined with erosive rains and the occurrence of Vertisols. In Vertisols, headcut retreat is

controlled by soil piping. Because no adequate techniques exist to control gully initiation and development in Vertisols, alternative techniques should be developed that deactivate soil pipes.

Key words: Africa; Gully Erosion; Headcut Retreat; Northern Ethiopia; Repeat Photography; Vertisol.

1 Introduction

In Sub-Saharan Africa, gully erosion (Poesen et al., 2003) causes severe land degradation, which, in turn, disrupts the often-poor local communities. Gullies impede agricultural activities, while the reduction of water tables, caused by the incision of gullies, reduce agricultural production. Once deepened, gullies decrease the accessibility of the land and can cause severe damage to infrastructure. Human life and health is potentially endangered by bank failures, the flooding of valley bottoms and water pollution caused by sediment and urban wastewater. In developing countries, urban wastewater is generally diverted straight into gully systems.

Reported cases of gully erosion indicate that both urban and rural areas are affected in many African countries, e.g., Burkina Faso (Marzoff and Ries, 2007), the Democratic Republic of Congo (DRC; Ndonga and Truong 2011), Ethiopia (Frankl et al., 2011), Kenya (Oostwoud Wijdenes and Bryan, 2001; Katsurada, 2007), Lesotho (Showers, 1996); Namibia (Eitel et al., 2002), Niger (Leblanc et al., 2008), Nigeria (Gobin et al., 1999), Rwanda (Moeyersons, 1991), Senegal (Poesen et al., 2003), South Africa (Boardman et al., 2003), Swaziland (Felix-Henningsen et al., 1997) and Zimbabwe (Stocking, 1980). In these regions, gully erosion is mainly related to the degradation of the vegetation cover, as a consequence of overgrazing, and the intensification of agriculture. This increases the runoff response of the land, often resulting in flash floods in semi-arid areas. Another major cause of gully erosion is runoff concentration resulting from modifications in the natural drainage pattern near settlements or roads. In urban areas, such as Kinshasa (DRC), the careless deforestation and urbanization of slopes has led to deep gullies in the midst of residential areas. Extreme examples of gully erosion are recorded for Southeast Nigeria (Poesen et al., 2003). Since the second half of the twentieth century, gullies reaching the unusual depth of 50 m have developed as a result of the degradation of the vegetation cover and the establishment of artificial drainage networks (near roads). In the Great Karoo in South Africa, gullies reaching up to eight meters deep originated as a result of overgrazing in the period between 1937 and the 1960s (Boardman et al., 2003). In the Southwestern Sahel in Niger, the drainage density almost tripled between 1950 and 1992 (from 6 to 15 m ha⁻¹; Leblanc et al., 2008). In Northern Ethiopia, gully systems were re-activated and expanded from the 1960s onwards as a result of intensified land use and a series of droughts in the 1970s and 1980s (Frankl et al., 2011). Gully systems that developed have a drainage density of approximately 25 m ha⁻¹, which is one of the densest networks in the world, with gullies that are ten to fifteen meters deep.

Despite the development of important gully networks in Sub-Saharan Africa, quantitative research on gully headcut erosion rates is very limited. In Kenya, Oostwoud Wijdenes and Bryan (2001) studied eleven gully heads over a period of three years and found linear headcut retreat rates that varied between 0.8 and 15 m y⁻¹. During the same period, linear gully head erosion rates in Burkina Faso varied between 3.16 and 9.85 m y⁻¹ for two gully heads (Marzolff and Ries, 2007). Although several studies reported significant gully erosion in Ethiopia (Virgo and Munro, 1978, Nyssen et al., 2000, 2002, 2004, 2006; Billi and Dramis, 2003; Daba et al., 2003; Moges and Holden, 2008; Munro et al., 2008; Reubens et al., 2009), there is insufficient data on gully head retreat rates, the size of the area affected by retreating gullies and the sediment volumes produced by gully head erosion in Ethiopia. This finding is especially true for the large areas covered by Vertisols, which are susceptible to soil piping. Vertisols are churning, heavy clay soils that are rich in swelling clays and cover 2.4% of the global land surface area (311 million ha), mainly in Sudan, Ethiopia, India and Australia (FAO, 2007). They are usually found in lower landscape positions on (weathered) deposits that are rich in smectitic clays (e.g., Sudan) or on extensive basalt plateaus (e.g., Ethiopia), and they typically cover large surfaces suitable for agriculture (an estimated 150 million hectares worldwide; FAO, 2007). Vertisols especially develop in the semi-arid tropics, where the precipitation ranges from 500 to 1000 mm y⁻¹ and the climate is marked by dry and wet seasons, which are favorable for the periodic shrinking and swelling of the soil (FAO, 2007). Soil piping is recognized as an important reason for the development of gullies (Valentin et al., 2005). For Vertisols, this development is related to the periodic shrinking and swelling. In a dry Vertisol, shrinking results in the development of wide cracks, which can reach up to two meters deep. Runoff water subsequently infiltrates into the subsoil (bypass flow) and drains underground. Intense subsurface erosion of the dry, dispersive clays results in the development of soil pipes, which, once collapsed, initiates gullies (Fig. 1). When a Vertisol gets wet, swelling causes cracks to close, and the Vertisol becomes almost impermeable. Consequently, the runoff production is very high, and large runoff volumes drain through pipes to the gully heads.

Few studies exist on the importance of soil piping in the development of gullies; for example, these studies have been performed only in Lesotho (Faber and Imeson, 1982), Spain (Ries and Marzolff, 2003; Faulkner et al., 2004) and Southwest USA (Parker, 1963; Swanson et al., 1989). For Southern Ethiopia, Moges and Holden (2008) stress the importance of soil piping in valley bottom deposits for the initiation and development of gullies. In Northern Ethiopia,

Nyssen et al. (2000) indicate that piping is important for the development of gullies in Vertisols.

When considering techniques to study headcut retreat, most studies rely on monitoring by fieldwork (e.g., Oostwoud Wijdenes and Bryan, 2001; Wu and Cheng, 2005) or small-scale aerial photographs and their Digital Elevation Model derivatives (e.g., Martinez-Casasnovas et al., 2004; Parkner et al., 2006; Marzolff et al., 2011). In several cases, topographical maps (e.g., Radoane et al., 1995), dendrochronology (e.g., Vandekerckhove et al., 2001) or interviewing local residents serve as a basis (e.g., Nyssen et al., 2006; Moges and Holden, 2008). For a more complete overview, refer to Poesen et al. (2003). In a recent study, Frankl et al. (2011) showed that repeat terrestrial photography can also be of great value for studying gully erosion development, although this technique was rarely used previously. When recording gullies, historical photographs provide clear insights into the expansion, size and activity of gully networks. Furthermore, historical terrestrial photographs are often available for periods far before aerial photography data were available, and they can be used to increase the observation density in-between aerial photography surveys.



Fig. 1. Gully erosion initiated by soil piping in a Vertisol near May Mekdan (see Fig. 2, August 2010). The soil pipe inlet is located directly in front of the person standing and connects to the 4 m deep gully in the background.

The objective of this study is to quantify short-term and medium-to-long-term (1-47 years) gully head erosion rates using, among other methods, terrestrial repeat photography. The linear headcut retreat, the size of the surfaces affected by the gully head retreat, as well as the volumes of sediment produced are quantified, and the erosion rates are related to gully and environmental factors. Particular attention is devoted to the effects of soil piping, which in Ethiopia, occurs in Vertisols, and to the impact of new road infrastructure on gully head erosion.

