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Effects of drainage ditches and stone bunds on topographical thresholds for gully head development in North Ethiopia

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ABSTRACT

Gully erosion is an extreme process of land degradation operating in different regions of the world. A common way to quantify the susceptibility of land to gully incision is the use of topographical thresholds for different land use types. However, the impact of various management practices in cropland on these thresholds has not been studied to date, although land management may significantly affect runoff production, erosion processes and rates. Here, the impact of different land management practices on gully head development in cropland is studied based on a standardized procedure for topographical threshold analysis: $s > kA^{-b}$, where s represents the slope gradient of the soil surface, A the drainage area at the gully head, b an exponent and k a coefficient reflecting the resistance of the land to gully head development. A case study area was chosen around Wanzaye, North Ethiopia, where three different cropland management practices were studied in 75 catchments: (i) the catchment-wide use of stone bunds on the contour, (ii) the use of slightly sloping drainage ditches (*feses*), and (iii) the combined use of stone bunds and *feses*. The lowest k-values (0.078–0.090) are found for catchments treated with *feses*, the highest k-values (0.198–0.205) are observed for stone bund catchments, and medium k-values (0.092–0.099) are found for mixed catchments. This finding implies that catchments with the exclusive use of drainage ditches are the most vulnerable to gully head development compared with mixed catchments and stone bund catchments. However, on-site sheet and rill erosion rates are reduced by *feses* as they lower the gradient of the overland flow lines. Three trends in cropland management around Wanzaye and the wider region are observed: (i) *feses* are exclusively made on rather steep slopes where small drainage areas lead to the rapid development of gully heads; (ii) stone bunds are constructed on both steeper and gentle sloping cropland; and (iii) larger and gently sloping catchments seem to be most suitable for the combined use of drainage ditches and stone bunds.

1. Introduction

Gully erosion is a widely studied geomorphological process, as it affects soil quality, the water table, trafficability and sediment connectivity (e.g., Poesen et al., 2003; Le Roux and Sumner, 2012). International attention to this process is explained by its on-site and off-site impacts on large areas and the economic losses to farmers (e.g., Poesen et al., 2003; Valentin et al., 2005; Vrieling et al., 2007). Therefore, gully erosion needs to be better understood and managed, and its effects should be mitigated (Torri and Poesen, 2014).

A common way to quantify the susceptibility of cropland to gully erosion is to apply a coupled criteria analysis of topographic factors controlling the gully head position (e.g., Vandaele et al., 1996; Vandekerckhove et al., 1998; Nyssen et al., 2002; Morgan and Mngomezulu, 2003; Poesen et al., 2003). Topographic thresholds are commonly presented as double logarithmic plots of upslope drainage area (A) and slope gradient of the soil surface at the gully head (s). Patton and Schumm (1975) and Begin and Schumm (1979) were pioneers in modelling gully erosion as a threshold process:

$$s \geq kA^{-b} \tag{1}$$

$$s = \tan\gamma \tag{2}$$

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Table 1
Values of the coefficient k (Eq. (1)) for different land use types for two values of the exponent b (0.38 and 0.50). N. obs. is the number of studies from which a threshold *s*–*A* was calculated (Torri and Poesen, 2014). Values corrected for rock fragment cover of the study area (68%) are presented in brackets.

	Cropland	Rangeland, pasture	Forest, grassland
b = 0.38			
Average	0.043 [0.067]	0.154	0.628
St. dev.	0.029	0.139	0.318
Median	0.040	0.085	0.485
N. obs.	24	18	12
b = 0.5			
Average	0.037 [0.058]	0.149	0.698
St. dev.	0.024	0.144	0.491
Median	0.030	0.080	0.440
N. obs.	24	18	12

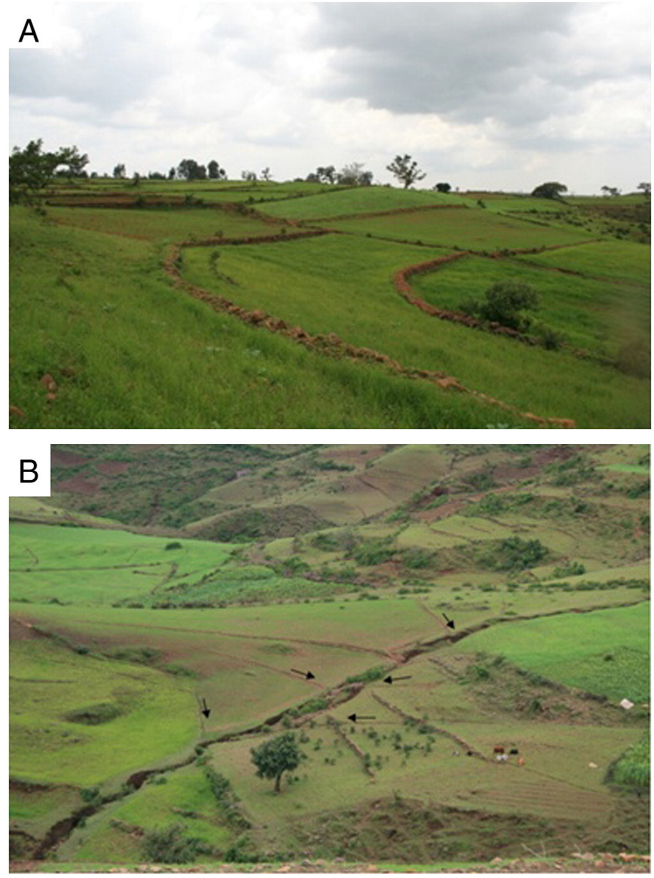

Fig. 2. Typical land management situations in the study area. (A) Stone bund catchment. (B) Mixed catchments with *feses* and stone bunds (summer of 2013). Direction of overland flow in the *feses* is indicated by arrows (after Monsieurs et al., 2014, published with permission from John Wiley & Sons).

where γ is the local slope angle (°) of the soil surface, k is a coefficient that reflects the resistance of the land to gully head development and b is an exponent. The latter is controlled mainly by soil type and land use. The upslope area (A) draining towards the gully head is expressed in ha. Slope gradient (s) represents the local slope gradient of the soil surface near the gully head (Vandaele et al., 1996; Vandekerckhove et al., 1998).

