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ABSTRACT

Gully cut-and-fill dynamics are often thought to be driven by climate and/or deforestation related to population pressure. However, in this case-study of nine representative catchments in the North Ethiopian Highlands, we find that neither climate changes nor deforestation can explain gully morphology changes over the 20th century. Firstly, by using a Monte Carlo simulation to estimate historical catchment-wide curve numbers, we show that the landscape was already heavily degraded in the 19th and early 20th century – a period with low population density. The mean catchment-wide curve number (>80) one century ago was, under the regional climatic conditions, already resulting in considerable simulated historical runoff responses. Secondly, 20th century land cover and runoff coefficient changes were confronted with 20th century changing gully morphologies. As the results show, large-scale land cover changes and deforestation cannot explain the observed processes. The study therefore invokes interactions between *authigenic* factors, small-scale plot boundary changes, cropland management and sociopolitical forces to explain the gully cut processes. Finally, semi-structured interviews and sedistratigraphic analysis of three filled gullies confirm the dominant impact of (crop)land management (tillage, check dams in gullies and channel diversions) on gully cut-and-fill processes. Since agricultural land management – including land tenure and land distribution – has been commonly neglected in earlier related research, we argue therefore that it can be a very strong driver of 20th century gully morphodynamics.

Keywords: hydrogeomorphology, sedistratigraphy, gully incision, land management, soil erosion, land use change

1. INTRODUCTION

Gully incision (*cut*) and subsequent aggradation (*fill*) occur in successive cycles (Vanwalleghem et al., 2005a). At the first stage of gully initiation, mechanic actions of water on the soil are predominant at the gully bottom and rapid mass movement occurs on the gully sides (Sidorchuk, 1999). Gully channel formation is very intense during this early period of gully initiation, when the morphological characteristics of the gully (length, depth, width, cross-sectional area, and volume) are far from stable. Kosov et al. (1978), quoted in Sidorchuk (1999), showed that the first gully incision stage is relatively short and lasts for about 5% of the gully's lifetime, but 90% of the gully's length, 60% of the gullied area and 35% of the gully's volume are formed during this period. Hence, at first gully length development is an important geomorphic process, followed by subsequent width development (Schumm, 2005). After the first 'dynamic' incision phase, a long period of geomorphic 'maturity' occurs (Sidorchuk, 1999). In particular, the growth of gully volume is exponentially decaying in rate with time (Thomas et al. 2004), while in the North Ethiopian Highlands gully volume follows a sigmoidal trend (Nyssen et al., 2006). Maturity is then followed by gully infill, which was measured by Vanwalleghem et al. (2005a) in Belgium, showing very rapid infill rates (*in casu* 6.4 cm a^{-1}). Fuller and Marden (2010) showed that gully incision and aggradation can even be yearly processes. Vanwalleghem et al. (2005a) therefore concluded that gully incision and infilling under cropland can be relatively rapid processes, as they found five cycles of cut-and-fill in 350 years.

Worldwide often a combination of intensive land use change and extreme rainfall is blamed for gully formation (e.g. Stankoviansky, 2003; Vogt, 1953; Fryirs & Brierley, 1998; Carnicelli et al., 2009). A literature review regarding the drivers of Holocene terrestrial gully cut-and-fill processes all over the world (Table 1) shows influences of (neo)tectonics, road building, climate changes, land cover change and deforestation, overgrazing, cropland management and sea-level change. As expected, land cover and climate changes are mentionned as the main gully cut-and-fill drivers in most of the studies. Meanwhile, the impact of cropland management (with 4 relevant studies) is not often investigated and therefore highly underrepresented in such geomorphic studies (Table 1). However, cropland management could have a very significant influence on gully cut and fill processes, even under stable land cover. Stolz (2011) showed for example from a case study in Germany that the historical introduction of the improved three-field crop rotation system intensified agriculture and led to increased soil erosion and gully formation. Nagasaka et al. (2005) discussed the same phenomenon under mechanization of agriculture in modern Japan. The study of Zaimes & Schultz (2012) focused on the effect of riparian land management on gullying; while Casali et al. (1999) showed the impact of tillage practices, stubble maintenance, and gully refill by local farmers.

TABLE 1

In the Ethiopian Highlands, Frankl et al. (2011, 2013) pointed to the re-activation of a dense gully network in the 1960s, which results in relatively wide gullies at present (Figure 1). The gully channels are already visible on historical photographs of the 19th and early 20th century as a dormant system inherited from a pre-20th century activation. During the re-activation of the system, there were high denudation rates, a high sediment supply and activation of first-order streams (Frankl et al., 2011). Related 20th century land degradation in Northern Ethiopia is amongst others linked to interplays of drought and land cover changes (de Mûelenaere et al., 2012; Biazin and Sterk, 2013). Land cover changes induce vulnerability for climatic shocks, resulting in environmental degradation in the Highlands (Frankl et al., 2011; 2013). Based on repeating historical landscape photographs, it can be seen that the Northern Ethiopian landscape was already largely deforested in the 19th century (Nyssen et al., 2009; Meire et al., 2013). However, if deforestation was mainly a pre-20th century process, it would be less responsible as a direct driver of 20th century land degradation processes. This would then lead to the need to investigate other driving factors of 20th century land degradation, which are more related to agricultural management (*agro-management*; e.g. including land tenure changes, environmental management programs, agricultural intensification and land distribution). Yet, the historical evolution of agricultural management is difficult to assess. For instance, the spatial distribution of the historical dynamics of overgrazing, land ownership and cropland management (e.g. fertilization, plowing frequency) are poorly known as they are invisible on historical aerial and terrestrial photographs.

FIGURE 1

Taking these elements into account, two research issues arise. First, the direct impact of land cover changes on 20th century gully cut-and-fill processes was never quantified and estimated for the Highlands. Second, as stated before, the impact of agro-management on gully cut-and-fill dynamics is not well understood worldwide and in particular in North Ethiopia. Therefore, this paper presents a simple method for estimating historical curve numbers. This Monte Carlo based method will be illustrated using case studies of 19th century and early-20th century gully activity in six catchments in North Ethiopia. Then, we will estimate the contribution of land-cover changes on changing gully peak discharges over the 20th century in these catchments. Finally, the impact of cropland management on gully infill will be studied in three additional catchments.

2. METHODS AND MATERIALS

2.1 Study region

The Tigray region is located in the North of the Ethiopian Highlands, and active gullies are dissecting its landscape (Frankl et al., 2013). Elevations in the Tigray Highlands range between 1500 and 4000 m a.s.l. (Figure 2). In this mountainous region, the geology comprises rocks of both Precambrian and Phanerozoic ages. At the base, Precambrian metavolcanics are situated; with on top relatively thin Paleozoic formations. The Paleozoic rocks include the Enticho Sandstone Formation (of fluvioglacial origin) and the Adaga Arbi glacial deposits (tillites) (Bussert and Schrank, 2007). Later, Mesozoic sandstones (Adigrat sandstone), limestones (Antalo limestone) and shales (Agula shale) were deposited (Merla et al., 1979), followed by the Amba Aradam sandstone (a lateritised sandstone of the Lower Cretaeceous with the upper part containing tuffaceous mudstone). These sedimentary rocks were subsequently covered by Tertiary volcanics, such as the trap basalts of the Ashangi group (black alkali olivine basalts of the Paleocene, Oligocene and Miocene, that are often interbedded with lacustrine deposits of silicified limestone and diatomite with gastropods). Drainage occurs mainly towards the Tekeze-Nile river system and partially to the Danakil depression of the African Rift Valley.