2 Materials and methods

2.1 Study area

The area of study (13°23'N, 14°05'N – 39°08'E, 39°36'E) covers an area of 50 km x 75 km near the city of Mekelle in Northern Ethiopia (Fig. 2). This region is part of the source area of the Atbara River and features a young accidental relief between 1400 m and 2800 m a.s.l. The lithology consists mainly of (sub)horizontal strata of sandstone, limestone and basalt that have been uplifted with the formation of the East African Rift (Williams and Williams, 1980). The semi-arid climate is characterized by a major dry season lasting from October until March. The rainy season peaks from July until the beginning of September. The annual precipitation is approximately 700 mm y⁻¹ and usually takes the form of heavy showers that seldom last longer than ten minutes (Nyssen et al., 2005). Compared to other regions in the world, rain erosivity is mainly due to the large raindrop sizes rather than high rainfall intensities because 88% of the rain falls with an intensity less than 30 mm h⁻¹ (Nyssen et al., 2005). The volume-specific kinetic energy (Ek_{vol}) (in J m⁻² mm⁻¹) is defined by $Ek_{vol} = 36.65(1 - (0.6/I))$, with I representing the rain intensity in mm h⁻¹ (Nyssen et al., 2005). Young soils prevail in the study area (HTS, 1976). Leptosols are found in high landscape positions, while Regosols or Cambisols occur on steep slopes. In footslope positions, fine-textured soils are found with undifferentiated Vertisols and typically exceed one meter in thickness on basalt or basalt colluvium, and Calcisols are found on limestone. In remnant forests, Phaeozems occur (Descheemaeker et al., 2006). Far-reaching deforestation and overgrazing explain why the vegetation cover in Northern Ethiopia is low. The original Afro-Montane forest only appears as patches around churches. During the last twenty years, however, critical zones were selected, where vegetation is now protected against logging or grazing (Descheemaeker et al., 2006). Today (in the year 2011), such enclosures cover 10% to 15% of the land surface. Land degradation is severe in Northern Ethiopia, where significant soil losses occur because of sheet, rill and gully erosion (Nyssen et al., 2009a). Gullies affect nearly all slopes and all surfaces. During the last twenty years, measures have been taken to reduce the runoff response and soil erosion of the land, such as the terracing of slopes, demarcating enclosures and the construction of check dams in gullies (Nyssen et al., 2004). As a result of these measures, 23% of the gully and river network is currently stabilized (Frankl et al., 2011).

A detailed study of gullies was conducted in May Ba'ati (Fig. 2), which contains the small headwater basin (4 km²) characteristic of the Northern Ethiopian Highlands. The topography, comprising a steep sloped, flat-topped *amba* relief, lies between 2100 and 2550 m a.s.l. Slope gradients vary between 0.03 and 0.56 m m⁻¹. Cliff-forming layers of limestone and sandstone have developed structural flats. On top of these flats are Vertisols that developed in basalt (colluvium) and cover 10% to 15% of the area, which is completely under arable land. Land

use consists mainly of cropland. Twelve percent of the area is covered by forests or exclosures, which are typically located on the steepest slopes. Rangeland covers 8% of the area. The population density is approximately 200 persons km⁻² (Stock, 2011).

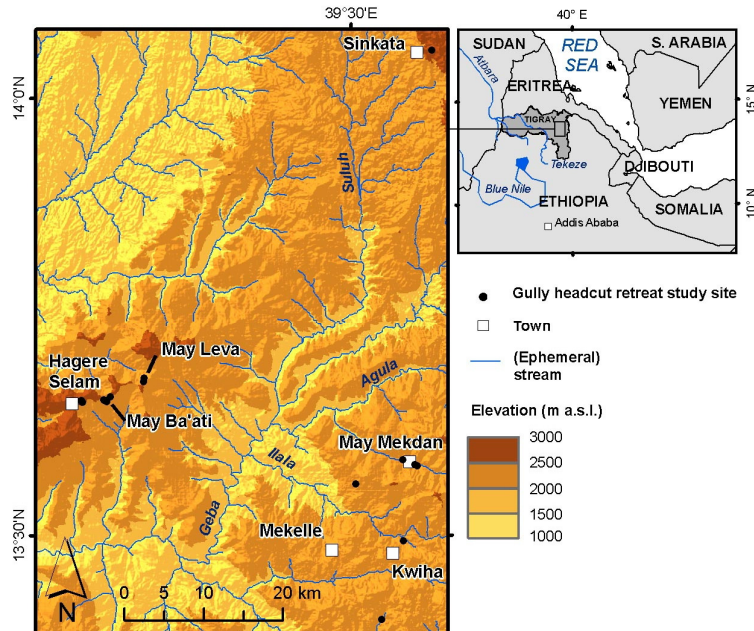


Fig. 2. Gully headcut retreat study sites. Oro-hydrography based on SRTM data (<http://srtm.csi.cgiar.org>).

2.2 Monitoring short-term gully headcut retreat

Between July 9, 2010 and September 5, 2010, the linear, areal and volumetric headcut retreat rates were measured for 24 gully heads in May Ba'ati (Fig. 2). These measurements can be equated to the annual headcut retreat rate for three reasons: (1) 71±7% of the annual precipitation occurs within the rainy season, between July 1 and September 15, calculated over the period of 1998-2006 for the nearby station of Hagere Selam (MU-IUC, 2007). In 2010, September 5th marked the abrupt end of the rainy season because no rainfall occurred between September 5th and September 15th when the field was last visited. (2) During the dry season and the early rainy season (September – June), rainfall events generate limited runoff (rarely entering gullies) because infiltration rates in the dry (cracked) soils are significantly high. (3) Observations in late July 2011 showed that practically no change occurred at the gully heads since the last measurement was obtained on September 5, 2010. Consequently, this allowed for the assessment of present-day (short-term) gully head activity.

Daily linear headcut retreat rates L (m d^{-1}) were established by taking daily measurements of the distance between the most upslope branch of the gullies and a fixed upslope point, such as the trunk of a shrub or a marked rock. Summing the values of L over the monitoring period provided us with the annual linear headcut retreat rates (R_l , m y^{-1}). The volumetric headcut retreat rates (V_e , in $\text{m}^3 \text{y}^{-1}$) were obtained by subtracting the volume of the gully heads at the beginning of the rainy season from the volume of the headcuts at the end of the rainy season. The volume, in turn, was determined by multiplying the gully head length and the average cross-sectional area of the headcut. Two to four channel cross-sections were positioned in the field by paint-marked rock fragments or wooden stakes. From the changes in the gully length and the average top width, the areal headcut retreat rate (R_a , in $\text{m}^2 \text{y}^{-1}$) could be calculated. The measurements in the field were conducted with a measuring tape. Minima, maxima, averages and standard deviations were calculated for L , R_l , R_a and V_e . To determine which gully and environmental characteristics control the variability of L , R_l , R_a and V_e , data were collected on the headcut type, the headcut height, the slope gradient, the lithology, the occurrence of soil piping, land use in 2010 at the gully head, the catchment area and the precipitation. Concerning the headcut type, single, branched and rill-abrupt gully heads were distinguished, as is the case in previous classifications (Oostwoud Wijdenes et al., 1999; Nyssen et al., 2002). The slope gradient at the gully head was determined by measuring the inclination of the soil surface with a clinometer, between locations with a five-meter upslope and a five-meter downslope on the gully head. In the field, observations were made on the presence of soil piping to determine if pipes were active at the gully head. The catchment area (A , m^2) of the headcuts was delimited by Global Positioning System recordings (Garmin GPSMap 60®, 5 m standard deviation). This delimitation was performed shortly after rainfall events when the runoff paths could be easily observed. The daily precipitation was recorded by installing three simple rain gauges that were composed of a large tin installed in an open space 1–1.5 m above the ground on a farmer's compound. The rain gauges were positioned in such a way that every gully head could be linked to a particular site.

