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

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24 **Abstract**

25 Gully erosion is an extreme process of land degradation operating in different regions of the
26 world. A common way to quantify the susceptibility of land to gully incision is the use of
27 topographical thresholds for different land use types. However, the impact of various
28 management practices in cropland on these thresholds has not been studied to date, despite the
29 important effect land management may have on runoff production, erosion processes and rates.
30 Here, the impact of different land management practices on gully head development in cropland
31 is studied based on a standardized procedure for topographical threshold analysis: $s > kA^{-b}$,
32 where s represents the slope gradient of the soil surface, A the drainage area at the gully head, b
33 an exponent and k a coefficient reflecting the resistance of the land to gully head development. A
34 case study area was chosen around Wanzaye, North Ethiopia, where three different cropland
35 management practices were studied in 75 catchments: (i) the catchment-wide use of stone bunds
36 on the contour, (ii) the use of slightly sloping drainage ditches (*feses*), and (iii) the combined use
37 of stone bunds and *feses*. The lowest k -values (0.078–0.090) are found for catchments treated
38 with *feses*, the highest k -values (0.198–0.205) are observed for stone bund catchments and
39 medium k -values (0.092–0.099) are found for mixed catchments. This finding implies that

40 catchments with the exclusive use of drainage ditches are the most vulnerable to gully head
41 development compared with mixed catchments and stone bund catchments. However, on-site
42 sheet and rill erosion rates are reduced by *feses* as they lower the gradient of the overland flow
43 lines. Three trends in cropland management around Wanzaye and the wider region are observed:
44 (i) *feses* are exclusively made on rather steep slopes where small drainage areas lead to the rapid
45 development of gully heads; (ii) stone bunds are constructed on both steeper and gentle sloping
46 cropland; and (iii) larger and gently sloping catchments seem to be most suitable for the
47 combined use of drainage ditches and stone bunds.

48

49 Keywords: Topographical threshold; Gully; Drainage ditch; Land management; Erosion;
50 Cropland

51

52 **1. Introduction**

53 Gully erosion is a widely studied geomorphological process, as it affects soil quality, the water
54 table, trafficability and sediment connectivity (e.g., Poesen et al., 2003; Le Roux and Sumner,
55 2012). International attention to this process is explained by its on-site and off-site impacts on
56 large areas and the economic losses to farmers (e.g., Poesen et al., 2003; Valentin et al., 2005;
57 Vrieling et al., 2007). Therefore, gully erosion needs to be better understood and managed, and
58 its effects should be mitigated (Torri and Poesen, 2014).

59 A common way to quantify the susceptibility of cropland to gully erosion is to apply a coupled
60 criteria analysis of topographic factors controlling the gully head position (e.g., Vandaele et al.,
61 1996; Vandekerckhove et al., 1998; Nyssen et al., 2002; Morgan and Mngomezulu, 2003; Poesen

62 et al., 2003). Topographic thresholds are commonly presented as double logarithmic plots of
63 upslope drainage area (A) and slope gradient of the soil surface at the gully head (s). Patton and
64 Schumm (1975) and Begin and Schumm (1979) were pioneers in modelling gully erosion as a
65 threshold process:

$$66 \quad s \geq kA^{-b} \quad (1)$$

$$67 \quad s = \tan \gamma \quad (2)$$

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

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

$$80 \quad \sin(\gamma) \geq 0.73c e^{1.3RFC} (0.00124S_{0.05} - 0.037)A^{-b} \quad (3)$$

81 where the sine of slope gradient was used to compile a dataset that comprises steep slopes ($\gamma >$
82 15°), which conforms to the original threshold approach of Patton and Schumm (1975) and

83 Begin and Schumm (1979), where the flow shear stress equation uses the sine of the slope angle
84 (for discussion, see Torri and Poesen, 2014); the coefficient c represents other factors and
85 processes (e.g., piping) as a source of variation for k ; RFC is rock fragment cover affecting the
86 infiltration rate and runoff velocity (Poesen et al., 1990); and $S_{0.05}$ is the maximum potential
87 losses to runoff, with 0.05 as the fraction of S which represents the initial abstraction. $S_{0.05}$ can be
88 determined by the Runoff Curve Number Method (Hawkins et al., 2009). This model requires a
89 detailed description of local environmental characteristics. Torri and Poesen (2014) set the value
90 of the exponent b to be constant because b does not show a trend for different land use types. The
91 exponent b has been set at 0.38 and 0.5 by Torri and Poesen (2014), based on values obtained by
92 Montgomery (1994), Nachtergaele et al. (2002) and Knapen and Poesen (2010). These values
93 have been assessed using two overland flow functions: (i) the Manning formula and (ii) the
94 stream power per unit volume (P) for which 0.38 and 0.5 proved to be good estimates of b . The
95 value 0.38 is preferred to 0.5 as it performs better in predicting threshold conditions (Torri and
96 Poesen, 2014).

97 Studies reporting topographic thresholds for gully head development quantify the different
98 threshold values for different land use types. The most common land use categories investigated
99 are cropland (e.g., Vandaele et al., 1996), rangeland (e.g., Vandekerckhove et al., 2000), pasture,
100 grassland and forest (e.g., Vanwalleghem et al., 2003, 2005; Achten et al., 2008). The value of k
101 increases for soils with more protection from erosion by vegetation cover (Table 1) (Torri and
102 Poesen, 2014). As to the authors' knowledge, no differentiation for different management
103 practices within the cropland category has ever been studied, although land management has an
104 important effect on erosion processes and rates (e.g., Casali et al., 1999; Ligdi and Morgan,
105 1995; Nyssen et al., 2007; Maetens et al., 2012; Taye et al., 2013). Therefore, we have chosen

106 the particular condition of the north western Ethiopian highlands where three types of land
107 management practices are used side by side on cropland to reveal the effect of such land
108 management practices on threshold conditions for gully head development. These three types of
109 land management are: (i) stone bunds, a soil and water conservation practice established along
110 the contour; (ii) drainage ditches, locally known as *feses*; and (iii) the combined use of stone
111 bunds and *feses* (Monsieurs et al., 2014). Stone bunds have widely been applied in North
112 Ethiopia and have proven successful in controlling soil erosion (Nyssen et al., 2007; Taye et al.,
113 2013).