The threshold relationships in the form of Eq. (1) are not robust; its weakness lies in the arbitrary procedure of the construction of the threshold line due to a poor number of datasets comprising the threshold situation (Torri and Poesen, 2014). Standardisation of this procedure is required to enhance a large dataset on threshold values from different studies in various environments, which enables the calculation of threshold parameters in a robust statistical way for different environmental conditions. Torri and Poesen (2014) therefore proposed the following equation based on a large compiled dataset of threshold parameters:

$$\sin(\gamma) \geq 0.73c\, e^{1.3RFC}(0.00124S_{0.05} - 0.037)A^{-b} \quad (3)$$

where the sine of slope gradient was used to compile a dataset that comprises steep slopes ($\gamma > 15°$), which conforms to the original threshold approach of Patton and Schumm (1975) and Begin and Schumm (1979), where the flow shear stress equation uses the sine of the slope angle (for discussion, see Torri and Poesen, 2014); the coefficient c represents other factors and processes (e.g., piping) as a source of variation for k; RFC is rock fragment cover affecting the infiltration rate and runoff velocity (Poesen et al., 1990); and $S_{0.05}$ is the maximum potential

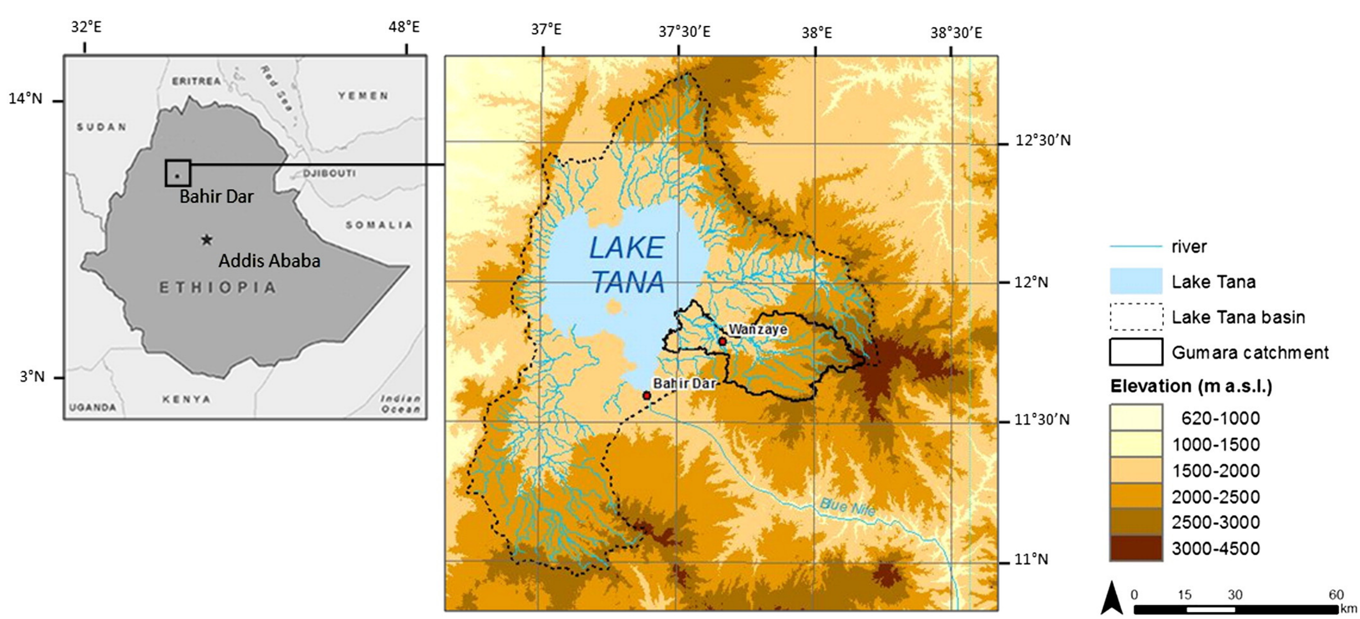

Fig. 1. Location of Wanzaye and the Gumara catchment in the Lake Tana basin (Ethiopia).

losses to runoff, with 0.05 as the fraction of S which represents the initial abstraction. $S_{0.05}$ can be determined by the Runoff Curve Number Method (Hawkins et al., 2009). This model requires a detailed description of local environmental characteristics. Torri and Poesen (2014) set the value of the exponent b to be constant because b does not show a trend for different land use types. The exponent b has been set at 0.38 and 0.5 by Torri and Poesen (2014), based on values obtained by Montgomery and Dietrich (1994), Nachtergaele et al. (2002) and Knapen and Poesen (2010). These values have been assessed using two overland flow functions: (i) the Manning formula and (ii) the stream power per unit volume (P) for which 0.38 and 0.5 proved to be good estimates of b. The value 0.38 is preferred to 0.5 as it performs better in predicting threshold conditions (Torri and Poesen, 2014).

Studies reporting topographic thresholds for gully head development quantify the different threshold values for different land use types. The most common land use categories investigated are cropland (e.g., Vandaele et al., 1996), rangeland (e.g., Vandekerckhove et al., 2000), pasture, grassland and forest (e.g., Vanwalleghem et al., 2003, 2005; Achten et al., 2008). The value of k increases for soils with more protection from erosion by vegetation cover (Table 1) (Torri and Poesen, 2014). As to the authors' knowledge, no differentiation for different management practices within the cropland category has ever been studied, although land management has an important effect on erosion processes and rates (e.g., Ligdi and Morgan, 1995; Casali et al., 1999; Nyssen et al., 2007; Maetens et al., 2012; Taye et al., 2013). Therefore, we have chosen the particular condition of the north western Ethiopian highlands where three types of land management practices are used side by side on cropland to reveal the effect of such land management practices on threshold conditions for gully head development. These three types of land management are: (i) stone bunds, a soil and water conservation practice established along the contour; (ii) drainage ditches, locally known as *feses*; and (iii) the combined use of stone