The relation between L and the daily precipitation was analyzed using the Pearson correlation coefficient r , also taking into account other gully and environmental characteristics (see above) that control headcut retreat. Before analyzing the data on R_l , R_a and V_e in relation to the gully and environmental characteristics, a logarithmic transformation of the data was performed. This approach was necessary to obtain datasets with normal frequency distributions and homogeneous variances that are suitable for statistical analyses. This approach was verified using a Kolmogorov-Smirnov test ($\alpha = 0.05$) and a Levene test ($\alpha =$

0.01). Subsequently, significant associations ($\alpha = 0.05$) between $\text{Log}R_l$, $\text{Log}R_a$, $\text{Log}V_e$ and continuous explanatory variables were detected using a correlation matrix. For the categorical variables of headcut type, soil piping, lithology, and land use in 2010, t -tests ($\alpha = 0.05$) were performed.

2.3 Medium- to long-term (1-47 years) gully headcut retreat rates

Eighteen gully heads, which could be clearly observed from terrestrial or aerial photographs, were selected in the Northern Ethiopian Highlands for the analysis of headcut retreat rates over a period of 1 to 47 years. Eight gully heads could be studied by means of historical terrestrial photographs, and ten gully heads could be studied by means of historical aerial photographs. In addition, intermediate observations could be performed for four gully heads using terrestrial or aerial photographs, focused interviews (see Nyssen et al., 2006) or field observations.

Eleven archival terrestrial photographs used in this study were taken during field visits in 1998 or 2008. Two terrestrial photographs from 1975 were originally taken by Neil Munro. The aerial photographs (scale ranging between 1:35,000 and 1:45,000) were collected from the Ethiopian Mapping Authority with dates of 1963, 1965, 1974 and 1994.

The assessment of the annual headcut retreat rates, R_l , R_a and V_e by means of terrestrial or aerial photographs could be completed using field measurements on the basis of the relocated historical gully heads. The latter was possible whenever the historical gully heads were situated close to landscape elements, such as stone bunds (Fig. 3) or footpaths. Several gullies that developed as bank gullies did not yet exist at the time when the aerial photographs of 1963, 1965 or 1974 were taken. In those cases, it was sufficient to locate the downslope gully end for the calculations of R_l , R_a and V_e . Because the gully was not yet present in 1963, 1965 or 1975, the values for R_l , R_a and V_e were interpreted as minimum values. When interviews or field observations from 2009 served as the basis for the positioning of historical gully heads, people's indications were used and cross-checked for consistency. Analogous to the previous section, the measurements of the gully dimensions in the field were performed using a measuring tape.

The maximum error of the relocation of the historical gully heads in the field was estimated to be 2 m, which introduced an error in the values of R_l , R_a and V_e that ranged between 0.2% and 31%, which was $8\pm 1\%$ on average.

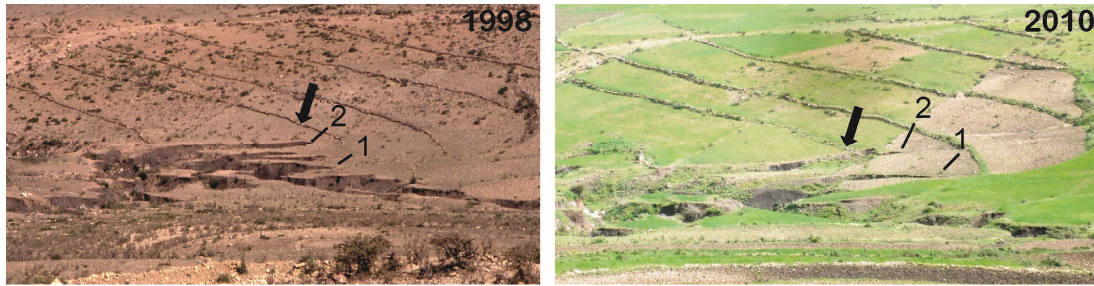


Fig. 3. Quantifying gully head retreat from repeat photography. Due to the presence of stone bunds (black arrows), the 1998 location of two gully heads in May Leva could be detected in the field between 1998 and 2010. The May Leva 1 and May Leva 2 headcuts retreated by 13.1 m and 20.7 m, respectively. Both gullies did not yet exist in 1963. Photograph in 1998 was taken by J. Poesen, and a repeat photo was taken in 2010 by A. Frankl.

To analyze gully head erosion in relation to the controlling factors, descriptive statistics for R_l , R_a and V_e were computed: minima, maxima, averages and standard deviations. Subsequently, the effect of the following gully and environmental characteristics on $\text{Log}R_l$, $\text{Log}R_a$ and $\text{Log}V_e$ was determined: gully head type, headcut height, slope gradient, lithology, occurrence of soil piping, land use at the gully head in 2010, catchment area and precipitation. For the latter, data were collected from the Global Climatic Data database (accessed from www.worldclim.org; Hijmans et al., 2005) for the period of 1960-2000 and included averages for the annual precipitation, the precipitation during the wettest month and the Fournier Index. This index, which combines the annular precipitation (p) and the precipitation of the wettest month (P) in the equation $c = P^2/p$, expresses the relative importance of both variables and the rainfall erosivity (Fournier, 1960). The data were generated through the interpolation of average monthly climatic data from weather stations on a 30 arc-second resolution grid (Hijmans et al., 2005).

First, the analysis determined the strength of the relationship between $\text{Log}R_l$, $\text{Log}R_a$ and $\text{Log}V_e$ and the continuous and categorical explanatory variables. For the continuous variables of the gully (headcut height, slope gradient, catchment area and precipitation), the significance of the association ($\alpha = 0.05$) was determined using the correlation coefficient r . For the categorical variables, including gully head type, lithology, soil piping and land use in 2010, t -tests were performed to determine whether the averages of the populations were significantly ($\alpha = 0.05$) different from each other.

Second, a multiple regression analysis (in SPSS) was performed to detect the relevant parameters (gully head type, headcut height, slope gradient, lithology, occurrence of soil

pipings, land use at the gully head in 2010, catchment area and precipitation; $\alpha = 0.05$), and a linear model was computed for the relationships between $\text{Log}R_i$, $\text{Log}R_a$ or $\text{Log}V_e$ and the relevant gully and environmental characteristics.

In the case of the four gully heads with multiple observations, the variabilities of R_i , R_a and V_e were analyzed.

2.4 Gully head erosion after road construction

To study the effects of the recent modifications to the road infrastructure (with relocations of road outlets) on gully head erosion, data from Nyssen et al. (2002) were adapted. These data comprise the catchment area, the gully width and depth, the total length of the headcut retreat and the eroded volume of 15 gullies after the construction of a new road during 1993-1994 east of Hagera Selam (Fig. 2). For R_i , R_a and V_e , descriptive statistics were calculated (minima, maxima, averages and standard deviations). T-tests were performed to determine if the population averages of $\text{Log}R_i$, $\text{Log}R_a$ or $\text{Log}V_e$ after the recent road construction were significantly different from the data presented in Section 2.3 for which the recent road modifications had no influence on the drainage patterns.