114 ***Table 1 approximately here***

115 Man-made drainage ditches have a wide range of benefits for farmerland, although no consensus
116 has been reached about the final balance of their positive and negative effects. In regions with
117 high seasonal rainfall, nearly all sloping farmlands require drainage for crop production
118 (Monsieurs et al., 2014). Drainage ditches capture the temporary excess of runoff water, guiding
119 it downhill to reduce the negative effects of water logging on crops such as ponding water, soil
120 compaction, subsurface anoxic conditions and a shallow root zone (Luthin, 1966; Robinson,
121 1990; Spaling and Smit, 1995; Zhang et al., 2013). On sloping cropland drainage ditches are also
122 used as a physical soil conservation practice to divert runoff to decrease sheet and rill erosion
123 rates of topsoil and seedlings (Shiferaw, 2002; Pathak et al., 2005). Nevertheless, the
124 construction of drainage ditches is often perceived as a mismanagement of farmland as the
125 increased concentrated flow erosion and its on-site and off-site effects cannot be neglected. On-
126 site land degradation can be initiated by the malfunctioning of drainage ditches, diverting the
127 water and creating a rill or gully, or the deepening of the drainage ditch by increased peak flow
128 discharges (Holden et al., 2004; Simon and Rinaldi, 2006). Drainage ditches can also initiate off-

129 site gully erosion and increase concentrated flow discharges (e.g., Shiferaw, 2002; Turkelboom
130 et al., 2008; Simane et al., 2013; Zhang et al., 2013). Reij et al. (1996) state that for regions with
131 annual rainfall approaching 1000 mm or more, combinations of soil and water conservation
132 structures (such as stone bunds) and drainage systems in farm fields with a risk of water logging,
133 are common (e.g., in the Mandara Mountains in North Cameroon).

134
135 The aim of this paper is threefold: (i) to assess the topographic threshold values for gully head
136 development for three cropland management practices which are common in Ethiopia, (ii) to
137 compare the effect of these land management practices on off-site gully erosion using
138 topographical threshold analysis, and (iii) to discuss the effects of the use of drainage ditches.

139

140 **2. Study area**

141 *2.1. Environmental conditions of the Lake Tana basin*

142 Fieldwork was conducted during the rainy season (July–September) of 2013 around the village
143 of Wanzaye (Fig. 1), located 20 km from the nearest shore of Lake Tana and 40 km from Bahir
144 Dar, the capital city of the Amhara region in North Ethiopia. The study area is situated in the
145 Gumara sub-basin (1279 km²), which makes part of the Lake Tana basin. Lake Tana is the
146 largest lake in Ethiopia with a total population in its basin of ca. 2.5 million. It is an important
147 region for Ethiopia in many aspects such as agriculture, biodiversity, tourism, fishery and
148 hydroelectric production at the Tis Abay and Tana-Beles stations (Setegn et al., 2009). The
149 climate in the Lake Tana basin is cool to cold tropical highland monsoon, with an average air
150 temperature of 18±4°C and large diurnal variation of ±15°C (Dargahi and Setegn, 2011). The
151 study area covers 18.2 km² for which we assume a spatially uniform seasonal rainfall depth. The

152 average seasonal rainfall depth in the *kremt* (rainy) season (June–September) at the National
153 Meteorological Services Agency rain gauge in Wanzaye (11.77 °N, 37.6 °E) is 1120 mm
154 (Rientjes et al., 2013), which represents more than 70% of the yearly total rainfall.

155 ***Figure 1 approximately here***

156 The major soil types of the Lake Tana basin are Nitisols, Vertisols, Luvisols, Regosols and
157 Phaeozems with a dominant presence of the Vertisols and Nitisols (Colot, 2012). The soils of the
158 Lake Tana basin are derived from weathered volcanic rocks. Quaternary volcanoes and Tertiary
159 volcanic plugs are visible in the landscape (Poppe et al., 2013). The most important parent
160 materials are mafic rocks and lacustrine deposits (Colot, 2012). The majority of the basin has
161 deep to very deep soils whereas soils on the hillslopes are shallow or very stony (Easton et al.,
162 2010; Kebede et al., 2011).

163

164 2.2. *Land management practices*

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

174

175 ***Figure 2 approximately here***

176

177 Stone bunds, i.e., physical soil and water conservation structures in dry masonry built along the
178 contour, are implemented in specific areas in the Lake Tana basin according to the policy of the
179 Ministry of Agriculture, Ethiopia. The altitude of the area is one of the decision criteria as the
180 policy reads that soil erosion control has to start from the upper parts of catchments, gradually
181 taking the lower areas into account as well. Farmers are not always happy with this decision
182 criterion because they know better the local areas vulnerable to erosion, which are not only those
183 at high altitudes but also areas where other factors such as slope angle, slope aspect and land use
184 are decisive (Wei et al., 2007). The construction of stone bunds is a time-consuming and tough
185 labour task; therefore, the government organizes a rotational system in which all farmers from
186 the neighbouring villages help with constructing stone bunds in the designated village. As a
187 consequence, and due to time constraints, farmers are not able to construct stone bunds in the
188 areas they know to be vulnerable to erosion. Nevertheless, the farmers around Wanzaye have
189 agreed that the construction of stone bunds is the best way to prevent soil erosion on sloping
190 farmland.

191

192 *Feses* are established by preparing widely-spaced furrows with the ox-drawn ard during the rainy
193 season across sloping farmland (Fig. 3) for different reasons according to the farmers: (i) to
194 avoid soil erosion by runoff, (ii) to avoid loss of seeds directly after sowing, and (iii) to drain
195 accumulating runoff water away from their fields. After establishment, the *feses* in the study area
196 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)

197 (Monsieurs et al., 2014). *Feses* density measured in cropland in the study area is $25 \pm 18 \text{ km km}^{-2}$.
198 *Feses* are established at an average angle of $44.7 \pm 7.2^\circ$; $n = 96$ with the contour line and a mean
199 gradient of $0.055 \pm 0.054 \text{ m m}^{-1}$; $n = 96$. *Feses* gradients and plot gradients in the study area range
200 from 0.000 to 0.372 m m^{-1} (Fig. 4), and the former is usually smaller than the latter. On average,
201 the gradient of *feses* increases with an increasing plot gradient, for which we could establish the
202 following relation in the study area (Fig. 4):

$$204 \quad FG = 0.6507PG \quad (R^2 = 0.69) \quad (4)$$

205
206 where FG is the *feses* gradient (m m^{-1}) and PG is the plot gradient (m m^{-1}). A wide range of
207 *feses* gradients is observed, which can be explained by the fact that construction variables of
208 *feses* (Fig. 3) depend on the farmers' decisions that take into account their planted crop,
209 indigenous knowledge, relation with neighbouring farmers and the dimensions of the *maresha*.