FIGURE 2

Monsoonal precipitation occurs from June until September as intense rainstorms with large raindrop sizes (Nyssen et al., 2005). Annual precipitation increases from north to south, ranging between 500 and 900 mm yr^{-1} (Jacob et al., 2013). Inter-annual rainfall variability is equally important, as Nyssen et al. (2005) showed average yearly rainfall depths in the study area range between 546 mm in 2002 to 879 mm in 1998 in Hagere Selam.

In Northern Ethiopia, before the late 19th century, the agro-system was organised in a ‘tributary’ way (locally named *gult-system*), and later the agro-system became ‘feudal’ and highly unequal (Ståhl, 1974). Local noblemen owned most of the lands (Bruce, 1976), and these *risti* lands were often lent out in a sharecropping system, locally named *mwufar* (Segers et al., 2010). The military regime (1974-1991) tried to implement a land reform, which succeeded only partially in the study area (Lanckriet et al., 2014). After the end of military regime in 1991, another land redistribution was organised, so all households received about three farm plots. Croplands are commonly cultivated with wheat (*Triticum* sp.), barley (*Hordeum vulgare* L.), *hanfez*, which is wheat and barley sown together, and teff (*Eragrostis tef* (Zuccagni) Trotter), and are ploughed with the local ard plough or *mahresha*. For Ethiopia, the total population was estimated at 6.6 million in 1868 while it was about 82 million people in 2011 (Nyssen et al., 2014).

Due to highly erosive rainfall, soil erosion in the region is intensive, notably due to the occurrence of intensive gullying (Nyssen et al., 2004). In the Northern Ethiopian Highlands, three main phases in gully development are identified during the 20th century: (i) a phase of relatively stable gullies that was evidenced from historical photographs since 1868 and lasted until the 1960s, (ii) a gully incision phase with region-wide activation of the gully channels between the 1960s and ca. 2000, and (iii) an initial gully stabilization phase related to reduced flash flood peaks after 2000 (Frankl et al., 2011, 2013).

2.2 Case-study sites in North Ethiopia

2.2.1 Repeat photography sites with one century interval

Historical gully top widths (*W*) were identified based on the quantification of historical changes in gully cross-sections using repeat photography (Frankl et al., 2011) (Figure 3) (Table 2). Frankl et al. (2011) measured the observable top width, maximum depth and bottom width of the gully cross-sections for the 19th and early 20th century by comparing it to the early 21st century situations. This was done by calibrating gully top widths on digitized terrestrial photographs with field measurements. For a full description of this methodology, the reader is referred to Frankl et al. (2011). Frankl et al. (2011) showed that the accuracy of these top width measurements is 10%, as assessed by five replicates of the measurement procedure by experienced geomorphologists. In order to compare the early 20th century situation with the early 21st century for relatively ‘stabilized’ gullies, only the photographs taken before 1943 and after 2000 could be used in this study. This included six repeated photograph couples in six catchments on basalt near Bolago (1 couple), Atsela (2 couples) and Ashenge (3 couples); (Figure 2). The reader must consider the fact that the gully widths identified on the photographs are reflecting the environment ‘at its most degraded state’. The channel widths from the early 21st century are therefore probably the result of flashfloods occurred during the 1980s-1990s; while the channel widths of the early 20th century are the results of flashfloods occurred during the 19th or early 20th century.

FIGURE 3

TABLE 2

2.2.2 Filled gullies

Additionally, three partially silted channels were chosen in distinct environments in the Highlands of Northern Ethiopia (Figure 4), depending on the occurrence of different lithologies and based on short interviews with local farmers that focused on changes in local gully morphodynamics (Figure 2). The partially filled channel in Ma’ay Bati (13.65126°N – 39.21895°E) is located downslope of the Amba Aradam sandstone cliff. The channel itself has been incised in colluvium overlying oolitic limestones and marls of the Antalo formation (Merla et al., 1979). The filled channel in Sinkata (14.04785°N – 39.58263°E) is situated downslope of a cliff of Paleozoic Enticho Sandstone. The channel itself has been incised in colluvium overlying Precambrian metavolcanics (Bussert and Schrank, 2007). The paleochannel in

Atsela (12.93180°N – 39.52446°E) is incised in colluvium overlying trap basalts of the Ashangi group (Merla et al., 1979).

FIGURE 4

2.3 Monte Carlo simulation of curve numbers using land cover data

Based on existing historical land cover data obtained using warped repeat photography (see Meire et al., 2013) with a particular areal extent A_x for a particular land cover type x, and with runoff coefficients C_x calibrated for these land cover types (Descheemaeker et al., 2006; Lanckriet et al., 2012), catchment-weighted runoff coefficients C_i could be calculated as:

$$C_i = \frac{\sum C_x . A_x}{\sum A_x} \qquad (1)$$

The areal extent of the land cover types was calculated by warping land cover units from terrestrial photographs to the horizontal plane of the map, including a meticulous quality check of the warping results (Meire et al., 2013). These catchment-weighted runoff coefficients C_i could be converted to catchment-weighted curve numbers CN_i, by combining the following equations based on the calibrations by Descheemaeker et al. (2006) and Descheemaeker et al. (2008) for the Tigray Highlands (on basalt and limestone):

$$\begin{cases} C_i = \kappa - \lambda * \ln(VEG_i) & (2) \\ CN_i = 100 - \xi * e^{(\mu * VEG_i)} & (3) \end{cases}$$

where calibration parameters κ = 165.4 and λ = 37.6 (Descheemaeker et al., 2006); VEG_i the total woody vegetation cover (VEG; in %) and calibration parameters μ = 0.021 and ξ = 8.99 (Descheemaeker et al., 2008). Because the VEG term disappears while combining Equation 2 and 3, there is no need to determine vegetation cover. CN represents the catchment-wide average curve number defined as:

$$Q = \frac{(P - 0.2s)^2}{P + 0.8s} \text{ with } s = \frac{25400}{CN} - 254 \qquad (4)$$

where Q is the runoff (mm), P is the rainfall (mm) and s is the storage parameter (SCS, 2004). According to Boughton (1989), curve numbers are widely used to predict runoff under varying land cover conditions in catchments from 0.25 ha up to 1000 km2. For relevant land cover types, one can empirically calibrate the curve number and derive S, which is the maximum storage of the catchment. Despite their empirical nature, curve numbers are useful runoff prediction tools in semi-arid areas (see El-Hames, 2012; Teka et al., 2013). Here, hydrological models are not always directly applicable. When rigorously calibrated under local conditions, the method can provide accurate predictions of runoff, which is the case in Tigray (Descheemaeker et al., 2008). Hence, we preferred to use this method, since it is a very well calibrated runoff model in the Tigray Highlands and because of the possibility of integrating the curve numbers with runoff coefficients.

However, since the runoff coefficients C_x calculated by Descheemaeker et al. (2006) and Lanckriet et al. (2012) have considerable standard deviations, the curve numbers had to be estimated using a Monte Carlo simulation, in order to account for error propagation. The simulation was based on 10 000 runs, following the rule of thumb that such simulations yield errors less than 1% (Koop et al., 2007). As shown by the runoff plot data of Descheemaeker et al. (2006) and Lanckriet et al. (2012), we can apply a normal distribution of the runoff coefficients (variance taken as 0.1Cx). Given a standard deviation of 0.09 on the runoff coefficients (Lanckriet et al., 2012), allowing such a large variance ensures us that all errors are surely incorporated. Monte Carlo sensitivity analysis allowed assessing the impact of the different land cover types on the catchments' runoff vulnerability. Using the curve number method, runoff responses to a given daily rainfall sequence could be simulated with the obtained catchment-wide curve numbers. This daily rainfall sequence was taken for a random year (2006), measured at the Mekele-Quiha Airport meteorological station, which represents a high-quality record for the region.

