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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:

$$s \geq kA^{-b} \quad (1)$$

$$s = \tan\gamma \quad (2)$$

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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

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

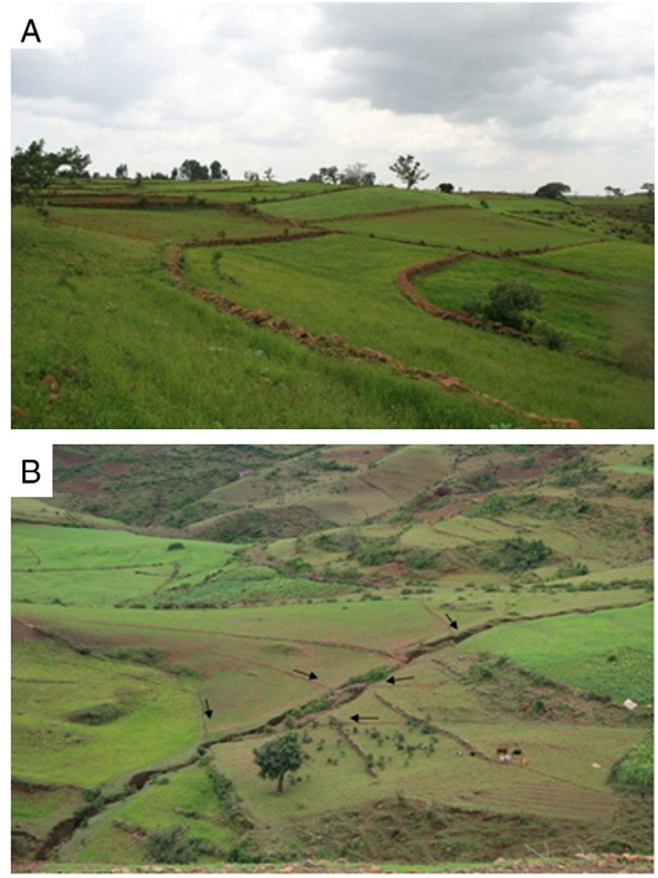

Fig. 2. Typical land management situations in the study area. (A) Stone bund catchment. (B) Mixed catchments with *feses* and stone bunds (summer of 2013). Direction of overland flow in the *feses* is indicated by arrows (after Monsieurs et al., 2014, published with permission from John Wiley & Sons).

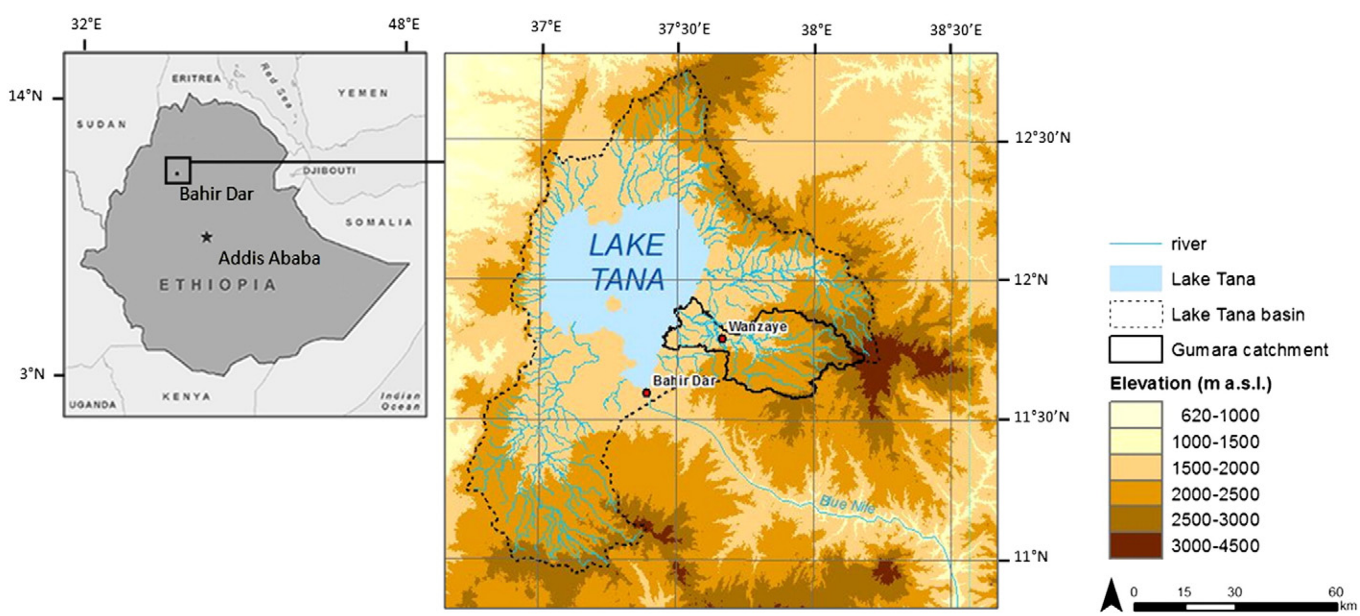

Fig. 1. Location of Wanzaye and the Gumara catchment in the Lake Tana basin (Ethiopia).