210
211 ***Figure 3 approximately here***

212 ***Figure 4 approximately here***

213
214 *Feses* are constructed at the farmers' own initiative, rather than by mass mobilization by the
215 authorities as is done for the construction of stone bunds. When the functions of *feses*, as
216 discussed above, are not needed anymore, i.e., as the growing crops reach a certain height, these
217 *feses* are purposely filled with weeded materials including the soil attached at its roots. Although
218 farmers are aware of the on-site soil erosion caused by *feses*, i.e., local removal of fertile topsoil,
219 they perceive *feses* as the best conservation practice if no stone bunds are present. *Feses* draining
220 the excess runoff water into the field of a neighbouring farmer may cause tensions between

221 upslope and downslope farmers as this excess water may cause increased erosion in the
222 downslope area (Smit and Tefera, 2011). Although the combined use of stone bunds and *feses* is
223 formally forbidden by the regional Ministry of Agriculture because stone bunds can be destroyed
224 by *feses*, a common practice in the study area is the joint implementation of both stone bunds and
225 *feses* on cropland (Fig. 3), which is referred to as ‘mixed’ hereafter. The poor functioning of
226 stone bunds or an excess of water that needs to be drained away are reasons reported by farmers
227 for the use of the mixed management. The above observation indicates that the three distinctive
228 land management practices (stone bunds, *feses*, mixed) affect the erosion processes and rates on
229 cropland in different ways.

230

231 **3. Methodology**

232

233 *3.1. Data collection*

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

240 The stone bund catchments (Fig. 5), *feses* catchments (Fig. 6) and mixed catchments, all draining
241 towards a gully head, were delineated using a handheld GPS. In total we mapped 26 *feses*
242 catchments, 27 stone bund catchments, and 22 mixed catchments (Fig. 7) for which the position

243 of the corresponding gully head was also recorded by GPS. Based on the catchment area, four
244 outliers were found using the outlier labelling rule (David, 1977; Hoaglin et al., 1986) which are
245 excluded from further analysis. Catchments comprising stone bunds constructed after 2003
246 (marked in Fig. 7) and catchments intersected by roads have been excluded from the dataset,
247 because roads may either reduce or increase the original catchment area (Nyssen et al., 2002).
248 For the latter, gullies might have been formed under past land management conditions without
249 stone bunds, and they would have been wrongly classified as ‘stone bund catchments’. This
250 analysis was made using historical Google Earth images (Fig. 8), which are available for the
251 study area for the years 2003, 2010 and partly also 2013.

252 The GPS data were further analysed using a GIS program (ArcMAP 10.0) to deduce s (m m^{-1})
253 and A (ha). The local slope gradient was derived from a DEM (resolution: 30x30m), for the pixel
254 where the gully head was located.

255

256 ***Figure 5 approximately here***

257 ***Figure 6 approximately here***

258 ***Figure 7 approximately here***

259 ***Figure 8 approximately here***

260

261 *3.2. Setting parameters and a threshold line*

262 For the exponent b in Eq. (1), two values 0.38 and 0.5 are used according to the standardized
263 procedure proposed by Torri and Poesen (2014). Because the latter corresponds to laminar flow,
264 which is rather exceptional in our study area, we prefer to use the former in this study. To
265 calculate s , we implement Eq. (2) rather than using sine as in Eq. (3), because the former better
266 reflects the concept of ‘slope gradient’ in relation to the flow shear stress concept upon which
267 Eq. (1) was originally based (Patton and Schumm, 1975; Begin and Schumm, 1979). The mean
268 slope angle for all catchments does not exceed 18° , which is close to 15° for which the tangent
269 can substitute sine without a significant effect on the topographic threshold (Torri and Poesen,
270 2014).

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

276

277 **4. Results**

278 *4.1. Group mean differences*

279 The characteristics of the gully heads and their catchments, grouped according to the land
280 management practices are shown in Table 2. The top width and depth of the gully heads have
281 been estimated by post-analysis of the photographs taken at the gully head. The size of all
282 catchments is defined as the drainage area corresponding to the uppermost gully head. Analyses
283 are based on the filtered dataset, i.e., excluding outliers and catchments with stone bunds less

284 than 10 years old. *Feses* catchments are characterised by an area ranging from 0.15 ha to 0.89 ha,
285 with a mean of 0.45 ± 0.20 ha and a mean slope gradient of 0.29 ± 0.12 m m⁻¹. Catchments with
286 stone bunds exclusively have an area ranging from 0.31 to 2.75 ha with a mean of 1.24 ± 0.78 ha
287 and a mean slope gradient of 0.33 ± 0.18 m m⁻¹. The selected mixed catchments have areas
288 ranging from 0.28 to 2.93 ha with a mean of 1.19 ± 0.81 ha and a mean slope gradient of
289 0.21 ± 0.13 m m⁻¹.

290

291 ***Table 2 approximately here***

292

293 4.2. Topographic threshold analysis

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

301 The average k-values for the Wanzaye cropland are 0.131 ± 0.052 for $b = 0.38$, and 0.123 ± 0.054
302 for $b = 0.5$, which are larger than those for cropland reported by Torri and Poesen (2014) (Table
303 1). It should be noted that k-values increase with *RFC* and content of the topsoil (Torri and

304 Poesen, 2014). We found in our study area a mean *RFC* value of $68 \pm 26.1\%$ ($n = 38$), which
305 partly explains the larger *k*-values observed in this study.