3 Results

3.1 Short-term gully headcut retreat rates

The average seasonal precipitation for the three measuring sites was 359 ± 42 mm with 30 days with rain (34%) and 58 days without rain during the period of study. In the former case, the daily precipitation was 12 mm on average with a maximum of 45 mm. These figures correspond to an average or above-average rainy season and were perceived by the farmers as a good year.

The 24 gully heads monitored in May Ba'ati during the rainy season of 2010 retreated by linear erosion during 2 to 16 rain events. The daily linear headcut retreat rate (L) varied between 0 and 0.55 m d^{-1} (Fig. 4). Due to the 2 mm rainfall, the gullies were able to become active. The number of active gullies showed a strong positive correlation with the daily precipitation ($r = 0.79$, $P < 0.001$). A linear regression indicates that 50% of the gullies retreat by linear erosion when the rainfall depth equals 20 mm. High rainfall events that should cause all of the gullies in the area of study to retreat at the same time did not occur during the monitoring period. This finding is mainly explained by the fact that rainstorms are generally small in size, and the correlation between L and daily precipitation was considerably low (average of $r = 0.25$, Table 1), with only thirteen gully heads showing a significant

relationship. The strength of the correlation between L and the daily precipitation was not influenced by gully and environmental parameters. However, seven out of thirteen significant correlations occurred on degraded soils. The high variability in L and the weak correlation with the daily precipitation are the result of the discontinuous retreat of the gully heads, which does not always occur when the precipitation is at a maximum. Along the gully head, tension cracks develop that cause soil falls, which are likely to occur in-between rainfall events because of gravity. Therefore, the values for L were summed to equal the annual linear headcut retreat rates R_l (Table 1).

The linear retreat rates R_l varied from 0.02 m y^{-1} to 1.93 m y^{-1} with an average of $0.34 \pm 0.49 \text{ m y}^{-1}$ (Table 1, Fig. 5). The areal retreat rates R_a varied from $0.11 \text{ m}^2 \text{ y}^{-1}$ to $4.57 \text{ m}^2 \text{ y}^{-1}$, with an average of $1.70 \pm 1.59 \text{ m}^2 \text{ y}^{-1}$ (Table 1). The volumetric headcut retreat rates V_e varied from $0.1 \text{ m}^3 \text{ y}^{-1}$ to $20.7 \text{ m}^3 \text{ y}^{-1}$, with an average of $5.2 \pm 5.1 \text{ m}^3 \text{ y}^{-1}$ (Table 1). The values of R_l , R_a and V_e were not normally distributed, they were skewed towards lower values and high outliers occurred. A logarithmic transformation of R_l , R_a and V_e resulted in normal distributions of $\text{Log}R_l$, $\text{Log}R_a$ or $\text{Log}V_e$ with homogeneous variances (insignificant Kolmogorov-Smirnov and Levene tests).

Eighteen of the gully head-type headcuts could be classified as single, three headcuts were rill-abrupt, and the remaining three were branched. The headcut height varied between 0.40 m and 2.93 m and was, on average, $0.96 \pm 0.62 \text{ m}$ (Table 1). The slope gradient at the gully head ranged between 1% and 49%, with an average of $14 \pm 11\%$. Soil piping occurred at six headcuts, which were all located in Vertisol areas. Ten gully heads were located in densely vegetated areas, such as exclosures, or in grassed seasonal waterways; five headcuts were in cropland; seven headcuts developed on surfaces with degraded vegetation and two headcuts showed mixed land use (Table 1). Six headcuts developed in limestone colluvium, twelve in sandstone colluvium and six in Vertisols. The catchment areas of the headcuts ranged from 590 m^2 to $243\,380 \text{ m}^2$, with an average of $57\,580 \pm 78\,520 \text{ m}^2$.

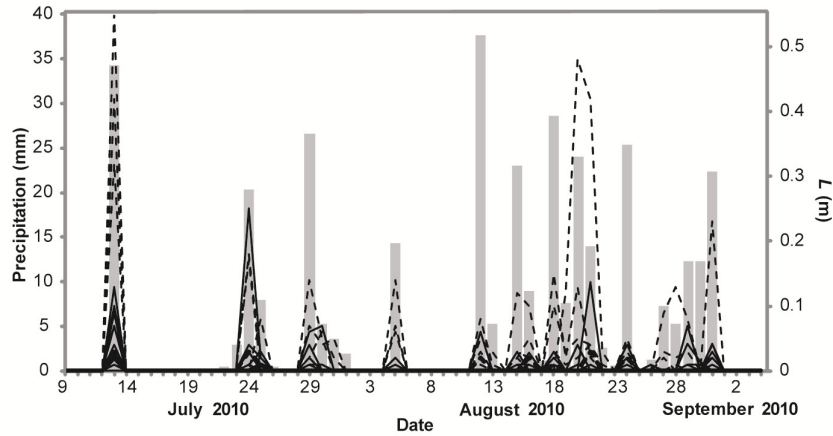


Fig. 4. The daily gully headcut retreat rate L (shown with the black line) and its relationship with the daily precipitation (grey bars) for all of the studied headcuts in 2010. The gully heads where soil piping occurs (in Vertisols) are indicated by the dashed line. The daily precipitation shown is the average rain recorded at the three measuring sites.

Table 1

Headcut retreat of 24 gullies in May Ba'ati during the rainy season of 2010.

Gully head	R_l (m y^{-1})	R_a ($\text{m}^2 \text{y}^{-1}$)	V_e ($\text{m}^3 \text{y}^{-1}$)	Headcut height	r between L and daily precipitation	A (m^2)	Soil piping	Land use at gully head (2010)
1	.14	.90	1.1	.93	.32	590		Exclosure (Acacia trees, poor undergrowth)
2	.03	.94	2.1	.89	.13	142 350		Exclosure (Acacia trees, shrubs)
3	1.52	5.79	7.1	.45	.71*	243 380	x	Grazed footpath
4	.45	.73	1.5	.40	.47*	230 620	x	Grazed footpath
5	.76	3.51	7.9	1.4	.28	6 70	x	Cultivated
6	1.93	3.61	10.2	1.3	.38	220 190	x	Cultivated
7	1.02	4.57	5.5	.46	.52*	2 770	x	Cultivated
8	.08	1.71	.9	.66	.07	27 090		Seasonal waterway (grasses)
9	.13	.19	.5	.53	.18	3 430		Seasonal waterway (grasses)
10	.28	.32	1.9	.92	.42*	5 580		Exclosure (shrubs and small trees)
11	.09	1.17	3.3	.78	.36*	67 290		Exclosure (trees, shrubs, grasses)
12	.09	1.28	5.8	1.41	.29	35 550		Cultivated
13	.09	3.65		2.93	.32	147 630		Degraded rangeland
14	.17	.3	9.5	.47	.44*	44 720	x	Degraded rangeland
15	.03	1.41	20.7	2.26	.46*	83 910		Cultivated/Degraded rangeland
16	.02	2.07	3.8	.75	.29	31 850		Seasonal waterway (grasses)
17	.18	1.62	9.1	.75	.39*	16 090		Cultivated/Grazed waterway
18	.43			1.52	.35*	9 630		Degraded rangeland
19	.12	.11	11.5	.22	.59*	1 830		Exclosure (Acacia trees, grasses)
20	.10	.97	8.0	1.1	.33	28 430		Cultivated

21	.11	3.52	.1	.42	.41*	2 990	Exclosure (large trees, dense shrubs)
22	.06	.11	.4	.89	.14	21 240	Eucalyptus plantation (dense undergrowth)
23	.19	.23	.2	.74	.44*	11 760	Degraded rangeland
24	.05	.26	2.6	.93	.45*	2 360	Degraded rangeland

* Correlation is significant at the 0.05 level.