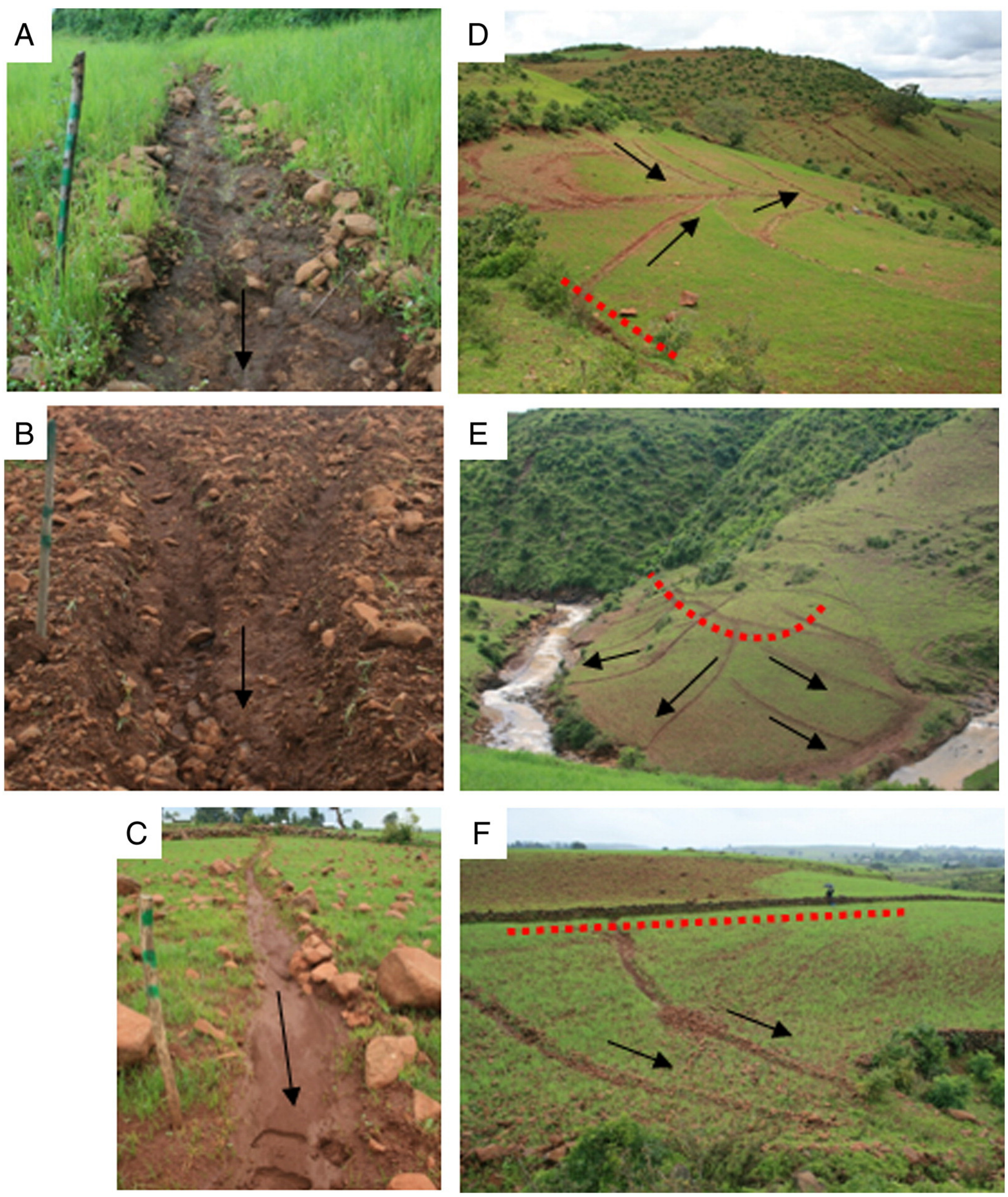

Fig. 3. Variations in cross section (A–C), gradient and density (D–F) of the *feses* (drainage ditches) in the study area. Wooden sticks are ca. 0.5 m long, direction of overland flow in the *feses* is indicated by arrows and a contour by a dashed line. (A) *Feses* which was deepened during the rainy season because of the erosive force of runoff water, (B) two *feses* constituting one larger *feses* perpendicular to the contour, (C) *feses* which became filled with sediment during the rainy season, (D) foreground illustrates *feses* in cropland during the rainy season; in the back, farmland without *feses* on which rill erosion occurs, (E) dense use of *feses*, and (F) mixed land management practice using both stone bunds and *feses* (August 2013).

bunds and *feses* (Monsieurs et al., 2014). Stone bunds have widely been applied in North Ethiopia and have proven successful in controlling soil erosion (Nyssen et al., 2007; Taye et al., 2013).

Man-made drainage ditches have a wide range of benefits for farmerland, although no consensus has been reached about the final balance of their positive and negative effects. In regions with high seasonal rainfall, nearly all sloping farmlands require drainage for crop production (Monsieurs et al., 2014). Drainage ditches capture the temporary excess of runoff water, guiding it downhill to reduce the negative effects of water logging on crops such as ponding water, soil compaction, subsurface anoxic conditions and a shallow root zone (Luthin, 1966; Robinson, 1990; Spaling and Smit, 1995; Zhang et al., 2013). On sloping cropland drainage ditches are also used as a physical soil conservation practice to divert runoff to decrease sheet and rill erosion rates of topsoil and seedlings (Shiferaw, 2002; Pathak et al., 2005). Nevertheless, the construction of drainage ditches is often perceived as a mismanagement of farmland as the increased concentrated flow erosion and its on-site and off-site effects cannot be neglected. On-site land degradation can be initiated by the malfunctioning of drainage ditches, diverting the water and creating a rill or gully, or the deepening of the drainage ditch by increased peak flow discharges (Holden et al., 2004; Simon and Rinaldi, 2006). Drainage ditches can also initiate off-site gully erosion and increase concentrated flow discharges (e.g., Shiferaw, 2002; Turkelboom et al., 2008; Simane et al., 2013; Zhang et al., 2013). Reij et al. (1996) state that for regions with annual rainfall approaching 1000 mm or more, combinations of soil and water conservation structures (such as stone bunds) and drainage systems in farm fields with a risk of water logging, are common (e.g., in the Mandara Mountains in North Cameroon).

The aim of this paper is threefold: (i) to assess the topographic threshold values for gully head development for three cropland management practices which are common in Ethiopia, (ii) to compare the effect of these land management practices on off-site gully erosion using topographical threshold analysis, and (iii) to discuss the effects of the use of drainage ditches.

2. Study area

2.1. Environmental conditions of the Lake Tana basin

Fieldwork was conducted during the rainy season (July–September) of 2013 around the village of Wanzaye (Fig. 1), located 20 km from the nearest shore of Lake Tana and 40 km from Bahir Dar, the capital city of the Amhara region in North Ethiopia. The study area is situated in the Gumara sub-basin (1279 km^2), which makes part of the Lake Tana basin. Lake Tana is the largest lake in Ethiopia with a total population in its basin of ca. 2.5 million. It is an important region for Ethiopia in many aspects such as agriculture, biodiversity, tourism, fishery and hydroelectric production at the Tis Abay and Tana-Beles stations (Setegn et al., 2009). The climate in the Lake Tana basin is cool to cold tropical highland monsoon, with an average air temperature of 18 ± 4 °C and large diurnal variation of ±15 °C (Dargahi and Setegn, 2011). The study area covers 18.2 km^2 for which we assume a spatially uniform seasonal rainfall depth. The average seasonal rainfall depth in the *kremt* (rainy) season (June–September) at the National Meteorological Services Agency rain gauge in Wanzaye (11.77 N, 37.6 E) is 1120 mm (Rientjes et al., 2013), which represents more than 70% of the yearly total rainfall.

The major soil types of the Lake Tana basin are Nitisols, Vertisols, Luvisols, Regosols and Phaeozems with a dominant presence of the Vertisols and Nitisols (Colot, 2012). The soils of the Lake Tana basin are derived from weathered volcanic rocks. Quaternary volcanoes and Tertiary volcanic plugs are visible in the landscape (Poppe et al., 2013). The most important parent materials are mafic rocks and lacustrine deposits (Colot, 2012). The majority of the basin has deep to

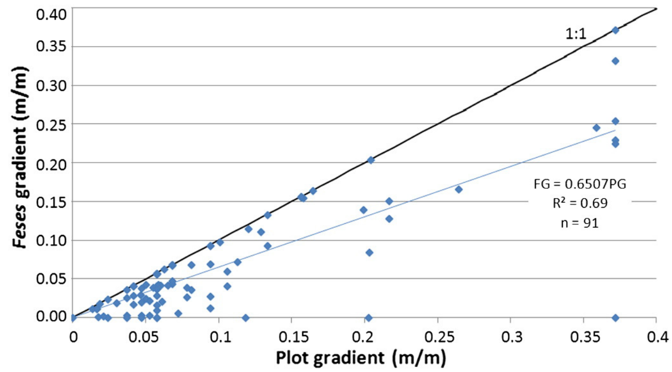

Fig. 4. Relation between plot gradient (*PG*) and *feses*' gradient (*FG*) for 91 *feses* in the study area (August 2013). 1:1 line is also shown.

very deep soils whereas soils on the hillslopes are shallow or very stony (Easton et al., 2010; Kebede et al., 2011).