2.4 Estimations of peak flow discharge changes from land cover changes

Based on the same existing historical land cover change data (Meire et al., 2013), and with the runoff coefficients calibrated for these land cover types (Descheemaeker et al., 2006; Lanckriet et al., 2012), peak discharge changes ΔQ_p induced by those land cover changes ΔC could be calculated following the rational formula (Dunne and Leopold, 1978):

$$Q_p = \gamma CIA \Rightarrow Q_p \propto C \Rightarrow \Delta Q_p = \Delta C \qquad (5)$$

where γ is a calibration parameter; C is the runoff coefficient; A is the runoff-contributing area (ha); Q_p is peak flow discharge (m^3/s); and I is the rainfall intensity (mm/h). The rational method is still widely used because it is a simple model that requires few input parameters (Vanwalleghem et al., 2005), and gives satisfactory results (Viessman et al., 1989; Titmarsh et al., 1995), even for dryland areas (Graf, 2002). The equation can however induce errors (Graf, 2002) and was therefore calibrated in our study area (Tesfaalem et al., 2014), who show that the model yields satisfactory results. Moreover, we use here only the proportionality between Q_p and C.

2.5 Estimation of peak flow discharges from gully top widths on photographs

Gully peak flow discharges Q_p can also be estimated from the gully channel top widths W. Nachtergaele et al. (2002) showed from field measurements, field experiments and laboratory experiments, that in general a good W-Q_p relation is valid for ephemeral gullies, but also for permanent stabilized gullies such relationships can be applied (Sidorchuk, 1999). Derivation of peak flow discharge (Q_p) can thus be done using the following equation (Nachtergaele et al., 2002):

$$W = \alpha . Q_p{}^{\beta} \Leftrightarrow Q_p = \sqrt[\beta]{\frac{1}{\alpha} W} \qquad (6)$$

In general, the exponent β takes values of ca. 0.3 for rills (Nachtergaele et al., 2002); and approaches 0.5 for flashfloods in semi-arid areas (Graf, 2002). Torri et al. (2006) show that differences in climate, air temperature, channel gradient, land cover, texture and presence of a dry season are negligible for the value of β, which is in general 0.51 for channels wider than 0.5 m. Reported values for α are 1.13 for rills (Gilley et al., 1990), and range between 2.51 (Nachtergaele et al., 2002), 3.0 and 3.17 (Sidorchuk, 1999; Nachtergaele et al., 2002) for gullies. In our study area, Frankl et al. (2013) found that channel widths are indeed strongly and positively related to a discharge proxy (catchment area), following a power relation. For our wide and permanent gullies, the overall β coefficient was chosen (0.51; Torri et al., 2006) and α was set at its most extreme values 2.51 and 3.17 (Sidorchuk, 1999).

2.6 Interviews, profile pits and literature review

In order to investigate the sedistratigraphy of the silted channels, eight profile pits of approximately 2 x 1 m² and 2 m depth were dug into the channels of the three gullies (December 2012). More pits were dug in the largest channels, in order to 'capture' the entire gully width signal. One pit was dug in the May Bati gully, two pits in the Sinkata gully (both in the middle of the channel, with 50 m separation) and five pits in the Atsela gully (all in the middle of the channel, with 10 m separation from each other). Stratigraphy (color, boundaries, fabric, and stoniness) was recorded for all four sides of all eight pits. At the middle of the downslope side of the pits, samples for laboratory analysis were taken at depth intervals of approximately 15 cm. Wet sieving was performed at 64 µm, and dry sieving of the largest fractions (at 2 mm, 1 mm, 500 µm, 250 µm, 106 µm and 75 µm). Mineralogy was determined with microscopy for the 250 µm - 106 µm fraction of the samples at 50 cm depth. Some 2.5-3 g of the remaining silt and clay fraction was mixed with a 40 ml 0.2% sodium hexametaphosphate solution, shaken by sonication, and analyzed with X-ray sedigraphy (Micromeritics, 2013). Texture was determined using the USDA classification. Finally, in the surroundings of the infilled gullies, 16 open interviews with key informants (elder farmers who had lived and worked in the area since their childhood) were conducted (4 around the May Bati gully, 6 around the Sinkata gully and 6 around the Atsela gully). Farmers were asked to describe the gully evolution and the timing and processes of the gully infill.

Further, in line with earlier research in the study area (e.g. Naudts, 2000; Smit & Tefera, 2011) and using experience with interviewing gained in earlier research (Lanckriet et al., 2014), the likely relation between a changing agro-management (including property rights, the size of land holdings, conservation activities and cropland management) and gully cut-and-fill could be identified.

3. RESULTS

3.1 Estimation of catchment-wide Curve Numbers

Based on the existing land cover data and runoff coefficients, catchment-scale runoff coefficients were calculated for the early 20th and 21st century using Eq. 1 (Table 3). It is clear that land cover changes and deforestation resulted *ceteris paribus* hardly in overall higher runoff responses over the 20th century (runoff coefficients +5.9, +3.3 and -32.8 % for the catchments); (Table 3).

TABLE 3

Curve numbers were then calculated under the 19th and early 20th century land cover situation using Eq. 2 & 3 (Table 3). The resulting average curve number based on the Monte Carlo simulation (Figure 5a) is $CN_{average}$ = 81.1; with st. dev. = 2.3 (Figure 5a). Since these simulated catchment-wide curve numbers are relatively high (on average >80), it is clear that the Highlands were already heavily degraded and deforested during the 19th and early 20th century. This can be illustrated by simulating the runoff response with the average early 20th century curve numbers as compared to curve numbers of contemporary croplands using Eq. 4 (Nyssen et al., 2010; Figure 6). For the same daily rainfall sequence, the early 20th century runoff response is simulated higher than the contemporary cropland runoff response. In general, and contrary to the common perception, the simulation shows that the impact of land cover on surface water runoff in the Highlands was one century ago about the same as today. Finally, Monte Carlo sensitivity analysis (effect of the land cover type on the curve number) showed that the curve numbers were very sensitive to the areal extent of bushland during the early 20th century (Figure 5b) – whereas runoff sensitivity shifted towards the areal extent of cropland during the early 21st century (Figure 5c).

It is worth mentioning that the recent photograph of the relatively wide gully in Bolago may not show a situation in equilibrium with the current environmental conditions, but instead may show a situation inherited from the 1970s or 1980s, before recent reforestation took place. As stated before, the largest peak discharges must indeed be a result of a situation when the catchments were in their most degraded state.

FIGURE 5

FIGURE 6

3.2 Reconstruction of the gully peak discharge changes over the 20th century

Historical peak flow discharges simulated for the different gully widths (Eq. 6) ranged between 7 and 53 m^3/s (Table 4).

TABLE 4

Average gully width increase over the 20th century was 6.4 m, with a significant t-test for the difference of means of the two periods ($p < 0.05$). Even under the extreme scenario of a 10% underestimation in historical top width measurements and a 10% overestimation in recent top width measurements, the average gully width increase over the 20th century was still 4.2 m. This corresponds to a minimum 20th century average peak discharge increase of 10.6 ± 3.7 m^3/s (Table 4), equal to a discharge increase of 71.2 % in Ashenge, 80.2 % in Atsela and 43.3 % in Bolago. Moreover, two downstream gully channels around Ashenge (AB and AC) did not exist in the early 20th century, but incised in the course of the late 20th century. However, over the 20th century, it is unlikely that rainfall intensities (I) changed, as from 1900 no long term changes in annual rainfall have been observed for the nearby Blue Nile basin (Nyssen et al., 2007): 'on average it rains as much around the year 2000 as around 1900'. Possibly, due to road building, some catchment areas (A) might have increased in the Highlands (Nyssen et al., 2002), but this was not the case for our study catchments. Therefore, the huge average increase in stabilized gully width (6.4 m), the important minimum increase in estimated gully peak discharges (10.6 ± 3.7 m^3/s) and the incision of the two downstream gully channels at Lake Ashenge during the second half of the 20th century must be related to changes in the runoff coefficient C.