R_l , R_a , V_e : annual linear/area/volumetric headcut retreat rate; L : daily linear headcut retreat; A : catchment area

The correlation between $\text{Log}R_l$ and the continuous gully and the environmental characteristics (i.e., the catchment area, the slope gradient and the headcut height) was low and insignificant. For the categorical variables (gully head type, lithology, land use in 2010 and the presence of soil pipes), only soil piping had a significant positive effect on $\text{Log}R_l$ ($t = -3.47$, $P = 0.003$). Therefore, the soils that were located where piping occurred (Vertisols) had larger values of $\text{Log}R_l$ (Fig. 5). The effects of the gully and the environmental characteristics on $\text{Log}R_a$ and $\text{Log}V_e$ could not be demonstrated due to the expectation of a weak correlation between $\text{Log}R_a$ and the slope gradient ($r = 0.43$, $P = 0.048$).

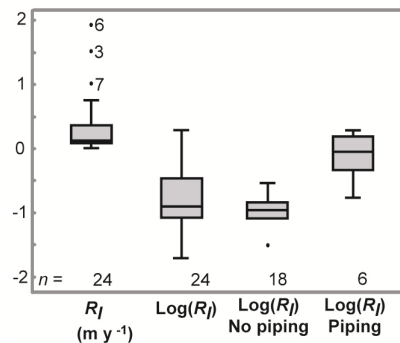


Fig. 5. The linear headcut retreat rate before and after logarithmic transformation. The logarithmic transformation of R_l creates a normally distributed parameter $\text{Log}R_l$. is higher in soils where piping occurs.

3.2 Medium- to long-term (1-47 years) gully headcut retreat rates

Table 2 shows the values of R_l , R_a and V_e for the 18 gully heads, the methods used to calculate the retreat rates (terrestrial photographs, aerial photographs, interviews and field observations), the period over which observations were made, the headcut height, the catchment area (A) of the gully head and the occurrence of soil piping.

Table 2

List of studied gully heads ($n= 18$) for the medium- to long-term retreat rates and their characteristics; and four intermediate observations.

Gully head	Method*	Period	R_l (m y ⁻¹)	R_a (m ² y ⁻¹)	V_e (m ³ y ⁻¹)	Headcut height	A (m ²)	Soil piping
Sinkata	AP	1994-2010	.64	3.5	3.3	.85	6 650	
May Leva 1	AP	1963-2010	1.10	8.2	13.0	1.72	10 090	x
May Leva 2	AP	1963-2010	.86	7.9	11.5	1.30 - 1.55	10 320	x
May Ba'ati 1	AP	1974-2010	.53	5.5	9.8	1.30	1 880	
May Ba'ati 2	AP	1974-2011	1.03	9.4	10.6	.47	44 720	x
May Mekdan 1	AP	1965-2010	9.79	63.1	40.1	.1 - 1.90	787 510	x
Hagere Selam 1a	TP	1998-2010	1.90	4.2	9.9	1.10	86 000	
May Ba'ati 3	AP	1994-2011	1.75	25.7	47.6	1.52	9 630	
May Ba'ati 4	AP	1974-2011	1.39	9.3	20.5	2.26	83 910	
May Ba'ati 5	TP	2008-2011	2.15	4.0	4.3	0.93	124 210	
Hagere Selam 2b	TP	1993/4-1999	7.27	58.2	58.1	0.82	141 000	x
Hagere Selam 2c	TP	2008-2011	8.93	33.7	45.1	1.76	141 000	x
May Mekdan 2	TP	1975-2010	.62	4.0	14.8	4.00	715 000	x
May Mekdan 3	AP	1965-2010	1.36	10.9	23.0	.50 - 1.30	24 530	x
May Mekdan 4	AP	1965-2010	18.4	201.6	425.4	.1 - 4.20	2 829 870	x
Mekelle Mesebo	TP	1998-2010	1.49	0.3	1.3	.85	138 830	
Kwiha 1	TP	1975-2010	1.85	69.2	66.9	.80 - 1.22	3 808 440	x
Kwiha 2	TP	1998-2010	7.33	48.3	52.5	1.10 - 1.15	1 558 860	x
Intermediate Observations								
May Leva 1	TP	1998-2010	1.73	8.1	10.9	1.72	10 090	x
May Leva 2	IV	1998-2010	1.09	6.3	8.2	1.30 - 1.55	10 320	x
May Leva 2	AP	2008-2011	3.15	7.1	7.0	1.30 - 1.55	10 320	x
May Ba'ati 1	TP	1998-2010	.65	5.1	6.9	1.30	1 880	
May Mekdan 2	FO	2009-2010	7.00	30.1	43.6	1.32	715 000	x

* TP: Terrestrial photography, AP: Aerial Photography, IV: Interview, FO: Field observation

R_l , R_a , V_e : annual linear/area/volumetric headcut retreat rate; A: catchment area

The average and standard deviation was 3.8 ± 4.7 m y⁻¹ for R_l , 31.5 ± 48.3 m² y⁻¹ for R_a , and 47.7 ± 96.5 m³ y⁻¹ for V_e (Table 3). The minima and maxima differ considerably as a result of extreme values and skewed distributions towards the lower values of R_l , R_a and V_e . The logarithmic transformation of R_l , R_a and V_e results in normal frequency distributions with homogeneous variances.

Table 3Descriptive statistics of the observed gully headcut retreat rates (R_l , R_a and V_e).

	R_l				R_a				V_e			
	All	Soil with piping	Other Soils	Recent road construction*	All	Soil with piping	Other Soils	Recent road construction*	All	Soil with piping	Other Soils	Recent road construction*
n	1											
Minimum	8	11	7	15	18	11	7	15	18	11	7	15
Maximum	.5	.6	.5	1.8	.3	4.0	.3	2.9	1.3	6	1.3	9.0
Mean	8.	18.4	2.2	91.6	1.6	.6	7	280.0	42	425	47.	2310.0
Std. Deviation	3.	5.3	1.4	21.3	31.	46.	7.5	21.5	47.	69.	13.	554.7
n	7	5.6	.6	24.4	48.	57.	8.5	83.1	96.	119	16.	849.5

*(Nyssen et al. 2002)

 R_l , R_a , V_e : annual linear/area/volumetric headcut retreat rate; A: catchment area

The head type of twelve gully headcuts was single, two headcuts were rill-abrupt, and four were branched. The headcut height varied between 0.47 m and 4.20 m and was, on average, 1.39 ± 0.80 m (Table 2). The slope gradient at the gully head ranged from 2% to 22% with an average of $9 \pm 6\%$. Soil piping occurred at eleven headcuts in which the majority was located in Vertisols. Three gully heads were located in densely vegetated areas, such as in exclosures or in grazed seasonal waterways, thirteen headcuts were located in cropland and two headcuts were located on surfaces with degraded vegetation. Three headcuts developed in limestone colluvium, five developed in sandstone colluvium and one developed in basalt colluvium. Nine headcuts developed in Vertisols. The catchment area of the headcuts ranged between 1 880 m² and 3 808 440 m², with an average of $584\,580 \pm 1\,085\,040$ m². The average annual precipitation over the period from 1960-2000 for all of the measuring sites was 637 ± 37 mm, with a minimum of 537 mm and a maximum of 678 mm. The average precipitation of the wettest month (August) during the same period ranged from 199 mm to 214 mm, with an average of 205 ± 7 mm. The Fournier Index was 66 ± 2 on average and ranged from 63 to 70.