2.2. Land management practices

The most common agricultural production system in the Lake Tana basin is the grain-plough complex, whilst the crop production consists of 70% of cereals which is typical for this system (Westphal, 1975). Rainfed farming agriculture is dominant, which is similar to most parts of Ethiopia (Hurni et al., 2005; Araya et al., 2012). Land preparation for cropping is done with the *maresha*, a single-tined ard plough, drawn by a pair of oxen (Gebreegziabher et al., 2009). The land management practices in the study area are strongly related to the highly seasonal rainfall pattern. We will focus on the three main land management practices applied in Wanzaye as well as in the wider region: i.e., (i) stone bunds, (ii) drainage ditches (*feses*), and (iii) the combined use of stone bunds and *feses* (Fig. 2).

Stone bunds, i.e., physical soil and water conservation structures in dry masonry built along the contour, are implemented in specific areas in the Lake Tana basin according to the policy of the Ministry of Agriculture, Ethiopia. The altitude of the area is one of the decision criteria as the policy reads that soil erosion control has to start from the upper parts of catchments, gradually taking the lower areas into account as well. Farmers are not always happy with this decision criterion because they know better the local areas vulnerable to erosion, which are not only those at high altitudes but also areas where other factors

Fig. 5. Gully formed by concentrated runoff from a catchment treated with stone bunds. The slope section on which the gully formed is much steeper than the overall slope of the stone bund catchment. The gully does not develop under the current cropland management practice (August 2013).

Fig. 6. Gully formed by concentrated runoff from a cropland catchment treated with *feses* (August 2013).

such as slope angle, slope aspect and land use are decisive (Wei et al., 2007). The construction of stone bunds is a time-consuming and tough labour task; therefore, the government organizes a rotational system in which all farmers from the neighbouring villages help with constructing stone bunds in the designated village. As a consequence, and due to time constraints, farmers are not able to construct stone bunds in the areas they know to be vulnerable to erosion. Nevertheless, the farmers around Wanzaye have agreed that the construction of stone bunds is the best way to prevent soil erosion on sloping farmland.

Feses are established by preparing widely-spaced furrows with the ox-drawn ard during the rainy season across sloping farmland (Fig. 3) for different reasons according to the farmers: (i) to avoid soil erosion by runoff, (ii) to avoid loss of seeds directly after sowing, and (iii) to drain accumulating runoff water away from their fields. After

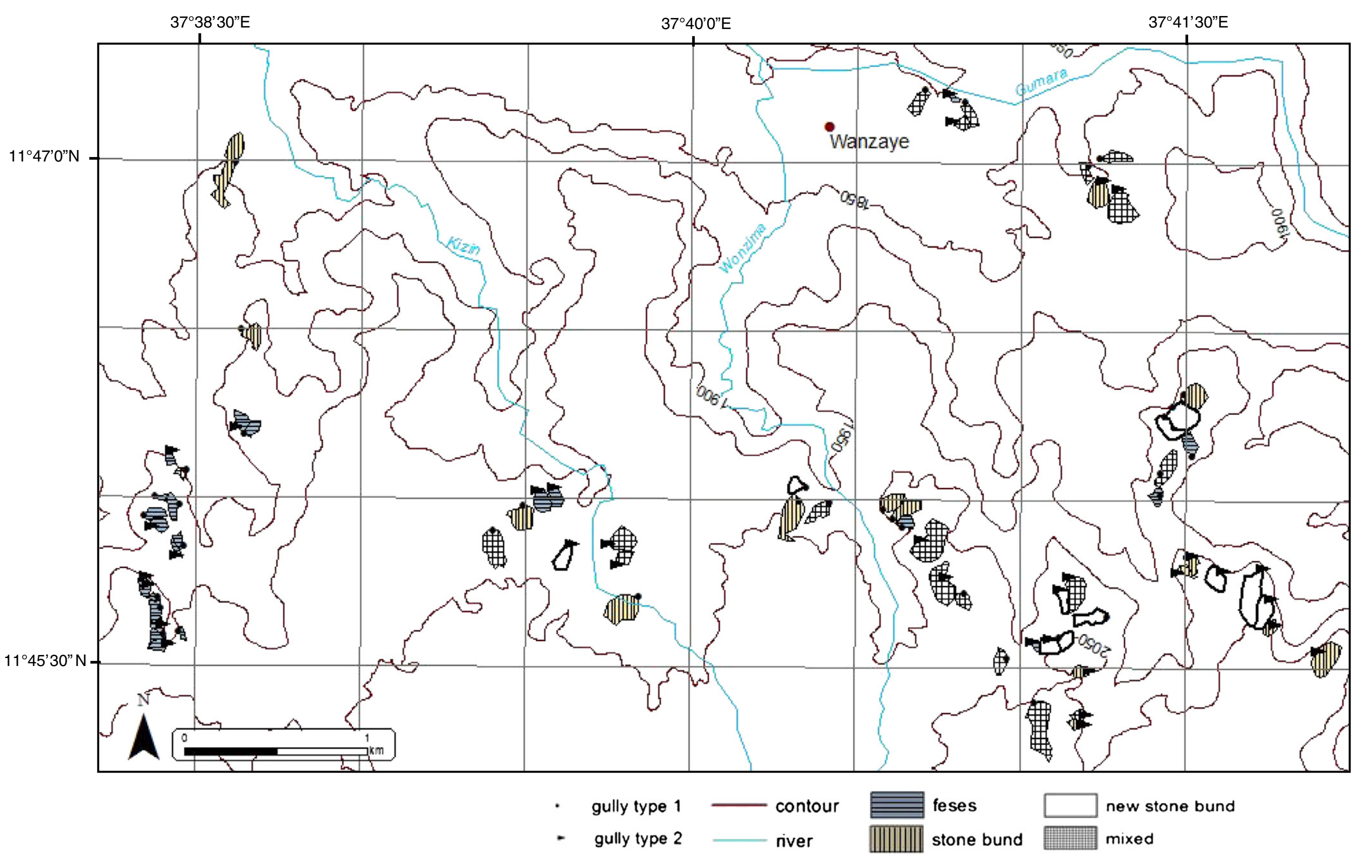

Fig. 7. Mapped gully catchments for analysing topographic threshold conditions. Catchments without shade comprise stone bunds younger than 10 years and are not further used for topographical threshold analysis as the related downstream gully is not in equilibrium with the current cropland management. 'gully type 1' represents a gully head on a slope section with a similar slope gradient as that of the catchment draining towards it; whereas, 'gully type 2' represents a gully head that developed on a slope section much steeper than the catchment draining into the gully.

establishment, the *feses* in the study area have a mean top width of 27 cm ($\pm$9 cm; $n = 41$) and a mean depth of 12 cm ($\pm$2 cm; $n = 37$) (Monsieurs et al., 2014). *Feses* density measured in cropland in the study area is 25 $\pm$ 18 km km^{-2}. *Feses* are established at an average angle of 44.7 $\pm$ 7.2°; $n = 96$ with the contour line and a mean gradient of 0.055 $\pm$ 0.054 m m^{-1}; $n = 96$. *Feses* gradients and plot gradients in the study area range from 0.000 to 0.372 m m^{-1} (Fig. 4), and the former are usually smaller than the latter. On average, the gradient of *feses* increases with an increasing plot gradient, for which we could establish the following relation in the study area (Fig. 4):

$$FG = 0.6507PG \left(R^2 = 0.69\right) \tag{4}$$

where FG is the *feses* gradient (m m^{-1}) and PG is the plot gradient (m m^{-1}). A wide range of *feses* gradients is observed, which can be explained by the fact that construction variables of *feses* (Fig. 3) depend on the farmers' decisions that take into account their planted crop, indigenous knowledge, relation with neighbouring farmers and the dimensions of the *maresha*.