3.3 Reconstruction of the gully infill

The influence of cropland management on gully cut-and-fill was clearly visible in the filled gully channels. The profile of the May Bati pit (Figure 7) suggests an unlayered antropogenic colluvial infill, given the fact that the texture of the black layer vertic material is the same (median grain size < 2 µm) as textures of the surrounding Vertisols (Lanckriet et al., 2012). The possibility of an alluvial aggradation was discarded, since the sediments were not layered and showed no sedigraphic variability. As confirmed by farmers and as suggested by the texture analysis, the process of infill here is probably caused by a combination of tillage erosion and sheetwash that occurred in the last ten years.

Six open interviews with local farmers around the gully of Atsela reveal that this channel flow had been diverted by farmers some decennia ago (Figure 8). Six interviews with farmers around the Sinkata gully reveal that the gully filled in due to the construction of large gabion dams, around ten years ago (Figure 8). The stratigraphic descriptions of the profile pits (Figure 7) confirm these hypotheses (colluvial unlayered vertic infill of the May Bati gully; and an alluvial layered infill with rounded gravel and boulders of the Atsela and Sinkata infill). As illustrated by the Atsela case, gullying is dependent on flow diversions by farmers around plot boundaries. Indeed, observations in the study area show that several gullies are not always situated in the lowest parts of the landscape. This social-qualitative information yields independent evidence, strengthening our main argument: gully systems are very sensitive to agro-management.

FIGURE 7

FIGURE 8

4. DISCUSSION

Over the second half of the 20th century, we observed a huge increase in stabilized gully width and an increase in estimated gully peak discharges. However, as shown in section 3.1, the impact of land cover on surface water runoff in the Highlands was one century ago about the same as today. In particular, instead of the expected peak discharge increases of 71.2 %, 80.2 % and 43.3%, peak discharge increases due to land cover changes are calculated (using Eq. 5) at only 5.9%, 3.3 % and -32.8 % respectively (Table 3). Therefore, neither climate, road building, deforestation nor large-scale land cover changes can explain the changing gully morphology and peak discharges (average $\Delta W = 6.4$ m; average minimum $\Delta Q_p = 10.6$ m^3/s; $p < 0.05$). Apart from *authigenic* factors (e.g. natural channel widening), we therefore invoke interactions between the management of the croplands, small-scale land boundary changes, and overuse of the lands that can explain the observed gully widening. In general, sociopolitical factors lead to land management decisions which have impact on gully widening.

Firstly, an upslope extension of croplands during the 20th century, as reported by Naudts (2002), probably further decreased the vegetation cover and increased the runoff coefficient (C), due to the removal of remnant vegetation on the slopes. This trend has to be considered in its complex sociopolitical context. For example, the upslope extension of cropland during the 19th and 20th century may reflect the unequal character of land rights during late-feudal times. This extension was strongly related to an unequal division of land holding sizes, property rights and political power within the peasant community. Lanckriet et al. (2014) showed that during this period, farmers who were unable to claim genealogical relations with the founding families of the villages had no land rights and were forced to construct their farms and cultivate land on steep sloping and marginal terrains, leading to higher area-weighted runoff coefficients and thus gully peak discharges. In the same political context, it is also important to note the huge impact of the civil war on land degradation processes (Lanckriet et al., 2014), and the land reorganizations that often follow periods of war.

Secondly, changes in the land boundaries (removal of vegetation strips and traditional *daget* conservation structures), equally increased the runoff coefficient of the catchment. According to Nyssen et al. (2007), traditional conservation structures (*dagets* and grass strips on plot boundaries) have been narrowed, from 2 m around 50 years ago, to even less than 0.5 m at present. Thirdly, there has been a steady intensification of the agricultural production during the second half of the 20th century in Northern Ethiopia. Fallowing (*mistigao*) was a common practice, especially till the 1970s, with fallow lands simultaneously being grazing land for the village herds (Corbeels et al., 2000). Grabham & Black stated in 1925 on the regional agricultural system that “it seems to involve an area remaining fallow nearly twice as large as that under crop. The consequence is that only about one-third of the land around villages is cultivated.” Runoff responses on fields with fallowing (CN = 89.5; Nyssen et al., 2010) were simulated using Eq. 4, confirming that the high runoff production on such fields could have contributed to the high historical runoff in our case-catchments (Figure 6). Possibly, the plowing frequency of croplands increased over the 20th century, which would result in more concentrated flows and lead to soil compaction, resulting in a higher runoff coefficient and offsetting the hydrological effect of reduced fallowing (Smit & Tefera, 2011). Tesmesgen et al. (2008) show that the high yearly tillage frequency in the Highlands (4-5 times for teff and 3-4 times for maize) stems from the need to plow before the soil is wetted by rainfall. Periodic dry spells during the rainy season force farmers to plow frequently in order to avoid soil moisture losses. The more the farmer is educated and experienced, and the bigger his land and family, the higher is the tillage frequency on his fields (Tesmesgen et al., 2008). As shown by Lanckriet et al. (2012), average runoff coefficients under reduced tillage experiments are about half of the values under the current high tillage frequency

(18.8% compared to 30.4%). Under a scenario of reduced tillage on all croplands in the early 20th century, area-weighted runoff coefficients would have been considerably smaller (22.9% for Ashenge 1936, 24.7% for Atsela 1944, 31.3% for Bolago 1868). Overall, the scenario indicates that these gully systems are very sensitive to increased tillage frequency.

Finally, increased cattle grazing can have an important impact on catchments' runoff coefficients. According to Nyssen et al. (2004), the contemporary stocking rates are well in excess of estimated optimum stocking rates, resulting in decreased surface roughness, soil compaction and decreased hydraulic conductivity. As a consequence, infiltration becomes difficult and runoff coefficients increase (Nyssen et al., 2004).

Given the environmental data scarcity in the Ethiopian Highlands, the methods presented here will reflect general environmental patterns. Since the equations employed are empirical, this study does not pretend to simulate gully peak discharges exactly. However, we presented a case-study in a limited number of catchments, with a simple methodology to estimate long-term trends in catchment-wide curve numbers. We showed that neither climate nor deforestation could explain the observed gully morphodynamics, which is in sharp contrast with most geomorphic gully studies (Table 1). The average historical curve number ($CN_{average} = 81.1$) was leading to considerable historical runoff responses. This contradicts several studies which claim that deforestation in North Ethiopia was mainly a 20th century process, although the origin of the data in these studies seems rather perfunctory. Parry (2003) states for example that "Ethiopia lost 98% of its forest cover during the last 50 years". Gore (1992) even claimed that Ethiopia's forested land had decreased from 40 to 1 percent from 1950 to 1992. Additionally, there is a common narrative that

Ethiopia and Eritrea had “44 % forest cover in 1885” (McCann, 1997), or “40 % in 1900’’ (Allen-Rowlandson, 1989; Robinson et al., 1995). The situation may be different in the South of the country, but this study confirms the findings by Nyssen et al. (2009) who conclude that the Northern Ethiopian Highlands were already highly degraded before the 20th century.