Considering the relationship between the gully headcut retreat rate and the gully and environmental characteristics recorded, only the catchment area ($\text{Log}A$) had a strong positive association with $\text{Log}R_l$, $\text{Log}R_a$ and $\text{Log}V_e$, with correlation coefficients of 0.65, 0.48 and 0.52, respectively, which were significant at the $\alpha = 0.05$ level. The correlations between the annual headcut retreat rates and the other characteristics, including the slope gradient, the headcut height, the precipitation of the wettest month and the Fournier Index, were low and not

significant ($\alpha = 0.05$). The positive effect of soil piping on the gully headcut retreat rates, as indicated by the numerical description (Table 3) and the graphical description (Fig. 6), leads us to conclude that for this study, soils in which piping occurs are more vulnerable to gully erosion. A t -test, which was used to compare the means of the observations on the gully headcut retreat rates for soils with piping and soils without piping, reveals that the null hypothesis, which assumes equal means, could be rejected for $\text{Log}R_a$ and $\text{Log}V_e$. The t -statistics are as follows: $\text{Log}R_l$, $t = -1.21$ ($P = 0.10$), $\text{Log}R_a$, $t = -2.88$ ($P = 0.01$) and $\text{Log}V_e$, $t = -2.73$ ($P = 0.015$). There proved to be no significant effect of the present land-use type on the gully headcut retreat rates, the lithology or the headcut type.

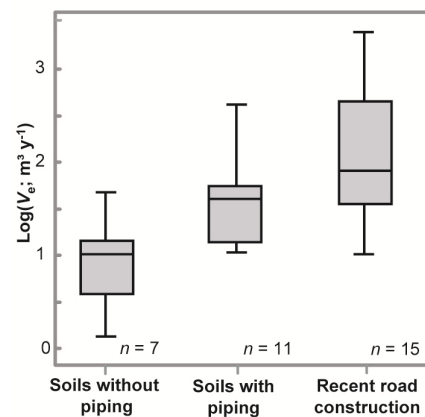


Fig. 6. Boxplots showing the distribution of the gully headcut retreat rates (in $\text{m}^3 \text{y}^{-1}$) after a logarithmic transformation for soils without piping, soils with piping (including Vertisols) and after road construction.

For the next step in the analysis, a multiple regression analysis was performed using $\text{Log}R_l$, $\text{Log}R_a$ and $\text{Log}V_e$ as response variables and gully and environmental variables as explanatory variables. The catchment area (A , m^2) showed to be the most important variable that is significantly related to the annual retreat rates (the power relations are shown by eqns. 1 to 3). Regarding the effect of soil piping, a trend could only be observed when considering the linear headcut retreat rate ($P = 0.55$). When considering the areal and volumetric headcut retreat rates, the effect of soil piping was such that significant associations could only be defined when considering gullies in which soil piping occurred. For these subgroups, given A , the retreat rates showed to be higher on the plot (Eq. 4 and 5; Fig. 7).

$$R_l = 0.06 A^{0.31} \quad (n = 18, r^2 = 0.42) \quad (1)$$

$$R_a = 0.27 A^{0.33} \quad (n = 18, r^2 = 0.23) \quad (2)$$

$$V_e = 0.53 A^{0.31} \quad (n = 18, r^2 = 0.27) \quad (3)$$

$$R_a \text{ "piping"} = 0.23 A^{0.38} \quad (n = 11, r^2 = 0.47) \quad (4)$$

$$V_e \text{ "piping"} = 0.45 A^{0.36} \quad (n = 11, r^2 = 0.52) \quad (5)$$

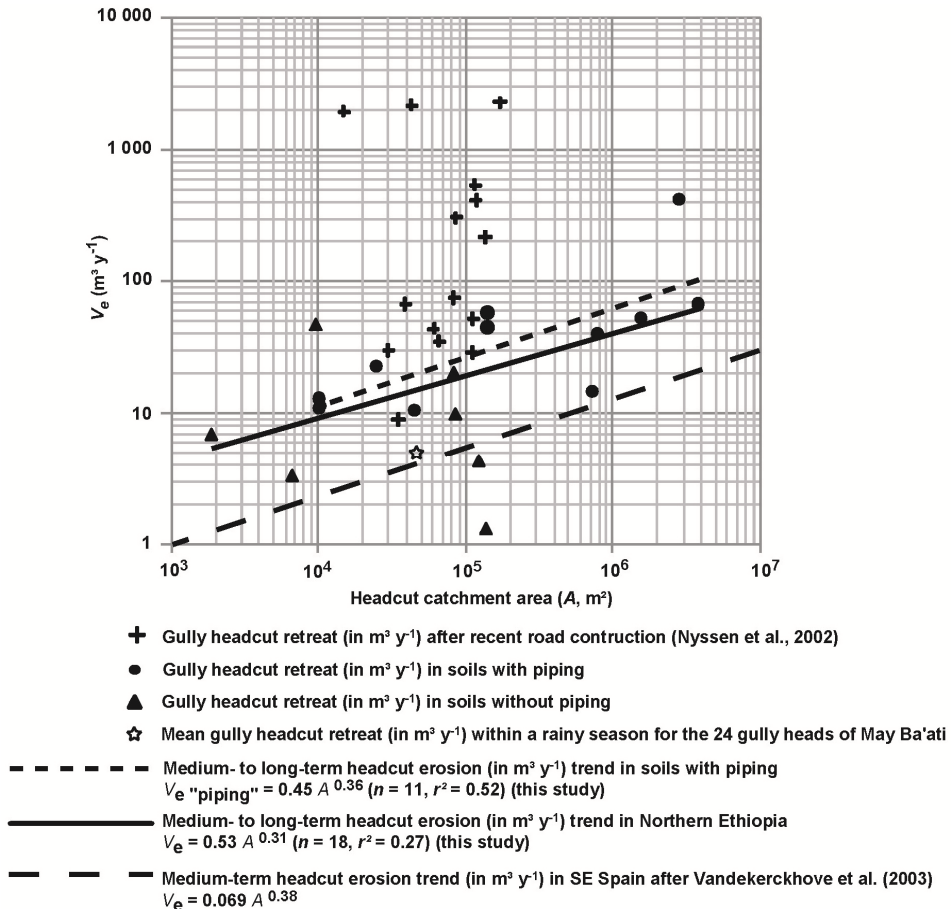


Fig. 7. Relationship between the annual volumetric retreat rate (V_e) and the drainage area (A) in the area of study area.

In the case of the sites of May Leva 1 and 2, May Ba'ati 1 and May Mekdan 2, the development of the gully volume (Fig. 8), the length and the surface over time could be determined. A negative exponential increase in the gully volume, the length and the surface could be observed over the period of study for three out of four gullies. For these gullies, the headcut retreat rates were larger during the early phases of gully development.

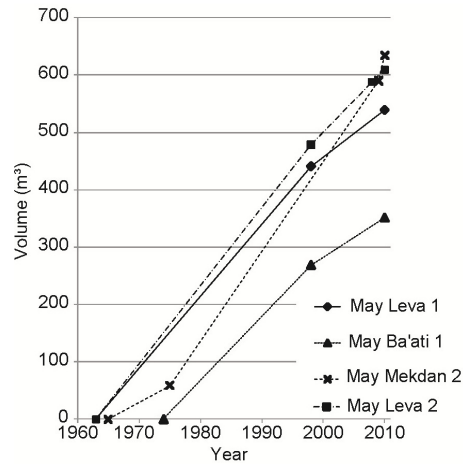


Fig. 8. Growth of gully head volume over time for the sites of May Leva 1 and 2, May Mekdan 2 and May Ba'ati 1.