Feses are constructed at the farmers' own initiative, rather than by mass mobilization by the authorities as it is done for the construction of stone bunds. When the functions of *feses*, as discussed above, are not needed anymore, i.e., as the growing crops reach a certain height, these *feses* are purposely filled with weeded materials including the soil attached at its roots. Although farmers are aware of the on-site soil erosion caused by *feses*, i.e., local removal of fertile topsoil, they perceive *feses* as the best conservation practice if no stone bunds are present. *Feses* draining the excess runoff water into the field of a neighbouring farmer may cause tensions between upslope and downslope farmers as this excess water may cause increased erosion in the downslope area (Smit and Tefera, 2011). Although the combined use of stone bunds and *feses* is formally forbidden by the regional Ministry of Agriculture because stone bunds can be destroyed by *feses*, a common practice in the study area is the joint implementation of both stone bunds and *feses* on cropland (Fig. 3), which is referred to as 'mixed' hereafter. The poor functioning of stone bunds or an excess of water that needs to be drained away are reasons reported by farmers for the use of the mixed management. The above observation indicates that the three distinctive land management practices (stone bunds, *feses*, and mixed) affect the erosion processes and rates on cropland in different ways.

3. Methodology

3.1. Data collection

Although we are aware of the extended standardized model for topographic thresholds (Eq. (3)), we opted in this research for the model given by Eq. (1) for its simplicity and its fast and practical implementation. *RFC* for each gully head catchment has not been measured systematically; neither is sufficient information available to calculate $S_{0.05}$ and c in Eq. (3). However, the variables of Eq. (1) are used to allow for the detection of trends by comparing our data with the large compiled dataset of Torri and Poesen (2014).

The stone bund catchments (Fig. 5), *feses* catchments (Fig. 6) and mixed catchments, all draining towards a gully head, were delineated using a handheld GPS. In total we mapped 26 *feses* catchments, 27 stone bund catchments, and 22 mixed catchments (Fig. 7) for which the position of the corresponding gully head was also recorded by GPS. Based on the catchment area, four outliers were found using the outlier labelling rule (David, 1977; Hoaglin et al., 1986) which are excluded from further analysis. Catchments comprising stone bunds constructed after 2003 (marked in Fig. 7) and catchments intersected by roads have been excluded from the dataset, because roads may either reduce or increase the original catchment area (Nyssen et al., 2002).

For the former, gullies might have been formed under past land management conditions without stone bunds, and they would have been wrongly classified as 'stone bund catchments'. This analysis was made using historical Google Earth images (Fig. 8), which are available for the study area for the years 2003, 2010 and partly also 2013.

The GPS data were further analysed using a GIS program (ArcMAP 10.0) to deduce s (m m^{-1}) and A (ha). The local slope gradient was derived from a DEM (resolution: 30 × 30 m), for the pixel where the gully head was located.

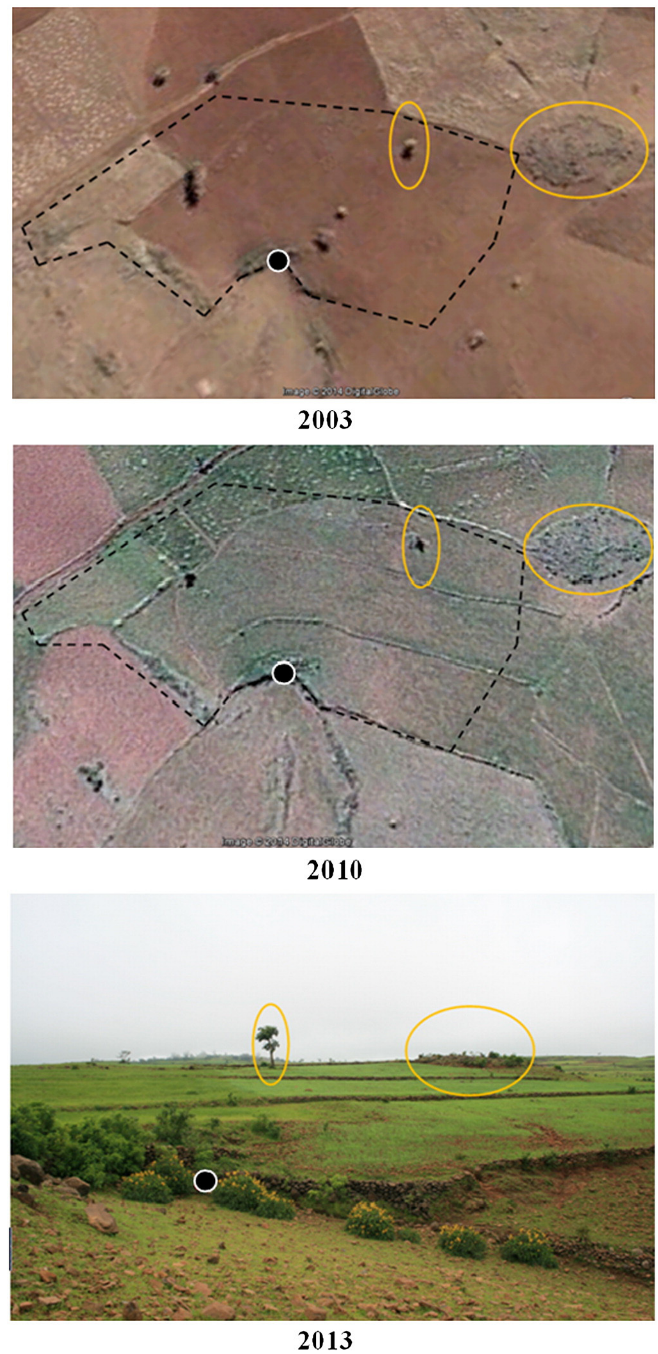

Fig. 8. Image analysis of a catchment comprising stone bunds. The lowest photo was taken during fieldwork in 2013. The corresponding gully head is marked by a black dot and two reference points (tree and bush) are circled. In 2003, the catchment could not be regarded as a stone bund catchment. In 2010, stone bunds appeared. Gullies might have been formed under land management conditions without stone bunds, so that they would be wrongly classified as 'stone bund catchments'.

3.2. Setting parameters and a threshold line

For the exponent b in Eq. (1), two values 0.38 and 0.5 are used according to the standardized procedure proposed by Torri and Poesen (2014). Because the latter corresponds to laminar flow, which is rather exceptional in our study area, we prefer to use the former in this study. To calculate *s*, we implement Eq. (2) rather than using sine as in Eq. (3), because the former better reflects the concept of 'slope gradient' in relation to the flow shear stress concept upon which Eq. (1) was originally based (Patton and Schumm, 1975; Begin and Schumm, 1979). The mean slope angle for all catchments does not exceed 18°, which is close to 15° for which the tangent can substitute sine without a significant effect on the topographic threshold (Torri and Poesen, 2014).