As population density in that period was rather low (Nyssen et al. (2009) estimated the population of Ethiopia in 1868 at about 9% of today’s population), this historical land degradation could not be of Malthusian origin. Indeed, gully cut processes prior to 1868 were observed from historical photographs, and are possibly related to the occurrence of droughts (Frankl et al., 2011). However, little information is available on the pre-19th century Northern Ethiopian climate (Little Ice Age; impact of El Niño) and pre-19th century land cover, so additional information should be gathered in this respect.

In line with observations in the filled gullies, a case study in the Amhara region (Smit and Tefera, 2011) shows that gullying in the Ethiopian Highlands is sometimes impacted by interactions between farmers who use their political power positions to avoid and divert harmful flows from the neighbors’ farmlands. In general, cropland management and sociopolitical aspects of rural societies deserves more attention in geomorphological studies.

5. CONCLUSIONS

This study incorporated different driving factors (land cover changes and changes in cropland management) that influence the shape and dimensions of gullies in the Northern Ethiopian Highlands. Gully incision was reconstructed by estimating historical peak flow discharges using values for historical gully width, as derived from recent photographs (2008-2009) and historical photographs (1868-1942). Average gully width increase over the 20th century was significant ($p < 0.05$) and was estimated at 6.4 m. Minimum peak discharges increased significantly (ΔQ_p: $p < 0.05$) during the 20th century and were calculated on average at $10.6 \pm 3.7\ m^3/s$. Monte Carlo simulation allowed to reconstruct curve numbers one century ago (on average 81.1). This shows that the North Ethiopian Highlands were already severely deforested during in the 19th century. If deforestation is mainly a pre-20th century process, it is a less direct driver of 20th century land degradation processes. Hence, interactions between agricultural management (e.g. including environmental management, agricultural intensification and land distribution), small-scale land boundary changes (e.g. removal of *dagets* and grass strips) and sociopolitical factors (e.g. land tenure change, civil war) could be strong contributing factors. The historical evolution of those drivers is not directly visible on historical photographs. The estimated catchments' runoff response resulting from 20th century land cover changes shows however that catchment-scale runoff changes and processes of gully widening can be partly linked to small-scale land-cover changes, but also to changes in the cropland management. Finally, sedistratigraphic analysis of recently filled gullies suggests a strong agronomic interference (tillage operations, conservation structures, channel diversions). Hence, a combination of simulations and historical evidence suggests that agro-management is an important driver of gullying and related land degradation processes.

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FIGURES

Figure 1: Example of a gully, in the Northern Ethiopian Highlands (13.65126°N – 39.21895°E; looking upslope from the study site in May Ba’ati); for illustration purpose. Livestock for scale.

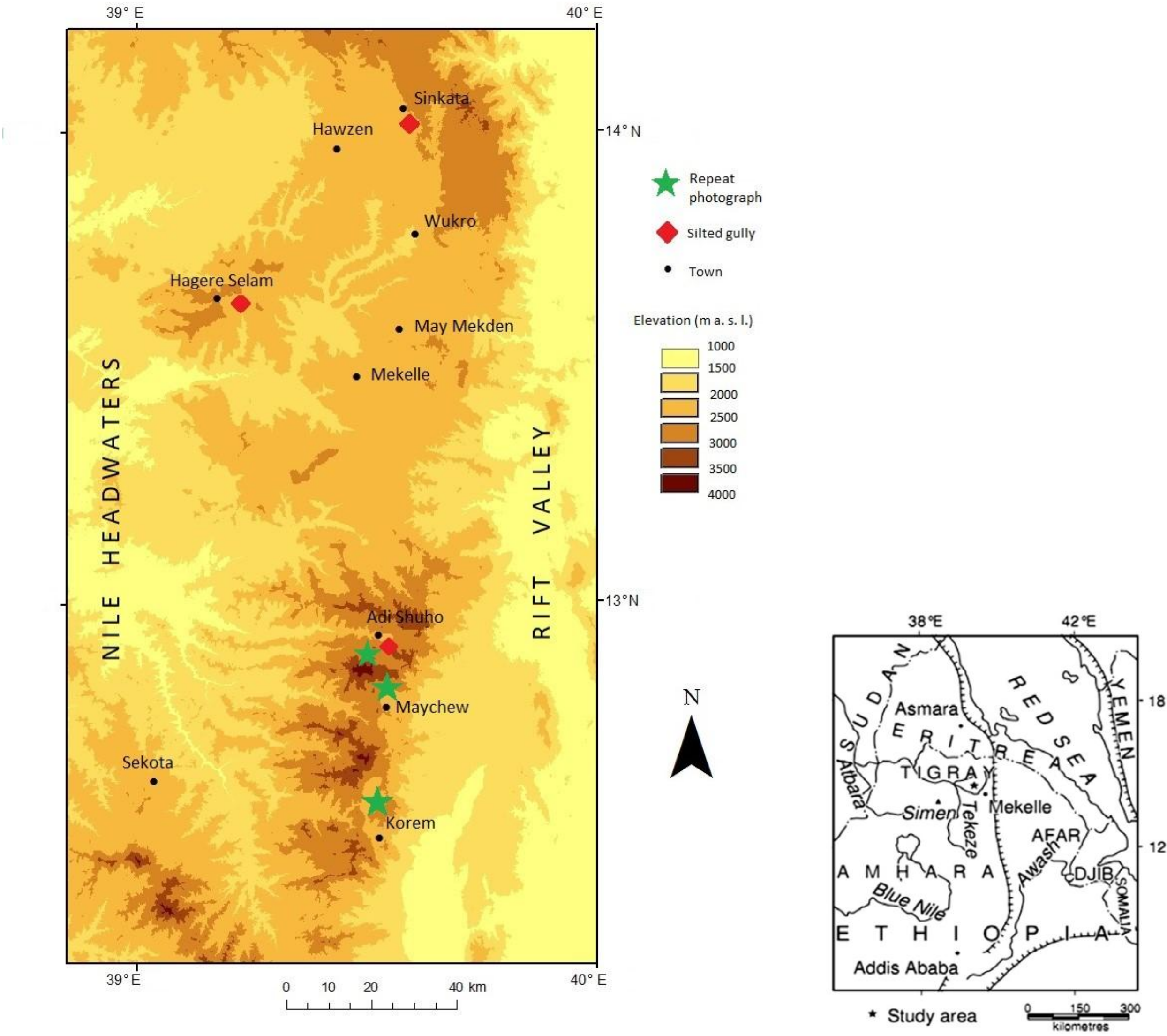


Figure 2: Study area with the location of the three investigated silted gullies (May Ba'ati is located next to Hagere Selam; the other gullies near Sinkata and Atsela (Adi Shuho)); and the location of the repeated photographs of gully cross-sections (2 sites near Atsela; 1 to the North of Maychew (Bolago); and 3 sites near Korem (Ashenge)).

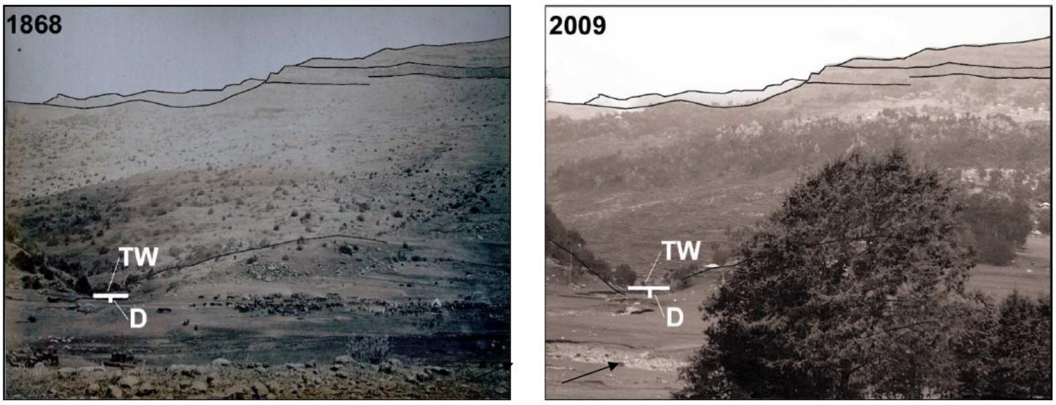


Figure 3: Example of a historical photograph (Royal Engineers, 1868) with modern analog (Amaury Frankl, 2009) in the Bolago catchment (Viewpoint: 12.82722° N, 39.51777° E), with indication of the calibrated gully top widths (W) and depths (D); (after Frankl et al., 2011); accuracy of the top width measurements is 10%, and accuracy of the depth measurement is 16% (Frankl et al., 2011).