306

307 ***Figure 9 approximately here***

308 ***Table 3 approximately here***

309

310 The different catchment types constitute different populations (Table 2, Fig. 10) regarding the
311 means of the catchment area, which was statistically validated by a t-test using independent
312 samples (significance level $\alpha = 0.05$; also for the following tests). The area of the *feses*
313 catchments is significantly smaller than that of stone bund or mixed catchments. However, there
314 is no significant difference between the area of the stone bund catchments and that of the mixed
315 catchments. The slope gradient at the gully heads of the mixed catchments is significantly
316 smaller than those of the *feses* and stone bund catchments, whereas no significant difference in
317 slope was found between the *feses* and stone bund catchments.

318

319 ***Figure 10 approximately here***

320

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

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

330

331 **5. Discussion**

332 *5.1. Data scatter in s–A plots*

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

340 Additionally, the topographical position of gully heads can bias our data. Regressive erosion of a
341 gully head on a hillslope will cease if it reaches a slope section with a gradient too small for
342 gullying (Fig. 5) (Poesen et al., 2003); whereas, a gully head retreats further upslope if the slope
343 gradient remains high (Fig. 11). For both gully types, however, only the steeper slope section
344 was used in the analysis of topographical thresholds. On the other hand, excluding catchments

345 with stone bunds less than 10 years old (see section 3.1), reduced the scatter in the s - A dataset
346 (Fig. 9).

347

348 ***Figure 11 approximately here***

349 An additional factor to be considered is the spatial variability of RFC . With increasing RFC ,
350 erosion by concentrated flow decreases exponentially (Poesen et al., 1999), and hence the
351 topographic threshold for gullying increases (Torri and Poesen 2004). Field observations in the
352 study area indicate that the highest RFC values are found on steeper convex slopes (Miserez,
353 2013), which is in line with observations made elsewhere (e.g., Lanckriet et al., 2012 in northern
354 Ethiopia). Spatial variability of RFC is caused by both natural processes (e.g., Poesen et al.,
355 1998) and anthropogenic processes such as tillage erosion (Poesen et al., 1997) and rock
356 fragment removal (Nyssen et al., 2001); these processes are encountered in the study area.

357 5.2. Explanatory variables for land management practices

358 Based on Table 2 and Fig. 10, three trends in land management practices are observed: (i) the
359 exclusive use of *feses* tends to be applied on steeper areas where only a small drainage area is
360 required for gully head development, (ii) stone bunds are used on both steeper and gentle slopes,
361 and (iii) gentle slopes with large drainage areas seem to be suitable for the mixed use of *feses* and
362 stone bunds. These findings correspond well to the explanations given by local farmers.
363 Especially on steep areas, conservation practices are needed to maintain soil's productivity, and
364 the farmers said that stone bunds are useful. They also construct *feses* for conservation, and
365 runoff will be guided downslope at a smaller gradient than the plot gradient (Fig. 4), reducing
366 sheet and rill erosion (Hurni, 1985, Liu et al., 1994). In some cases, farmers combine stone bunds

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

372 5.3. Threshold coefficient k for different land managements and RFC values

373 As the coefficient k reflects the resistance of an area to gully head development (Torri and
374 Poesen, 2014), we can deduce from Table 3 that catchments with the exclusive use of stone
375 bunds are more resistant to gully head development than those with *feses* or mixed catchments
376 which is consistent with previous research results (Nyssen et al., 2007; Taye et al., 2013). Table
377 3 also indicates that catchments with the exclusive use of *feses* are the most vulnerable to gully
378 head development, as illustrated in Fig. 10 that the threshold line for the *feses* catchments lies
379 below that of the mixed catchments, which in turn lies below that of the stone bund catchments.
380 Based on these results we cannot confirm the statements of Shiferaw (2002) and Pathak et al.
381 (2005) that the use of *feses* is a good soil conservation practice. This study demonstrates how the
382 analysis of topographical thresholds for gully head development under different land
383 management practices in cropland may contribute to better understanding and mitigating gully
384 erosion.

385 Torri and Poesen (2014) reported mean k values of 0.043 ($b = 0.38$) and 0.037 ($b = 0.5$) for
386 cropland, which are roughly one third of those found in this study: i.e., 0.131 and 0.123. This
387 difference can be attributed to fewer rock fragments in the case of Torri and Poesen (2014). To

388 adjust their values to k-values for cropland with abundant rock fragments, a correction factor can
389 be calculated using the equation of Torri and Poesen (2014):

$$390 \text{ correctedvalue} = \frac{\text{observed}}{\text{predicted}} = 0.69e^{1.2RFC} \quad (5)$$

391
392 For a mean *RFC* value of 68% in our study area, the correction factor equals 1.56. Taking this
393 factor into account, the mean k-values for cropland according to Torri and Poesen (2014)
394 increase: 0.067 (b = 0.38) and 0.058 (b = 0.5) (Table 1), although they are still only half of the k-
395 values found in our study area. This means that the cropland we studied is less vulnerable to
396 gully head development compared with the average cropland conditions in other regions of the
397 world. We also consider that our values can be only compared with the dataset of Torri and
398 Poesen (2014) for which the same procedure (Eq. 1) is used for calculating the coefficients.

399
400 *5.4. Sedimentation in gullies*

401 From Fig. 9 we observe that no gully heads were found on land with a slope gradient less than
402 6%. This is slightly different from observations by Poesen et al. (2003) in northern Europe where
403 they found the lower slope limit of gullying to be 2% to 4%, because sediment deposition
404 dominates on gentler slope gradients. When the rock fragment content of the topsoil increases,
405 however, the topographically induced sedimentation will take place on steeper slopes (Poesen et
406 al., 2002). The critical slope of the soil surface for sediment deposition for *RFC* = 68% as
407 observed in our study area would be 6% according to the data of Poesen et al. (2002) from
408 cropland in western Europe, which is similar to our findings.

409

410 **6. Conclusions**

411 In this paper, we have illustrated the practical use of topographic thresholds for gully head
412 development to study the effect of various cropland management practices on vulnerability to
413 gully. Values for the coefficient k in the topographical threshold equation (Eq. 1) can help
414 soil conservationists to identify which management practices reduce vulnerability to gully
415 erosion. In the case of our study area in Wanzaye, Ethiopia, three different land management
416 practices have been considered: stone bunds, drainage ditches (*feses*), and their mixed use. The
417 lowest k -values are found for catchments where *feses* are implemented, higher values are found
418 for mixed catchments, and the highest values are found for stone bund catchments. This implies
419 that the *feses* catchments are the most vulnerable to gully head development compared to the
420 stone bund and mixed catchments. Yet, on-site sheet and rill erosion are reduced by the use of
421 *feses* as they reduce the runoff gradient. The use of *feses*, however induces a range of other
422 effects on the productivity of cropland, which needs further research.