The topographic threshold lines have been defined by first fitting *s*–*A* threshold lines for b = 0.38 and 0.5 to the dataset, which were then positioned through the lower most data points. This positioning of the threshold lines was done by focusing on the small drainage areas, as these have a higher probability of meeting the assumption that the entire area contributes to overland flow (Torri and Poesen, 2014).

4. Results

4.1. Group mean differences

The characteristics of the gully heads and their catchments, grouped according to the land management practices are shown in Table 2. The top width and depth of the gully heads have been estimated by post-analysis of the photographs taken at the gully head. The size of all catchments is defined as the drainage area corresponding to the uppermost gully head. Analyses are based on the filtered dataset, i.e., excluding outliers and catchments with stone bunds less than 10 years old. *Feses* catchments are characterised by an area ranging from 0.15 to 0.89 ha, with a mean of 0.45 ± 0.20 ha and a mean slope gradient of 0.29 ± 0.12 m m^{-1}. Catchments with stone bunds exclusively have an area ranging from 0.31 to 2.75 ha with a mean of 1.24 ± 0.78 ha and a mean slope gradient of 0.33 ± 0.18 m m^{-1}. The selected mixed catchments have areas ranging from 0.28 to 2.93 ha with a mean of 1.19 ± 0.81 ha and a mean slope gradient of 0.21 ± 0.13 m m^{-1}.

4.2. Topographic threshold analysis

Drainage area and slope gradient of the soil surface at the gully head were plotted for the three land management practices (Fig. 9): *feses*, stone bund, and mixed. Catchments including stone bunds less than 10 years old were excluded when drawing the topographical threshold lines. The corresponding k-values (Eq. (1)) for b = 0.38 and 0.5 and for the three cropland management practices are presented in Table 3. The lowest k-values are found for the *feses* catchments, slightly higher k-values are found for the mixed catchments, and the highest k-values correspond to the stone bund catchments.

The average k-values for the Wanzaye cropland are 0.131 ± 0.052 for b = 0.38, and 0.123 ± 0.054 for b = 0.5, which are larger than those for cropland reported by Torri and Poesen (2014) (Table 1). It should be noted that k-values increase with *RFC* and content of the topsoil (Torri and Poesen, 2014). We found in our study area a mean *RFC* value of 68 ± 26.1% ($n = 38$), which partly explains the larger k-values observed in this study.

The different catchment types constitute different populations (Table 2, Fig. 10) regarding the means of the catchment area, which was statistically validated by a t-test using independent samples (significance level $\alpha = 0.05$; also for the following tests). The area of the *feses* catchments is significantly smaller than that of stone bund or mixed

Table 2
Characteristics of gully heads and their drainage areas. Approximate width (*W*) and depth (*D*) of the gully head, drainage area (*A*), and surface slope gradient (*s*) at the gully head for each individual gully head (GH) at the outlet of a *feses* catchment (F), stone bund catchment (S) and mixed catchment (M). Gully heads for which no photographs were taken to estimate their width and depth are marked by NA. Additional information on the gully catchments is given under 'I': (a) catchments where stone bunds were installed before 2003; (b) catchments where stone bunds were constructed after 2003, (c) catchments with a gully head positioned on a steeper slope section than the overall slope gradient of the drainage area, and (d) outliers based on the drainage area. Mean (*M*) and standard deviation (*SD*) were calculated excluding the catchments marked by b or d.

Feses catchment					Stone bund catchment					Mixed catchment				
GH	*W*; *D* (m)	*A* (ha)	*s* (m m^{-1})	I	GH	*W*; *D* (m)	*A* (ha)	*s* (m m^{-1})	I	GH	*W*; *D* (m)	*A* (ha)	*s* (m m^{-1})	I
F1	NA; NA	0.15	0.35		S1	0.5; 0.5	0.31	0.44	a, c	M1	2.0; 1.0	0.28	0.48	a
F2	0.5; 0.5	0.15	0.18	c	S2	1.0; 0.5	0.36	0.41	a, c	M2	1.0; 1.0	0.31	0.51	a, c
F3	1.5; 1.0	0.18	0.33	c	S3	1.5; 1.0	0.47	0.79	a, c	M3	1.5; 1.0	0.47	0.08	a, c
F4	3.0; 2.0	0.18	0.51		S4	1.0; 0.5	0.53	0.27	a, c	M4	5.0; 1.5	0.53	0.29	a
F5	0.5; 1.0	0.22	0.19	c	S5	1.0; 0.5	0.53	0.45	a, c	M5	1.0; 1.0	0.56	0.14	a
F6	1.0; 1.0	0.24	0.57	c	S6	1.0; 1.0	0.55	0.34	b	M6	2.0; 1.0	0.61	0.13	a, c
F7	2.5; 1.5	0.28	0.34	c	S7	0.5; 0.5	0.65	0.08	b, c	M7	3.0; 2.0	0.63	0.19	a
F8	2.0; 1.0	0.30	0.29	c	S8	2.0; 0.5	0.66	0.07	b	M8	NA; NA	0.74	0.08	a
F9	1.0; 1.0	0.33	0.41	c	S9	2.0; 1.5	0.86	0.11	b	M9	NA; NA	0.81	0.33	a
F10	1.5; 0.5	0.35	0.24		S10	NA; NA	0.94	0.24	a	M10	0.5; 0.5	0.83	0.13	b
F11	1.0; 1.0	0.38	0.49	c	S11	1.0; 1.0	0.98	0.18	b, c	M11	2.5; 0.5	0.86	0.22	a
F12	NA; NA	0.40	0.36		S12	0.5; 0.5	1.01	0.22	b	M12	NA; NA	0.86	0.33	a
F13	0.5; 1.0	0.45	0.15		S13	NA; NA	1.03	0.34	b	M13	3.5; 2.0	1.28	0.18	a
F14	NA; NA	0.48	0.09		S14	NA; NA	1.05	0.22	a	M14	1.0; 1.0	1.40	0.10	a, c
F15	2.0; 2.0	0.49	0.27		S15	1.5; 0.5	1.13	0.33	b, c	M15	1.0; 0.5	1.53	0.21	a, c
F16	1.0; 1.0	0.55	0.31	c	S16	1.5; 1.5	1.24	0.81	b, c	M16	1.0; 1.5	1.91	0.10	a
F17	1.5; 1.5	0.55	0.14	c	S17	1.5; 1.0	1.35	0.40	a, c	M17	0.5; 0.5	2.01	0.21	a, c
F18	1.5; 0.5	0.60	0.29	c	S18	NA; NA	1.39	0.47	a	M18	1.0; 0.5	2.12	0.12	a, c
F19	NA; NA	0.61	0.24		S19	1.0; 1.0	1.45	0.20	a	M19	1.0; 0.5	2.77	0.25	a
F20	2.0; 1.5	0.62	0.25		S20	1.5; 0.5	1.71	0.11	b	M20	NA; NA	2.93	0.06	a, c
F21	2.0; 1.0	0.63	0.15	c	S21	1.0; 0.5	1.90	0.44	a, c	M21	5.0; 1.5	4.90	0.09	d
F22	2.0; 1.0	0.64	0.40		S22	NA; NA	1.93	0.33	b	M22	2.5; 1.0	10.12	0.19	d
F23	NA; NA	0.69	0.21		S23	2.0; 2.0	2.10	0.06	a					
F24	1.0; 0.5	0.78	0.34	c	S24	1.5; 0.5	2.22	0.17	a					
F25	2.0; 0.5	0.89	0.17	c	S25	1.5; 1.5	2.57	0.72	b, c					
F26	1.0; 0.5	1.39	0.09	d	S26	2.0; 1.0	2.75	0.12	a					
					S27	NA; NA	4.88	0.11	d					
M	1.5; 1.0	0.45	0.29		*M*	1.3	1.24	0.33		*M*	1.9	1.19	0.21	
SD	0.7; 0.5	0.20	0.12		*SD*	0.5	0.78	0.18		*SD*	1.4	0.81	0.13	

catchments. However, there is no significant difference between the area of the stone bund catchments and that of the mixed catchments. The slope gradient at the gully heads of the mixed catchments is significantly smaller than those of the *feses* and stone bund catchments, whereas no significant difference in slope was found between the *feses* and stone bund catchments.