Figure 4: Infilled gully channels, for illustration purpose. From left to right, the upslope part of the May Bati gully (13.65126°N – 39.21895°E); the downslope part of the channel in Sinkata (14.04785°N – 39.58263°E) and the channel in Atsela (12.93180°N – 39.52446°E). The red arrow indicates the historical stream direction.

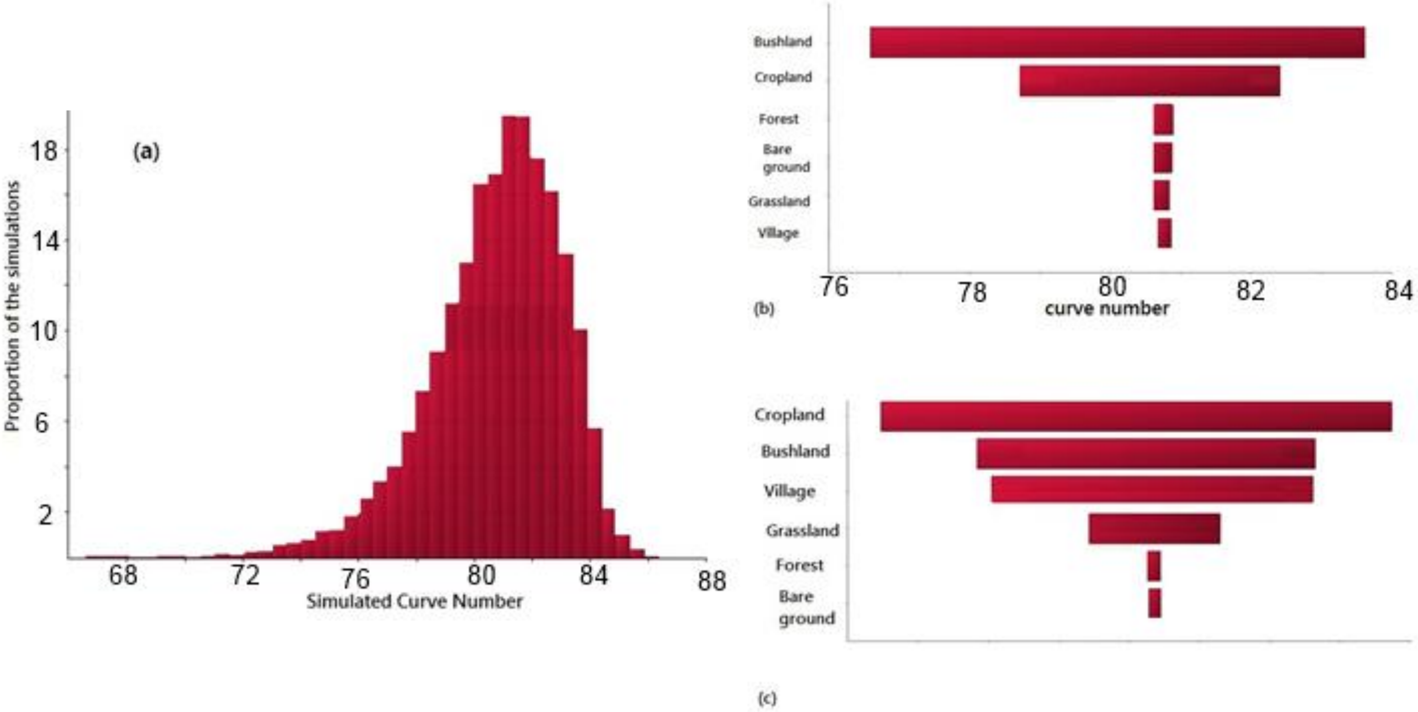


Figure 5: (a) Monte Carlo simulation (10 000 runs) of the curve numbers calculated with the data from Table 4; proportions in %; (b) results of the sensitivity analysis of the early 20th century landscape vulnerability to runoff; and (c) resulting sensitivity analysis of the early 21th century landscape vulnerability to runoff.

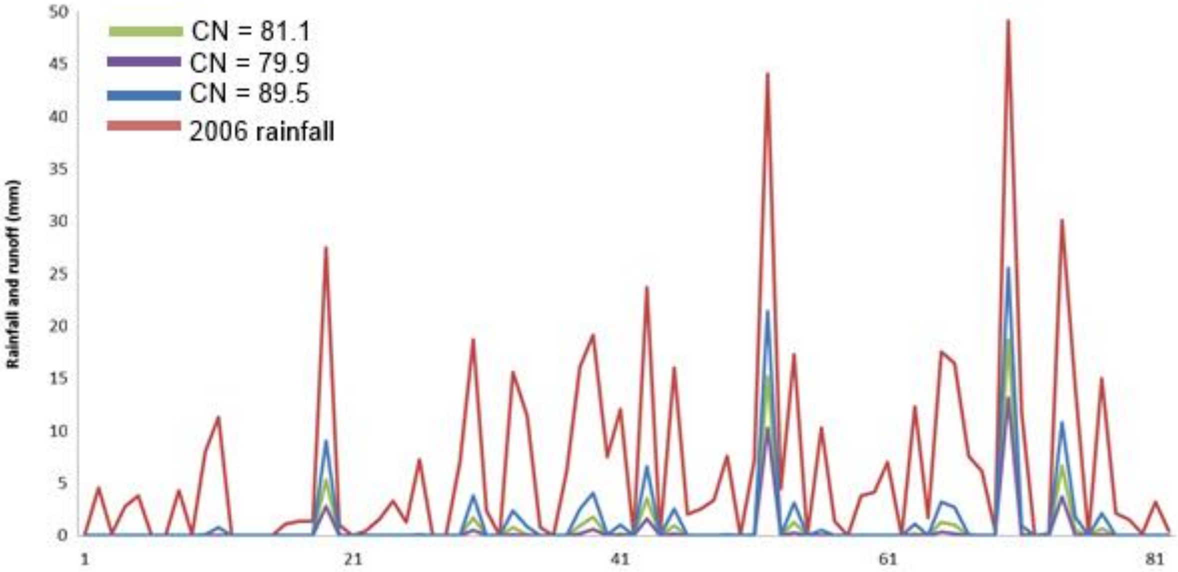


Figure 6: 2006 rainfall (in red - Mekelle Airport; days after 1 June) was used to simulate runoff (Curve Number method) during the early 20th century (CN = 81.1; weighted average; in green), under cropland (free grazing, no stone bunds; in purple; CN = 79.9; Nyssen et al., 2010) and for fallow lands (CN = 89.5; in blue; after Nyssen et al., 2010).