3.3 Gully headcut retreat after a recent road construction

Table 3 shows descriptive statistics for R_l , R_a and V_e that were obtained for the 15 gully heads studied after a recent road construction by Nyssen et al. (2002). The average values and the standard deviations for R_l , R_a and V_e were 21.3 m y^{-1} , $21.5 \text{ m}^2 \text{ y}^{-1}$ and $554.7 \text{ m}^3 \text{ y}^{-1}$, respectively. Both the descriptive statistics (average, maximum, minimum) and the boxplot (Fig. 6) indicate that headcut retreat was more severe (up to 10 times greater) when a new road caused a significant increase in the catchment area of the gullies, compared to the gullies described in section 3.2, where no recent roads were built in their catchments. We tested this observation with a t -test after a logarithmic transformation of the observations: $\text{Log}R_l$, $t = -4.62$, $P < 0.001$; $\text{Log}R_a$, $t = -1.05$, $P = 0.30$; and $\text{Log}V_e$, $t = -3.81$, $P < 0.001$. These results illustrate that in the case of $\text{Log}R_l$ and $\text{Log}V_e$, recent road construction had a significant positive effect on the headcut retreat rates. In the case of $\text{Log}R_a$, however, the averages for both populations (with/without recent road construction in the catchment) did not differ significantly. The 95% confidence interval for the increase in the gully head retreat rates due to the construction of a new road varied from $7.3 - 29.5 \text{ m y}^{-1}$ for R_l and from $158.2 - 861.2 \text{ m}^3 \text{ y}^{-1}$ for V_e . A regression between the response variables of $\text{Log}R_l$, $\text{Log}R_a$, $\text{Log}V_e$ and $\text{Log}A$ could not be performed because these variables did not correlate with each other ($r \approx 0$). Figure 7 shows, however, that for a given catchment area (A), the volumetric headcut retreat rates V_e were generally higher when considering the gullies in which a new road was constructed in a catchment.

4 Discussion

4.1 The use of repeat terrestrial photography for assessing gully head retreat rates

Repeat terrestrial photography offers a valuable tool for analyzing long-term changes in environmental features (Frankl et al., 2011). Gullies are often spectacular landscape features, attracting the attention of many photographers. Hence, they appear in many terrestrial photographs. In Northern Ethiopia, Nyssen et al. (2010) created a large dataset of historical landscape photographs, which allowed for repeat photography studies (e.g., Nyssen et al., 2009b; Munro et al., 2010) to analyze environmental changes over more than 140 years. However, photographing (mountainous) landscapes from the on-the-ground perspective results in large deformations of the scenery displayed on the photographs. For this reason, to date, few quantitative studies actually used repeat photography (e.g., Corripio, 2004). Such studies are primarily based on the projection of the photographs on a Digital Elevation Model (DEM) to create maps. Because this technique is difficult to apply and requires the availability of a high resolution DEM, Meire et al. (2011) developed a methodology that warps terrestrial photographs onto the horizontal plane of a map using GPS measurements of homogeneous topographies. To our knowledge, apart from the study of Frankl et al. (2011) that quantifies historical gully cross-sections and the brief study of Vincente et al. (2009) that observed gully expansion, no other study has successfully used repeat photography in a quantitative way when considering gully erosion. This study shows that repeat terrestrial photography can also be used to quantify gully head retreat rates, which enables the establishment of long-term headcut retreat rates when historical maps or large-scale aerial photographs are lacking for the period of interest. However, to avoid large errors, much care is required when determining the historical location of the headcuts. Only photographs that allow for the precise positioning of the historical headcut relative to the proximity of stable landscape elements should be selected.

4.2 Gully headcut retreat rates in Ethiopia compared to other semi-arid regions of the world

Headcut retreat rates are significantly smaller on the short-term compared to the medium-to-long-term time scale, which corresponds to results obtained in Spain (Vandekerckhove et al. 2001, 2003; Martinez-Casasnovas et al., 2003, 2004; Marzloff et al., 2011) and Romania (Ionita, 2006). This finding is partially explained by the occurrence of extreme rainfall events inducing strong headcut retreat, which are more likely to occur during longer observation periods. Furthermore, the soil and water conservation structures (e.g., enclosures, stone bunds, infiltration trenches and ponds) that have been implemented over the past 20 years in Tigray

had a significant influence on the catchment hydrology through the decrease of both the runoff coefficients and the sediment production (Descheemaeker et al., 2006; Nyssen et al., 2009a). As a consequence, gully activity is decreasing (Frankl et al., 2011), and the correlation between gully head erosion rates and gully and environmental parameters is weak. This phenomenon is most evident in small headwater basins, such as in May Ba'ati, where nine out of 24 gully heads have a linear retreat rate of less than 0.1 m y^{-1} . Similar findings on the decreasing effect of soil and water conservation measures on gully erosion rates were also obtained for a study in Romania (Ionita, 2006).

As in other Sub-Saharan countries (e.g., Marzloff and Ries, 2007, Oostwoud Wijdenes and Bryan, 2001) and semi-arid areas worldwide (e.g., Vandekerckhove et al., 2001, 2003; Wu and Cheng, 2005; Marzloff et al., 2011), the variability in gully head retreat rates is high in Ethiopia. For catchments of similar sizes and during the same observation period, the headcut retreat rates obtained in this study vary by a factor of ten. In Southeast Spain, Vandekerckhove et al. (2003) computed a regression equation linking drainage area and medium-term gully head retreat rates: $V_e = 0.069 A^{0.38}$ (Fig. 7). Marzloff et al. (2011) included observations from Northeast Spain and obtained an $A - V_e$ equation similar to that reported by Vandekerckhove et al. (2003). Comparing these equations with the $A - V_e$ equation obtained in this study, we conclude that for similar catchment areas, the gully headcut retreat rates (in $\text{m}^3 \text{ y}^{-1}$) that resulted from this study in Northern Ethiopia are approximately seven times larger than those obtained by the studies in Spain (Fig. 7).

This finding is most likely due to an environment that is more vulnerable to soil erosion with steeper slopes, a more degraded vegetation cover, the occurrence of intense rainstorms during the short rainy season and the presence of Vertisols. The exponents of the equations for Ethiopia and Spain (Vandekerckhove et al., 2003; Marzloff et al., 2011) do not differ notably (Spain: 0.37, Ethiopia: 0.38), reflecting the similar importance of the catchment area and the gully headcut retreat rate in both environments.

As indicated by the medium-to-long-term data and previous studies (e.g., Seginer, 1966; US Soil Conservation Service, 1966; Stocking, 1980; Burkard and Kostaschuk, 1997; Vandekerckhove et al., 2003; Marzloff et al., 2011), the catchment area at the gully head is the most important factor controlling gully head retreat rates, which translates into the importance of the runoff volume entering the gully. Other gully and environmental parameters are generally weakly correlated to the gully head retreat rates and depend on site-specific characteristics.

Precipitation characteristics are important in controlling gully initiation and development (e.g., Thompson, 1964; USSCS, 1966; Radoane et al., 1995; Martinez-Casasnovas et al., 2002). However, in this study, the annual headcut retreat rates weakly correlate with the precipitation characteristics. The reason for this is that the averages calculated over a 50-year time period do not reflect the large inter-annual variability in rainfall characteristics. Limited meteorological station data obtained over the period 2004-2006 for the towns of Hagere Selam, Mekelle and Wukro resulted in values for the annual precipitation, the precipitation of the wettest month and the Fournier Index that ranged between 390 mm and 850 mm, 171 mm and 314 mm and 74 and 164, respectively.