Table 2 and Fig. 10 indicate that the *feses* catchments tend to be smaller and steeper, whereas stone bund catchments are larger but also occur on steep slopes. On the other hand, the mixed catchments are located on gentler slopes.

We should be cautious when interpreting these findings because the catchments used in our analyses are not uniform in other characteristics such as rock fragment content and soil type, which can also influence gully head development. Nevertheless, some clear trends are visible in the data. We can deduce from Table 3 that the stone bund catchments are more resistant to gully head development than the *feses* or mixed catchments, whereas the *feses* catchments are the most vulnerable to gully head development (Fig. 10).

5. Discussion

5.1. Data scatter in s–A plots

There are several sources of scatter of the data points in the *s–A* plots of Fig. 9. One is the local slope gradient defined using the 30 × 30 m DEM, which may not fully capture the local slope gradient near the gully head (Nyssen et al., 2002). The other is the delineation of the catchment area, which may change over time due to tillage operations (Takken et al., 2001) and other land management interventions; for instance drainage ditch construction may enlarge the catchment area due to a waterway connected to another area. For this reason, we focus more on small drainage areas when constructing a threshold line, as mentioned above.

Additionally, the topographical position of gully heads can bias our data. Regressive erosion of a gully head on a hillslope will cease if it reaches a slope section with a gradient too small for gullying (Fig. 5) (Poesen et al., 2003); whereas, a gully head retreats further upslope if the slope gradient remains high (Fig. 11). For both gully types, however, only the steeper slope section was used in the analysis of topographical thresholds. On the other hand, excluding catchments with stone bunds less than 10 years old (see Section 3.1), reduced the scatter in the *s–A* dataset (Fig. 9).

An additional factor to be considered is the spatial variability of *RFC*. With increasing *RFC*, erosion by concentrated flow decreases exponentially (Poesen et al., 1999), and hence the topographic threshold for gullying increases (Torri and Poesen, 2014). Field observations in the study area indicate that the highest *RFC* values are found on steeper convex slopes (Miserez, 2013), which is in line with observations made elsewhere (e.g., Lanckriet et al., 2012 in Northern Ethiopia). Spatial variability of *RFC* is caused by both natural processes (e.g., Poesen et al., 1998) and anthropogenic processes such as tillage erosion (Poesen et al., 1997) and rock fragment removal (Nyssen et al., 2001); these processes are encountered in the study area.

5.2. Explanatory variables for land management practices

Based on Table 2 and Fig. 10, three trends in land management practices are observed: (i) the exclusive use of *feses* tends to be applied on steeper areas where only a small drainage area is required for gully head development, (ii) stone bunds are used on both steeper and gentle slopes, and (iii) gentle slopes with large drainage areas seem to be suitable for the mixed use of *feses* and stone bunds. These findings correspond well to the explanations given by local farmers. Especially on steep areas, conservation practices are needed to maintain soil's productivity, and the farmers said that stone bunds are useful. They also construct *feses* for conservation, and runoff will be guided downslope

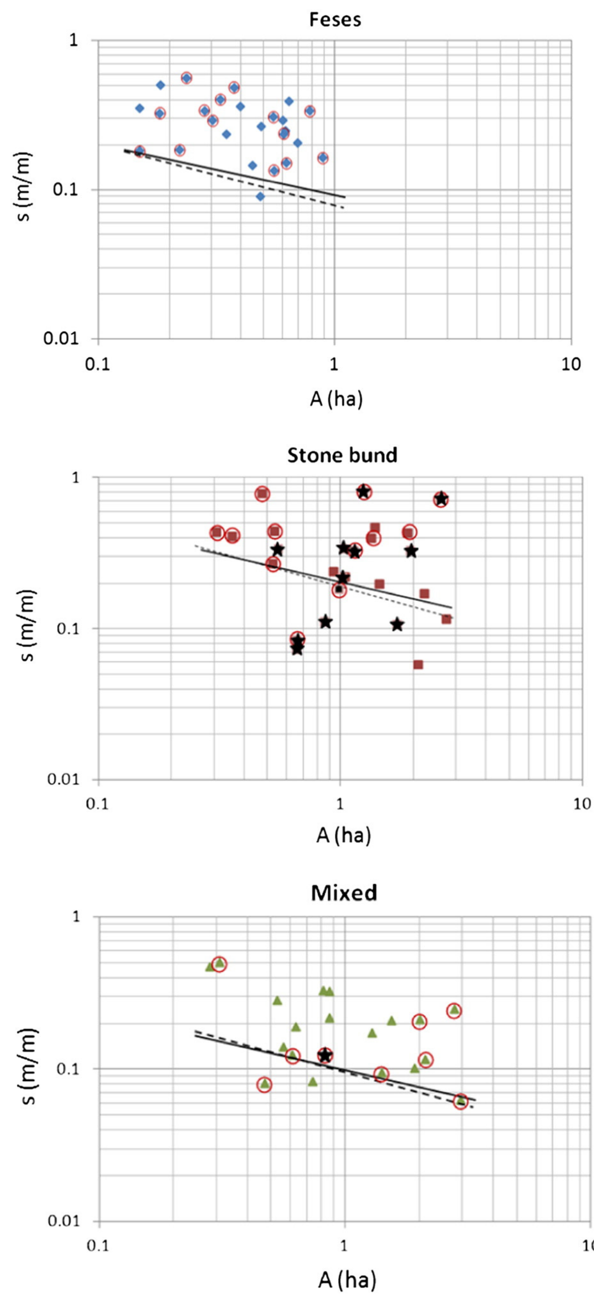

Fig. 9. Topographic thresholds based on *s* (slope gradient of the soil surface at the head) and *A* (drainage area) for gully heads under three cropland management practices in the study area and corresponding to two values of the exponent b in Eq. (1): 0.38 (solid line) and 0.5 (dashed line). Encircled data points refer to catchments for which the slope gradient of the soil surface at the gully head is much steeper than the overall slope gradient of the catchment. Data points marked as a star represent catchments including stone bunds less than 10 years old. These catchments were excluded from the analysis.

at a smaller gradient than the plot gradient (Fig. 4), reducing sheet and rill erosion (Hurni, 1985; Liu et al., 1994). In some cases, farmers combine stone bunds with *feses* to compensate for the malfunctioning

Table 3
Values of the coefficient k, where b of Eq. (1) was set at two values: 0.38 and 0.5, for three cropland management practices in the gully catchment: drainage ditches (*feses*), stone bunds or their mixture. The last column shows the average and standard deviation.