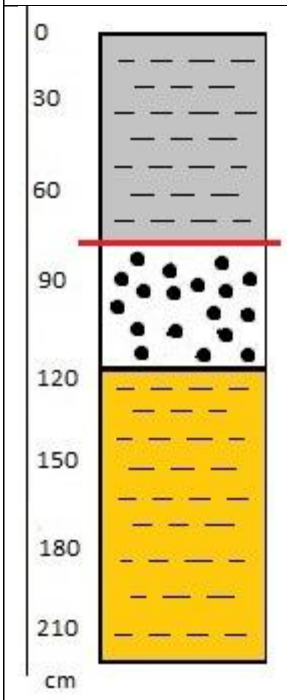
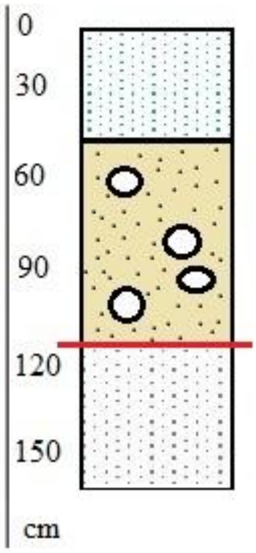
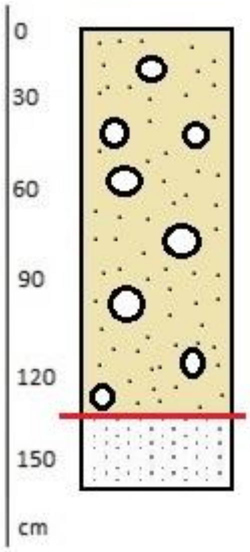
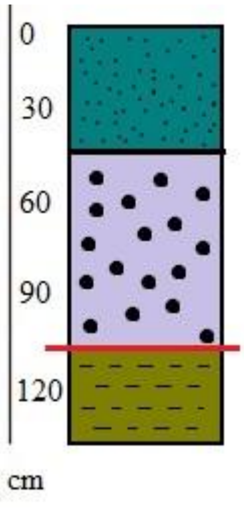
May Bati (13.65126°N; 39.21895°E)		Sinkata A (14.04785°N; 39.58263°E)	
	Black clayey layer of vertic colluvium, containing mainly open 2:1 phyllosilicates (smectites) and feldspars (Moulaert, 2012) – transported by tillage erosion & sheetwash. White calcareous rounded gravel indicating the paleo-bed Yellowish clayey weathered parent material, containing lime and some quartz, kaolinite, and micas; (Moulaert, 2012)		Alluvial white sand Alluvium of randomly distributed sandstone pebbles in a sandy layered matrix, containing some micritic limestone fragments, sparitic calcite, quartz, biotite and zircon Pale white sand, supposedly weathered Enticho sandstone
Sinkata B (14.04786°N; 39.58262°E)		Atsela (12.93180°N; 39.52446°E)	
	Alluvium of randomly distributed sandstone pebbles in a sandy layered matrix, containing some micritic limestone fragments, sparitic calcite, quartz, biotite and zircon Pale white sand; weathered Enticho sandstone		Alluvium of dark layered sands, containing hornblende, some plagioclase, quartz, zircon, biotite and muscovite Alluvial rounded gravel (diameter 5 cm) Heavy black (vertic) clay

Figure 7: Schematized stratigraphy of the downslope sides of all eight profile pits. Depths are given in centimeters (cm). For Atsela, only one profile is shown, since all six profile pits showed similar layered alluvial sands and gravel. The red lines indicate the interface between infill and original bed.

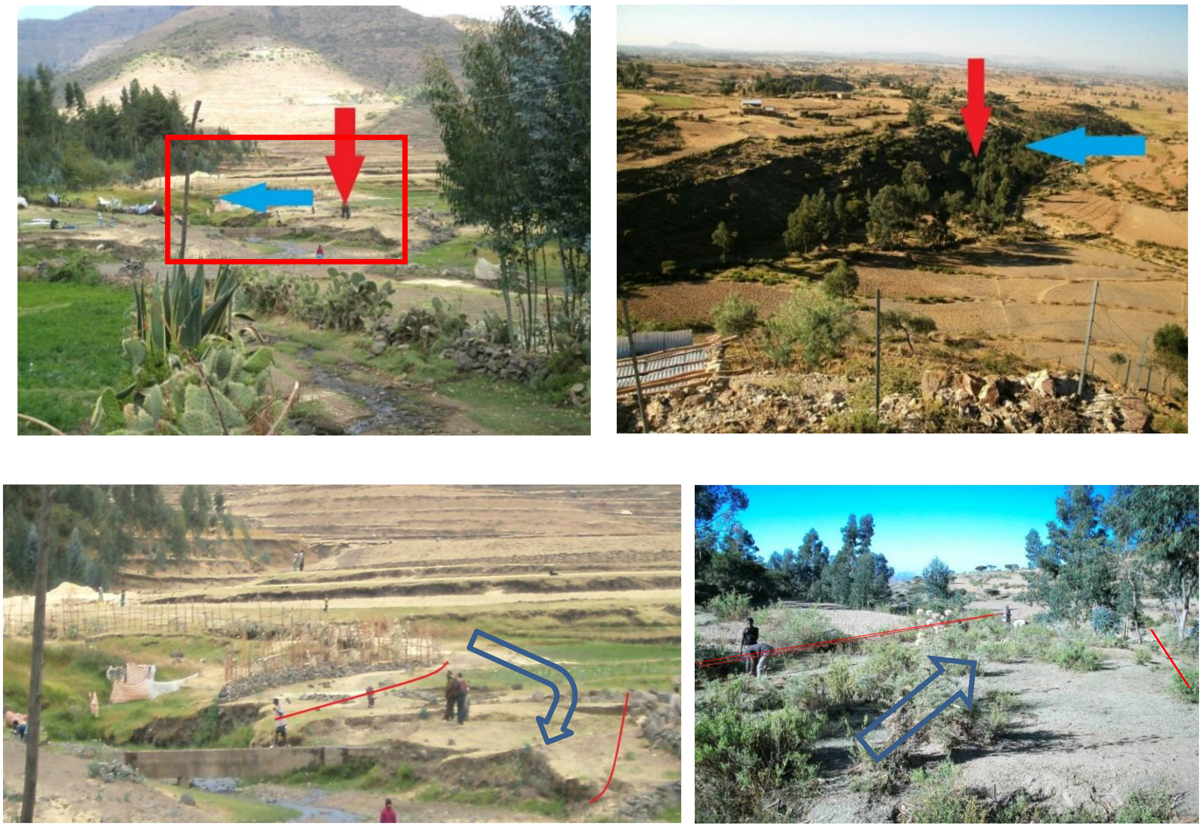


Figure 8: Location with red arrow of the silted gullies in Atsela (left; 12.93180°N – 39.52446°E) and Sinkata (right; 14.04785°N – 39.58263°E). The filled blue arrows show the direction of channel diversion for Atsela, and the location of the large gabions for Sinkata. Closer view of the channels in Atsela (lower left) and Sinkata (lower right). The red lines indicate the channel boundaries and the blue open arrow indicates the historical stream direction.

TABLES

Table 1: Drivers of Holocene terrestrial gully cut-and-fill cycles.