423 In the studied cropland and the surrounding region, three trends in land management have been
424 observed: (i) the exclusive use of *feses* is on steeper slopes for which only a small drainage area
425 is required to develop a gully head, (ii) stone bunds are used on both steeper and gentler
426 cropland, and (iii) gentle slopes with large upstream areas seem to be the most suitable for the
427 mixed use. It seems not possible to compare our findings with previous research on
428 topographical threshold conditions for gully, because: (i) to the authors' knowledge
429 topographic thresholds have not been used elsewhere to study the impact of land management
430 practices on gully erosion, and (ii) the standardized procedure for topographical threshold

431 analysis was only recently proposed by Torri and Poesen (2014). Therefore we recommend more
432 research on topographical threshold conditions for different land management practices
433 following this standardized procedure.

434

435

436

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443 (Ethiopia) contributed to sharpen our insights in the matter.

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633 Figure captions

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

635 Fig. 2. Typical land management situations in the study area. (A) Stone bund catchment. (B)

636 Mixed catchments with *feses* and stone bunds (summer of 2013). Direction of overland flow in

637 the *feses* is indicated by arrows (after Monsieus et al., 2014, published with permission from

638 John Wiley & Sons).

639 Fig. 3. Variations in cross section (A-C), gradient and density (D-F) of the *feses* (drainage

640 ditches) in the study area. Wooden sticks are ca. 0.5 m long, direction of overland flow in the

641 *feses* is indicated by arrows and a contour by a dashed line. (A) *Feses* which was deepened

642 during the rainy season because of the erosive force of runoff water, (B) two *feses* constituting

643 one larger *feses* perpendicular to the contour, (C) *feses* which became filled with sediment during

644 the rainy season, (D) foreground illustrates *feses* in cropland during the rainy season; in the back,

645 farmland without *feses* on which rill erosion occurs, (E) dense use of *feses*, and (F) mixed land

646 management practice using both stone bunds and *feses* (August 2013).

647

648 Fig. 4. Relation between plot gradient (*PG*) and *feses*' gradient (*FG*) for 91 *feses* in the study

649 area (August 2013). 1:1 line is also shown.

650 Fig. 5. Gully formed by concentrated runoff from a catchment treated with stone bunds. The

651 slope section on which the gully formed is much steeper than the overall slope of the stone bund

652 catchment. The gully does not develop under the current cropland management practice (August

653 2013).

654 Fig. 6. Gully formed by concentrated runoff from a cropland catchment treated with *feses*

655 (August 2013).

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

663 Fig. 8. Image analysis of a catchment comprising stone bunds. The photo below is taken during
664 fieldwork in 2013. The corresponding gully head is marked by a black dot and two reference
665 points (tree and bush) are circled. In 2003, the catchment cannot be regarded as a stone bund
666 catchment. In 2010, stone bunds have appeared. gullies might have been formed under land
667 management conditions without stone bunds, so that they would be wrongly classified as ‘stone
668 bund catchments’.

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

676 Fig. 10. Topographic threshold lines based on slope gradient s and drainage area A for gully head
677 development under three cropland management practices: i.e.; stone bunds (squares), drainage
678 ditches or *feses* (diamonds) and their mixture (triangles). Exponent b of Eq. (1) is set constant at
679 0.38.

680 Fig. 1. Gully head development under two different topographical conditions. The slope gradient
681 (s) of the soil surface on which the gully head developed can be much steeper than (a) or similar
682 to (b) the slope of the corresponding catchment with area (A). This will create a bias when
683 determining the topographical thresholds for gully head development. Catchments under
684 conditions (a) will produce a data point on the s – A graph located more to the right (bigger area A)

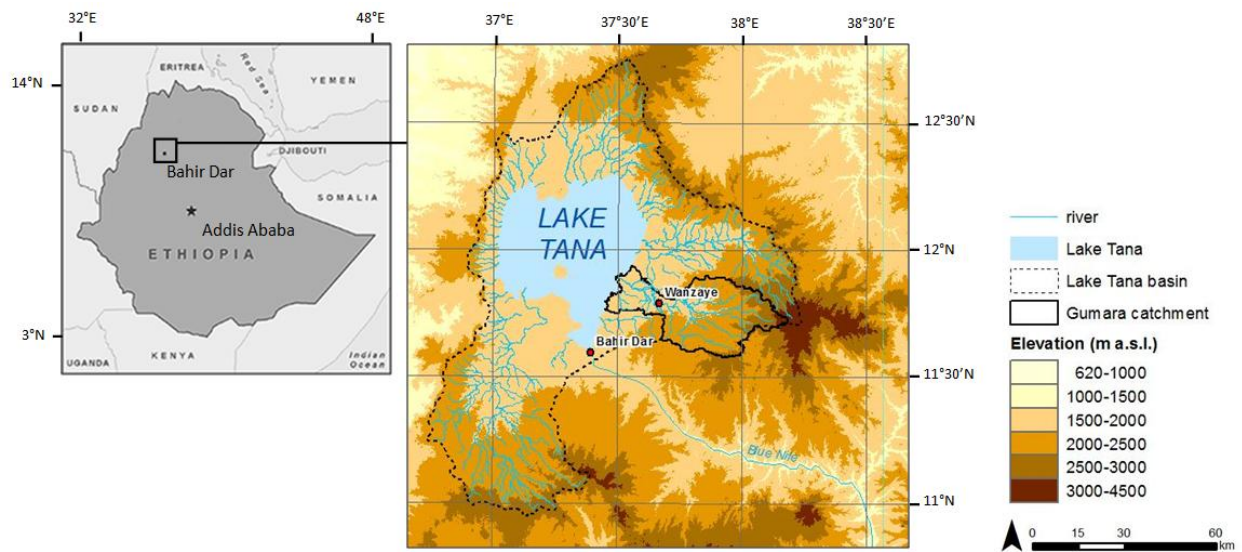
685 compared to a catchment that would have reached equilibrium (in terms of the slope gradient (s)
686 and the (smaller) area (A) draining into the gully head) for constant slope conditions.