	Feses	Stone bund	Mixed	Average
b = 0.38	0.090	0.205	0.099	0.131 (±0.052)
b = 0.5	0.078	0.198	0.092	0.123 (±0.054)

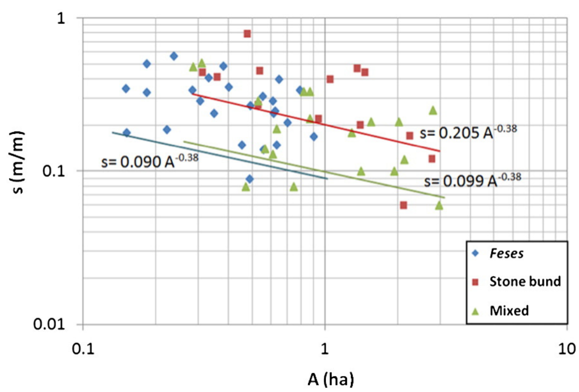

Fig. 10. Topographic threshold lines based on slope gradient *s* and drainage area *A* for gully head development under three cropland management practices: i.e.; stone bunds (squares), drainage ditches or *feses* (diamonds) and their mixture (triangles). Exponent b of Eq. (1) is set constant at 0.38.

or poor construction of stone bunds (e.g., no outlet for excess runoff water provided). However, this is discouraged by the authorities because the concentrated runoff in the *feses* may destroy the stone bunds. This explains why the mixed use of *feses* and stone bunds is applied on gentler areas where the concentrated runoff does not become too powerful.

5.3. Threshold coefficient k for different land managements and RFC values

As the coefficient k reflects the resistance of an area to gully head development (Torri and Poesen, 2014), we can deduce from Table 3 that catchments with the exclusive use of stone bunds are more resistant to gully head development than those with *feses* or mixed catchments which is consistent with previous research results (Nyssen et al., 2007; Taye et al., 2013). Table 3 also indicates that catchments with the exclusive use of *feses* are the most vulnerable to gully head development, as illustrated in Fig. 10 that the threshold line for the *feses* catchments lies below that of the mixed catchments, which in turn lies below that of the stone bund catchments. Based on these results we cannot confirm the statements of Shiferaw (2002) and Pathak et al. (2005) that the use of *feses* is a good soil conservation practice. This study demonstrates how the analysis of topographical thresholds for gully head development under different land management practices in cropland may contribute to better understanding and mitigating gully erosion.

Torri and Poesen (2014) reported mean k values of 0.043 (b = 0.38) and 0.037 (b = 0.5) for cropland, which are roughly one third of those found in this study: i.e., 0.131 and 0.123. This difference can be attributed to fewer rock fragments in the case of Torri and Poesen (2014). To adjust their values to k-values for cropland with abundant rock fragments, a correction factor can be calculated using the equation of Torri and Poesen (2014):

$$correctedvalue = \frac{observed}{predicted} = 0.69e^{1.2RFC}. \tag{5}$$

For a mean *RFC* value of 68% in our study area, the correction factor equals 1.56. Taking this factor into account, the mean k-values for cropland according to Torri and Poesen (2014) increase: 0.067 (b = 0.38) and 0.058 (b = 0.5) (Table 1), although they are still only half of the k-values found in our study area. This means that the cropland we studied is less vulnerable to gully head development compared with the average cropland conditions in other regions of the world. We also consider that our values can be only compared with the dataset of Torri and Poesen (2014) for which the same procedure (Eq. (1)) is used for calculating the coefficients.

5.4. Sedimentation in gullies

From Fig. 9 we observe that no gully heads were found on land with a slope gradient less than 6%. This is slightly different from observations by Poesen et al. (2003) in Northern Europe where they found the lower slope limit of gullying to be 2% to 4%, because sediment deposition dominates on gentler slope gradients. When the rock fragment content of the topsoil increases, however, the topographically induced sedimentation will take place on steeper slopes (Poesen et al., 2002). The critical slope of the soil surface for sediment deposition for *RFC* = 68% as observed in our study area would be 6% according to the data of Poesen et al. (2002) from cropland in Western Europe, which is similar to our findings.

6. Conclusions

In this paper, we have illustrated the practical use of topographic thresholds for gully head development to study the effect of various cropland management practices on vulnerability to gullying. Values for the coefficient k in the topographical threshold equation (Eq. (1)) can help soil conservationists to identify which management practices reduce vulnerability to gully erosion. In the case of our study area in Wanzaye, Ethiopia, three different land management practices have been considered: stone bunds, drainage ditches (*feses*), and their mixed use. The lowest k-values are found for catchments where *feses* are implemented, higher values are found for mixed catchments, and the highest values are found for stone bund catchments. This implies that the *feses* catchments are the most vulnerable to gully head development compared to the stone bund and mixed catchments. Yet, on-site sheet and rill erosion are reduced by the use of *feses* as they reduce

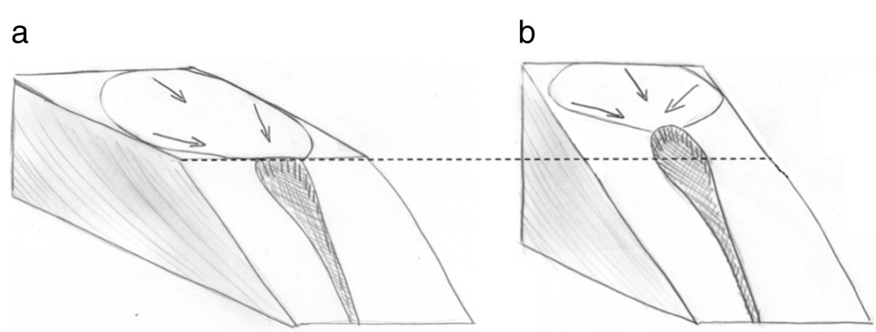

Fig. 11. Gully head development under two different topographical conditions. The slope gradient (*s*) of the soil surface on which the gully head developed can be much steeper than (a) or similar to (b) the slope of the corresponding catchment with area (*A*). This will create a bias when determining the topographical thresholds for gully head development. Catchments under conditions (a) will produce a data point on the *s*–*A* graph located more to the right (bigger area *A*) compared to a catchment that would have reached equilibrium (in terms of the slope gradient (*s*) and the (smaller) area (*A*) draining into the gully head) for constant slope conditions.

the runoff gradient. The use of *feses*, however, induces a range of other effects on the productivity of cropland, which needs further research.

In the studied cropland and the surrounding region, three trends in land management have been observed: (i) the exclusive use of *feses* is on steeper slopes for which only a small drainage area is required to develop a gully head, (ii) stone bunds are used on both steeper and gentler sloping cropland, and (iii) gentle slopes with large upstream areas seem to be the most suitable for the mixed use. It seems impossible to compare our findings with previous research on topographical threshold conditions for gullying, because: (i) to the authors' knowledge topographic thresholds have not been used elsewhere to study the impact of land management practices on gully erosion, and (ii) the standardized procedure for topographical threshold analysis was only recently proposed by Torri and Poesen (2014). Therefore we recommend more research on topographical threshold conditions for different land management practices following this standardized procedure.

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