Continent	Country	Location	Elevation (m a.s.l.)	Period considered	Number of cycles	Main contributing factors							Authors
						Sea-level change	Tectonics	Road building	Climate change	Land use chage	Cropland management	Overgrazing	
EU	UK	Isle of Wight	0	12 ka	1	X			X				Leyland & Darby (2009)
	Germany	Wolfsgraben – Bavaria	200-300	1200 BC - now	7				X	X			Dotterweich et al. (2003)
		Taunus	200-600	Early Medieval	1						X		Stolz et al. (2011)
	Poland	Silesia	200-300	1949-now	1				X				Malik (2008)
	Slovakia	Myjava	200-1000	1300s-1500s-now	2-3				X	X			Stankoviansky et al. (2003)
	Hungary	Balaton Lake (Tetves)	100-300	1968-2004	>4					X			Kertesz & Gergely (2011)
		Rakaca	100-300	1800-2003	1					X			Gabris et al. (2003)
	Belgium	Meerdaal	30-110	1743 BC – 364 AD	2			X					Vanwalleghem et al. (2003)
		Meerdaal & Tesaart	30-110		1					X			Vanwalleghem et al. (2006)
		Meerdaal	30-110		1					X			Vanwalleghem et al. (2008)
	Spain	Rambla Salada	100-400	1997	1					X			Wijdenes et al. (2000)
		Carcavo	200-900	2004-2007	1					X			Lesschen et al. (2007)
		Guadalentin & Sierra de Gata	120-1100	1996-1998	1					X			Vandekerkhove et al. (2000)
		El Cautivo	200-400	Pleisto/ Holocene	6				X	X			Alexander et al. (2008)
		Navarra	200-600	1994-1996	>2						X		Casali et al. (1999)
	Portugal	Alentejo & Serra de Negueira	150-900	1996-1998	1					X			Vandekerkhove et al. (2000)
	Italy	Basilicata	50-400	Neolithic - now	4				X				Boenzi et al. (2008)
		Sicily	200-400	1995-2000s	1				X				Capra et al. (2009)

		Basilicata	50-400	4500 BP	4				X				Piccarreta et al. (2012)
		Sardinia	0-400	1955-1999	1					X			Zucca et al. (2006)
	Greece	Lesvos	0-260	1996-1998	1					X			Vandekerkhove et al. (2000)
AF	Ethiopia	Ziway-Shala	1600-1900	5 ka	> 5		X		X				Carnicelli et al. (2009)
		Debre-Mawi	1900-2400	1980-2008	1					X			Tebebu et al. (2010)
		Umbulo	1500-3000	1965-2000	1					X			Moges & Holden (2009)
	Madagascar	Antananarivo Region	1000-2000	1985-1990	1			X	X	X			Wells & Andriamihaja (1993)
	Nigeria	Anambra	0-500	Quaternary	> 2		X						Egboka (1990)
	Kenya	Chesegan	1000-1400	2000s	1			X					Jungerius et al. (2002)
	South Africa	Sneeuberg (Great Karoo)	500-2000	19th century-now	1							X	Boardman et al. (2003)
		Keiskamma	600-900	1990s	1							X	Mhangara et al. (2012)
		Umtata	150-2800	2008	1							X	Le Roux & Sumner (2012)
AS	Israel	Yehezkel	100	2000s	1			X					Svoray & Markovitch (2009)
		Negev	0-1000	1400 BP – 2000s	1				X		X		Avni (2005)
	Iran	Hableh Rood	1000-2000	1957-2005	1				X	X			Samani et al. (2010)
	China	Gansu	1500-2500	Holocene	1				X	X			Schutt et al. (2011)
	Japan	Hokkaido	0-300	1960-now	1						X		Nagasaka et al. (2005)
	Mongolia	Karakorum	1000-3000	6 ka	2				X			X	Lehmkuhl et al. (2011)
AM	USA	Providence Canyon	100-140	1840-now	1			X		X			Hyatt & Gilbert (1999)
		South Carolina	300-800	1939-1999	1					X			Galang et al. (2007)
		Iowa	200-500	1990	1						X		Zaimes & Schultz (2012)
		Santa Cruz (California)	0-2000	19th century	1-2							X	Perroy et al. (2012)
OC	New Zealand	Waiapu	200-1200	1939-2003	1-3					X			Parkner et al. (2006)
	Australia	Naas River	600	14 ka	> 3				X	X			Eriksson et al. (2006)

	Australia	Queensland	50-600	1800s-now	1				X	X			Saxton et al. (2012)

Table 2: Historical and recent top widths of the cross-sections analyzed by Frankl et al. (2011), with an accuracy of 10%.

Code	date	$TW_{historical}$ (m)	date	TW_{recent} (m)	ΔTW (m)	Coordinates (WGS84)
M	1942	10.94	2009	14.82	3.88	12°54’44” N, 39°31’16” E
M	1942	8.81	2009	11.90	3.09	12°54’44” N, 39°31’16” E
P	1868	13.3	2009	16.00	2.70	12°49’37” N, 39°31’04” E
Q	1936	14.42	2009	19.00	4.58	12°33’45” N, 39°31’22” E
R	1936	0	2009	11.60	11.60	12°33’55” N, 39°31’27” E
S	1936	0	2009	12.50	12.50	12°33’55” N, 39°31’27” E
Average		7.9		14.3	6.4	

The codes are derived from Frankl et al. (2011); $TW_{historical}$ and TW_{recent} correspond to the gully top widths derived from the historical and recent photographs respectively; ΔTW corresponds to the difference between the two situations.

Table 3: Twentieth century land cover (A_x) changes in our study catchments (reported in Meire et al., 2013), runoff coefficients (C_x) calibrated by Descheemaeker et al. (2006) and Lanckriet et al. (2012) with normal distributions N (C_x, $0.1C_x$) chosen for the Monte Carlo simulation; and predicted catchment runoff coefficients C (Eq. 1).

Catchment	Ashenge		Atsela (1944-2008)		Bolago (1868-2008)		C_x
A_x (%)	1936	2008	1944	2008	1868	2008	
Cropland	64.8	64.8	61.6	55.0	5.0	14.2	30.4
Bush land	29.6	25.4	36.7	23.1	83.7	4.0	34.8
Village	0.0	5.6	0.0	13.0	0.0	16.0	60.0
Bare ground	5.6	4.2	0.0	0.0	0.0	0.0	7.7
Grassland	0.0	0.0	1.4	1.4	5.2	26.0	23.5
Forest	0.0	0.0	0.3	7.4	6.1	39.7	0.03
Weighted C	30.4	32.2	31.8	32.9	31.9	21.4	
$\Delta C = \Delta Q_p$	+5.9 %		+3.3 %		-32.8 %		
ΔQ_p from ΔW (Eq. 1)	+71.2 %		+80.2 %		+43.3 %		
$CN_{historical}$	80.8		81.3		81.3		

Table 4: Estimated peak flow discharges Q_p, with a minimum and a maximum estimation, as calculated with Eq. (6), required to cause the gully morphology (Δ corresponds to the difference between the two situations).

Locations	$Q_{p,\ historical\ MIN}$ (m^3/s)	$Q_{p,\ historical\ MAX}$ (m^3/s)	$Q_{p,\ recent\ MIN}$ (m^3/s)	$Q_{p,\ recent\ MAX}$ (m^3/s)	$\Delta\ Q_{p\ MIN}$ (m^3/s)	$\Delta\ Q_{p\ MAX}$ (m^3/s)	Coordinates (WGS84)
Atsela A	11.34	17.93	20.49	32.52	9.15	14.59	12.91911° N, 39.52189° E
Atsela B	7.42	11.73	13.33	21.15	5.91	9.42	12.91931° N, 39.52156° E
Bolago	16.62	26.30	23.81	37.79	7.19	11.49	12.82953° N, 39.51419° E
Ashenge A	19.48	30.82	33.35	52.93	13.87	22.11	12.56397° N, 39.52031° E
Ashenge B	x	x	12.68	20.11	12.68	20.11	12.56528° N, 39.52417° E
Ashenge C	x	x	14.68	23.29	14.68	23.29	12.56250° N, 39.52278° E
Average	9.14	21.69	19.72	31.30	10.58	16.8	