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689 Figures

690 **Figure 1.**



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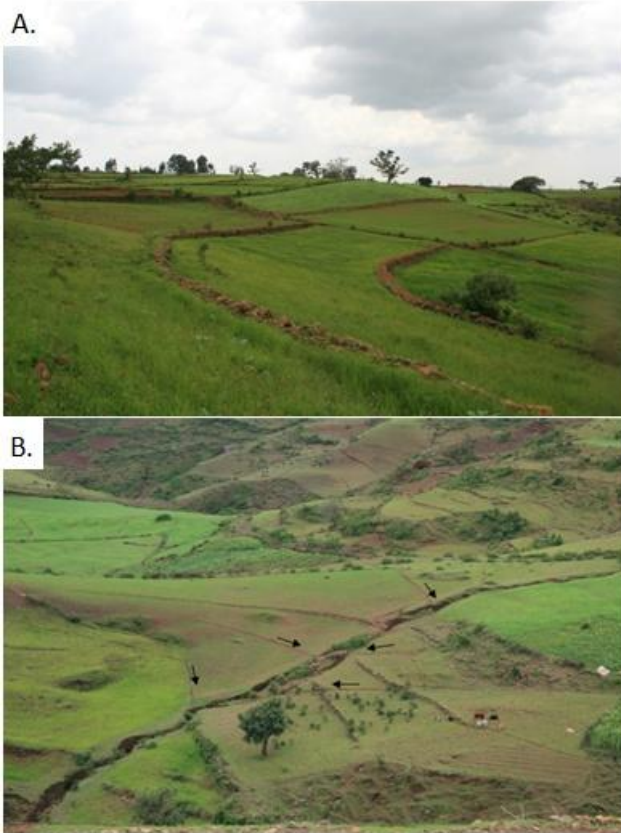
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701 **Figure 2.**



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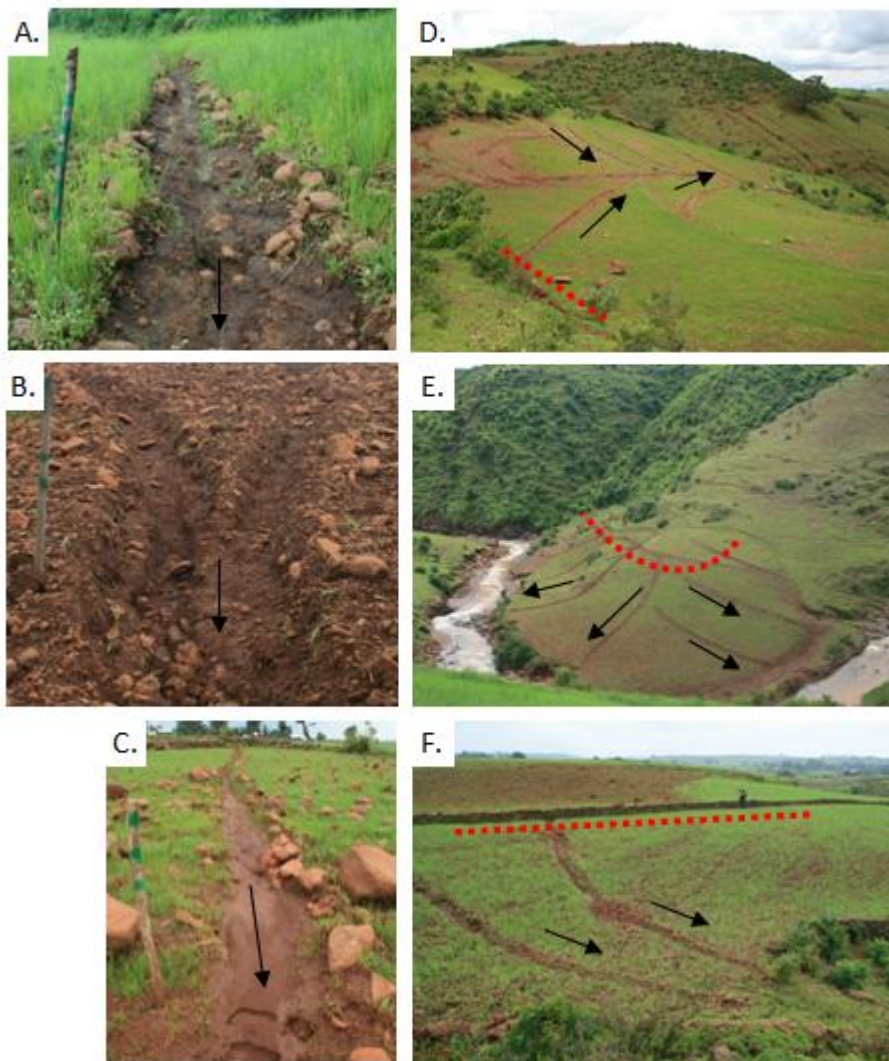
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715 **Figure 3.**