Graf (1977) suggested that gully head retreat rates display negative exponential growth on a long-term time scale. According to Oostwoud Wijdenes and Bryan (2001) and Nachtergaele et al. (2002), this finding is the result of the reduction in the contributing runoff area, while the headcut progresses upslope. Other site-specific explanations include the consequence of a decrease in the local slope gradient during headcut retreat, the increase of soil and water conservation practices through time and land abandonment. Laboratory (Kosov et al., 1978) and field studies (Oostwoud Wijdenes and Bryan, 2001; Nachtergaele et al., 2002; Nyssen et al., 2006) have confirmed this negative exponential growth. As is apparent in Fig. 8, a similar trend can be observed in this study.

Regarding the effect of artificial modifications to the drainage patterns, this study supports the findings of Nyssen et al. (2002), which claim that road construction considerably increases the risk of gully head activity, which, in turn, can affect both rural (e.g., Moeyersons, 1991) and urban areas (e.g., Archibold et al., 2003). We can derive from the data in this study that a strong increase in the catchment area activates (or initiates) gullies that will develop rapidly upslope (linear erosion) and will deepen. Only in a later phase will the gully gradually widen due to an oversteepening of the gully walls. Special care is therefore required when altering runoff pathways to not destroy valuable land located downslope the newly built roads (Valentin et al., 2005). A possible solution consists of increasing the local drainage by decreasing the distance between drifts or culverts (Croke and Hairsine, 2001; Nyssen et al., 2002) based on threshold values that indicate the maximum size a drainage area may have after road construction.

4.3 The effect of soil piping (especially in Vertisols) on gully head retreat rates

Under normal conditions, footslope positions have a low susceptibility to gully initiation because their slope gradients are low (Knighton, 1998). The presence of smectite clays (such

as those in Vertisols) strongly increases the susceptibility of these slopes to water erosion as a consequence of their susceptibility to soil piping. Once the gullies are initiated, they will be extended along the line of still-buried pipes (Knighton, 1998). Because of the frequent draining of large areas in footslope positions, high annual retreat rates can be observed. In California, the presence of smectite clays in valley floors strongly affects the gully erosion rates through soil piping (Swanson et al., 1989). Soil piping also plays an important role in the development of badlands in dispersive clays and silt-clays in the valley floors of the Ebro basin in Spain (Gutierrez et al., 1997). This study indicates that the occurrence of soil piping is related to the soil crack density and that in valley floors, large soil pipes (> 1 m in diameter) develop because of the increased infiltration on gentle slopes. In addition, in Spain, Faulkner et al. (2004) indicate that soil pipes develop into rills, which often precede gullies, after the collapse of the soil pipe roof. This finding explains part of the contrast in the headcut retreat rates between gullies with soil piping and gullies without soil piping on the medium-to-long-term time scale (Fig. 6 and Fig. 7). However, more data are required to better contrast gully erosion rates in Vertisols. In the catchment of May Ba'ati, where the implementation of soil and water conservation measures has reduced gully headcut erosion rates, only the gullies incised in Vertisols remain notably active with retreat rates of up to 1.93 m y^{-1} (Table 1). This finding indicates that current measures to prevent gullies in Vertisol areas from expanding upslope have a limited effect. In these areas, gully headcut retreat is strongly controlled by the development of soil pipes and their collapse (Fig. 9). Alternative measures are therefore required to control sub-surface drainage in Vertisol areas, especially upslope of existing gully heads. A new method that is currently being tested consists of introducing a subsurface geomembrane (vertical dam) at the gully head to increase the groundwater level and subsequently decrease soil cracking and hence, soil piping.



Fig. 9. Gully development as a result of soil piping. The collapse of a soil pipe in the rainy season of 2008 resulted in the initiation of a gully at the site of Hagere Selam 2c (Table 2).

Rapid regressive erosion occurred, resulting in a gully length of 26.8 m in 2011. The gully remains active with the occurrence of a 1.4-m-high and 0.6-m-wide soil pipe (see arrow). Photographs by Amaury Frankl.

5 Conclusions

As the first comprehensive quantitative analysis of gully head retreat rates in Sub-Saharan Africa, this study presents results from monitoring 24 gullies during the rainy season of 2010 and results from the study of 18 gullies on the medium-to-long-term time scale (1-47 years) in Northern Ethiopia. The study demonstrates the following conclusions:

- (1) Repeat terrestrial photography is a valuable tool for assessing medium-to-long-term gully headcut retreat rates.
- (2) Present (short-term) gully head retreat rates are an order of magnitude smaller than those on the medium-to-long-term time scale. The small values of R_l , R_a and V_e on the short-term time scale are explained by the increasing positive effect of gully stabilization through soil and water conservation structures that have been implemented at the catchment scale over the past 20 years and by the higher probability of extreme rainfall events during longer observation periods.
- (3) Compared to similar areas worldwide, present-day gully headcut retreat rates in Northern Ethiopia occur at the same order of magnitude. On the medium-to-long-term time scale, gully head retreat appears to be more severe in Northern Ethiopia. The power relationship, $V_e = 0.53 A^{0.31}$ ($r^2 = 0.27$), indicates that the vulnerability to gully headcut erosion rates is seven times higher in Ethiopia when compared to Southeast Spain as a result of a steeper topography, more degraded soils, more erosive rains and the presence of Vertisols.
- (4) The catchment area at the gully head is the most important parameter explaining linear, areal and volumetric gully headcut retreat on the medium-to-long-term time scale. Additional gully and environmental characteristics (gully head type, headcut height, slope gradient, lithology, soil piping and land use at the gully head in 2010, average annual precipitation, average precipitation of the wettest month, Fournier Index) that were studied have no significant effect on headcut retreat. Regarding the effect of soil piping, however, a trend can be observed, which requires more observations to be fully confirmed. For the short-term observations, except for the increasing effect of soil piping on $\text{Log}R_l$ and of the slope gradient on $\text{Log}R_a$, there is insufficient evidence to state that the studied gully and environmental parameters,

- including the gully head type, the headcut height, the slope gradient at the gully head, the lithology, the soil texture at the gully head, the occurrence of soil piping and the land use at the gully head in 2010, have a significant effect on the headcut retreat rates.
- (5) On the short-term and medium-to-long-term time scales, larger headcut retreat rates are observed in Vertisols where piping occurs. Particularly on the short-term, the occurrence of soil piping has clearly had an increasing effect on linear headcut retreat rates. This indicates that current soil and water conservation practices (e.g., slope terracing and exclosures) have only limited effects on regressive gully erosion in Vertisols where gully erosion is strongly influenced by soil piping. Therefore, alternative techniques should be developed to reduce the effect of soil piping on gully head erosion. One solution could be physically obstructing the soil pipes in Vertisol areas.
- (6) The effect of recent modifications to road infrastructures was studied for 15 additional gullies. Based on these data, we conclude that headcut retreat rates for gullies in which a new road has been recently constructed in their catchment are significantly higher when compared to gullies studied on the medium-to-long-term time scale. The 95% confidence interval for an increase in gully head retreat rates to occur due to the construction of a new road is $7.3 - 29.5 \text{ m y}^{-1}$ for R_1 and $158.2 - 861.2 \text{ m}^3 \text{ y}^{-1}$ for V_e .

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