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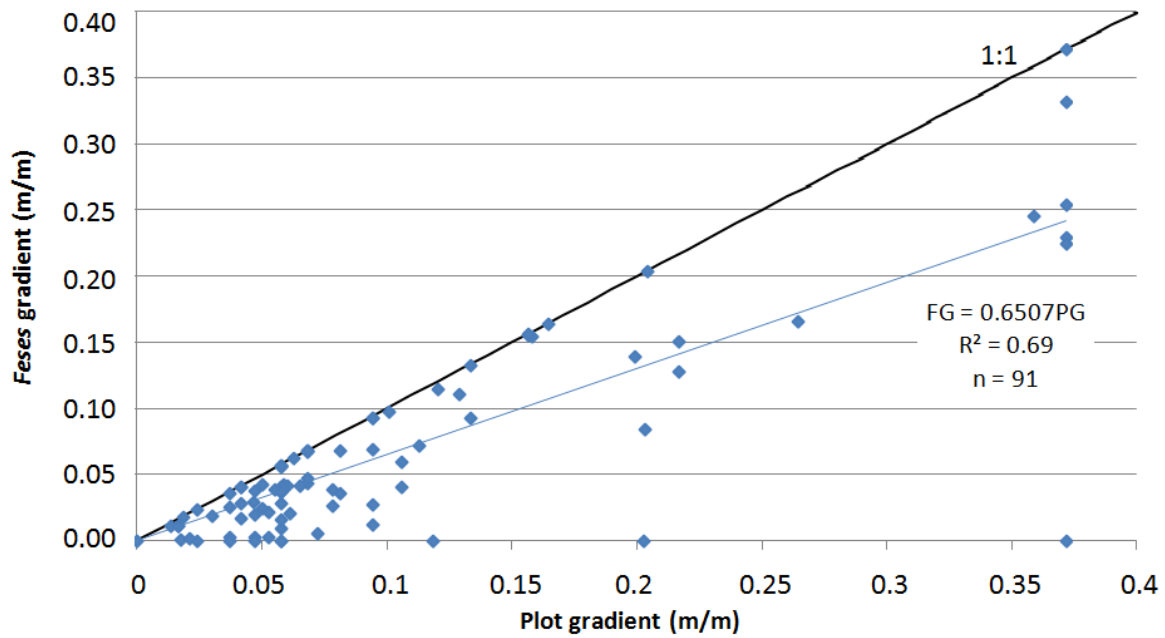
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Figure 4.



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752 **Figure 5.**



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754 **Figure 6.**

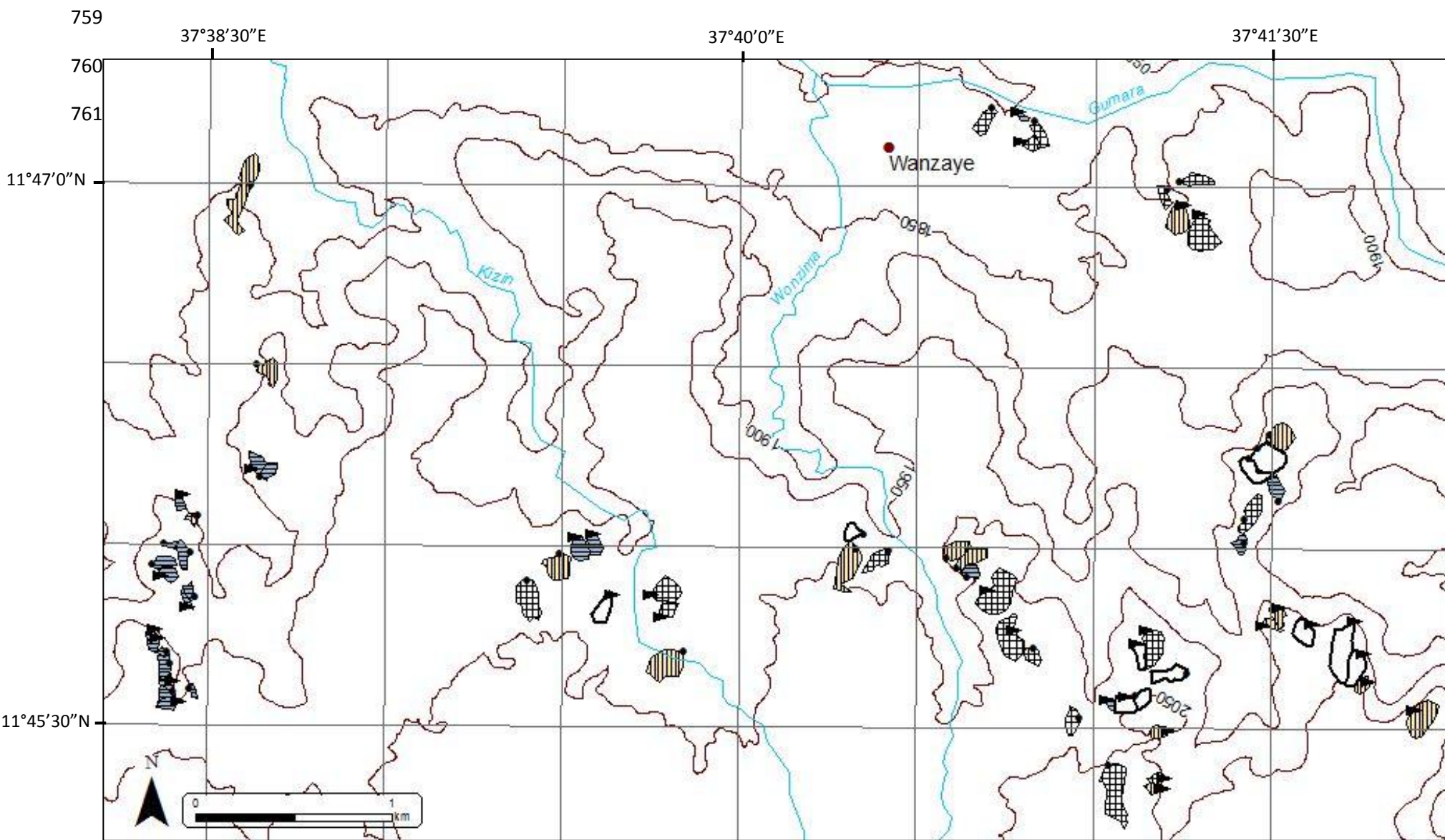


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758 **Figure 7.**



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|----------------|-----------|--------------|------------------|
| • gully type 1 | — contour | ▨ feses | ▭ new stone bund |
| ▴ gully type 2 | — river | ▨ stone bund | ▨ mixed |

762 **Figure 8.**



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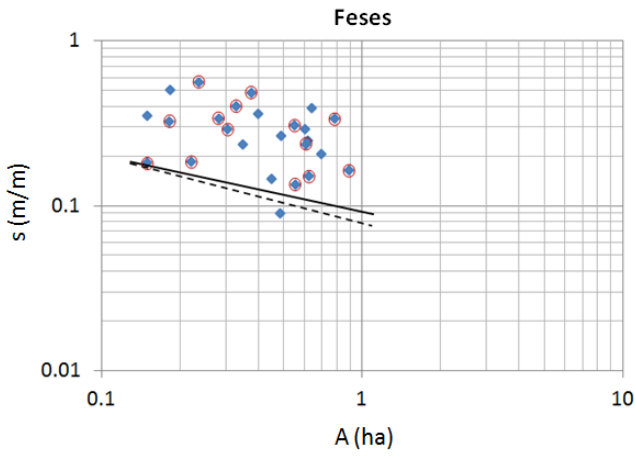
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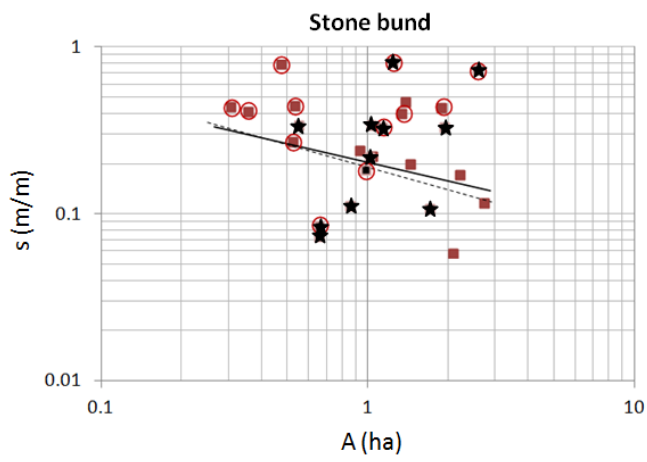
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770 **Figure 9.**



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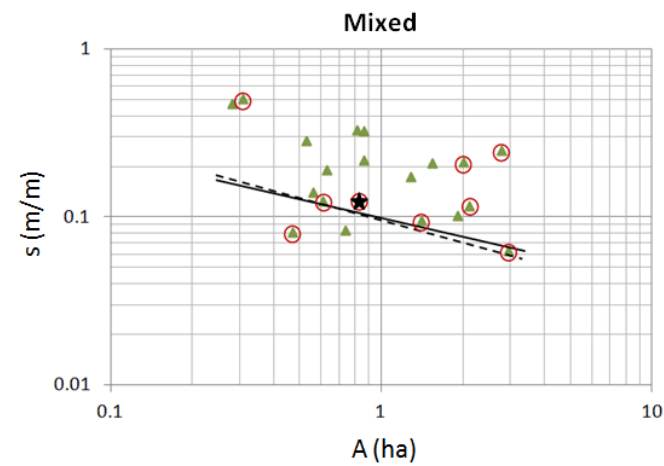
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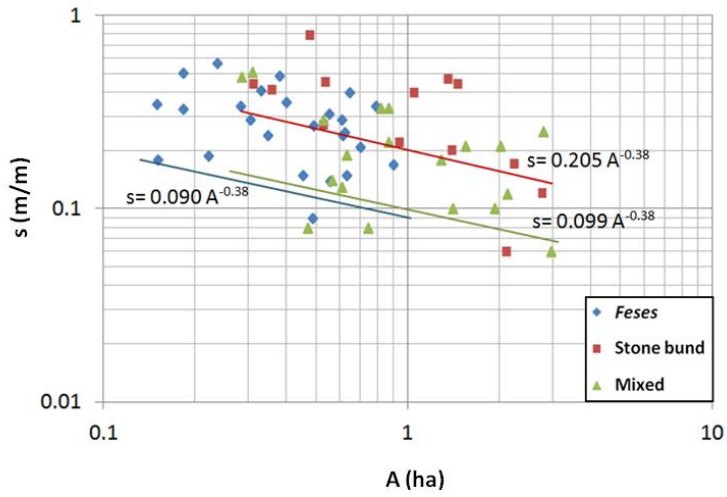
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789 **Figure 10.**



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794 **Figure 11.**

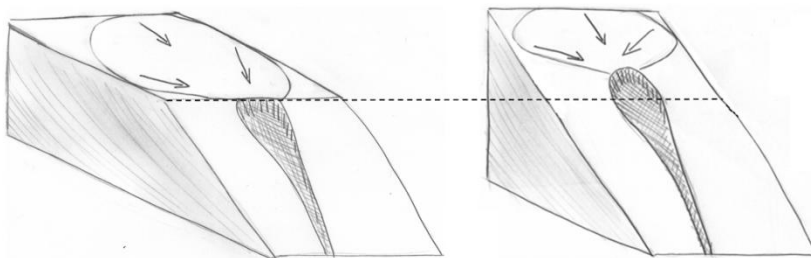
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800 (a)

(b)

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806 Table captions

807 Table 1. Values of the coefficient k (Eq. 1) for different land use types for two values of the
808 exponent b (0.38 and 0.50). N . Obs. is the number of studies from which a threshold $s-A$ was
809 calculated (Torri and Poesen, 2014). Values corrected for rock fragment cover of the study area
810 (68%) are presented in brackets.

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

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

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833 Tables

834 **Table 1.**

	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

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852 **Table 2.**

<i>Feses</i> catchment					Stone bund catchment					Mixed catchment				
GH	<i>W; D</i> (m)	<i>A</i> (ha)	<i>s</i> (m m ⁻¹)	<i>I</i>	GH	<i>W; D</i> (m)	<i>A</i> (ha)	<i>s</i> (m m ⁻¹)	<i>I</i>	GH	<i>W; D</i> (m)	<i>A</i> (ha)	<i>s</i> (m m ⁻¹)	<i>I</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	0.4	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	0.4									10.1		
F23	NA; NA	0.69	0.21		S22	NA; NA	1.93	0.33	b	M22	2.5; 1.0	2	0.19	d
F24	1.0; 0.5	0.78	0.34	c	S23	2.0; 2.0	2.10	0.06	a					
F25	2.0; 0.5	0.89	0.17	c	S24	1.5; 0.5	2.22	0.17	a					
F26	1.0; 0.5	1.39	0.09	d	S25	1.5; 1.5	2.57	0.72	b,c					
					S26	2.0; 1.0	2.75	0.12	a					
					S27	NA; NA	4.88	0.11	d					
<i>M</i>	1.5; 1.0	0.45	0.29		<i>M</i>	1.3	1.24	0.33		<i>M</i>	1.9	1.19	0.21	
<i>SD</i>	0.7; 0.5	0.20	0.12		<i>SD</i>	0.5	0.78	0.18		<i>SD</i>	1.4	0.81	0.13	

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859 **Table 3.**

	<i>Feses</i>	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)

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