Gully expansion and its temporal influence on catchment geomorphic characteristics and gully topographical thresholds in the semi-arid Ethiopian Rift Valley

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May 5, 2020

Abstract

To analyse the driving forces of gully network expansion using a present dataset of land use/cover involves limitations because past land use/cover strongly regulates gully formation and evolution. The vegetation cover in the gully catchment at the time of gully incision may best explain the topographical threshold levels. The recent development of photogrammetric techniques enabled to estimate temporal gully volume changes. This study conducted in semi-arid Ethiopian Rift Valley used field measurements and gully volume–length relation to (i) keep track of gully volume changes and (ii) analyse temporal transitions in catchment geomorphology and topographical threshold of gully heads to explain the difference in the gully volumes between two study sub-areas. The topographic thresholds of the gully heads, expressed by the slope (= s) and drainage area (= a), formed (i) in each catchment and (ii) in all the catchments in each sub-area during the same individual period (before 1957, 1957–1972, and 1972–2005) were approximated by power functions (s = ka-b). Transitions in these threshold lines showed clear temporal and spatial patterns: the threshold lines maintained almost the same exponent b specific to each sub-area while the threshold coefficient k decreased as time passed. The expansion of the gully network induced by land use/cover changes lowered the gully topographic threshold level in agroecology, which accelerated further gully expansion and influenced the exponential increase in gully volumes over time. Characteristics of temporal changes in catchment geomorphology partly explained the difference in the area-specific gully volumes between the sub-areas.

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KEYWORDS: gully evolution, area-specific gully volume, gully volume–length relation, catchment geomorphology, topographic threshold

INTRODUCTION

In East and South African countries, large-scale gullies can be seen almost everywhere (Katsurada et al., 2007; Ndomba, Mtalo, & Killingtveit, 2009; Boardman, 2014). In semi-arid Ethiopian highlands (Tigray), the area-specific gully erosion rates (gully erosion rate per unit area) since gully incision to 2001 were 6.2–17.6 Mg ha^{-1} y^{-1} (Nyssen et al., 2006; Frankl et al., 2013a). In sub-humid Ethiopian highlands (Amhara), the area-specific gully erosion rates were 8.7–155 Mg ha^{-1} y^{-1} (Tebebu et al., 2010; Zegeye et al., 2016; Yibeltal et al., 2019a). Most gully volumes showed an exponential increase since gully incision except for the ones in the areas where gully rehabilitation or soil and water conservation programmes at watershed scale were implemented (Nyssen et al., 2006; Frankl et al., 2013a). In semi-arid Ethiopian Rift Valley, the area-specific gully erosion rate was 16.2 Mg $ha^{-1}y^{-1}$ (Mukai, 2017). The mean gully erosion rate of 1.93 Mg y^{-1} (1957–1972) was exponentially increased to 10.18 Mg y^{-1} (1972–2005). The contribution of gullying to total soil loss from the area ranges from 28% in semi-arid highlands (Nyssen et al., 2008) to 64 to more than 90% in sub-humid highlands (Tebebu et al., 2010; Zegeye et al., 2016) of Ethiopia.

Gully formation and its evolution are regulated by various factors, such as several geomorphic properties of catchments, slope gradient, land use, vegetation, and rainfall characteristics (Poesen et al., 2003; Valentin, Poesen, & Li, 2005). It is well known that gully initiation and gully head positions are related to some critical conditions, e.g., the topographic threshold, a combination of the slope at the gully head (s) and upslope drainage area (a), which is expressed in equation (1):

$s = ka^{-b}$ (1),

where the exponent b and threshold coefficients k, are constants which depend on local climate, soil, and land use (Torri & Poesen, 2014). Land use that reduces vegetation cover through increases in cultivated area and transformation of forest to grassland tends to reduce the topographic threshold levels and increase the risk of gully erosion on sites (Parkner et al., 2006; Gómez Gutiérrez, Schnabel, & Lavado, 2009; Yibeltal et al., 2019a).

An understanding of gully development from historical and current perspectives is essential when addressing the causes and consequences of land degradation (Frankl et al., 2013a) and to predict the future behaviour of gullies (Li et al., 2017). Several studies recently analysed quantitatively the factors controlling gully morphology and gully network formation. Most of these studies used a statistical approach, such as multivariable analysis to predict the values of dependent variables, such as gully cross-sectional morphology (Frankl et al., 2013b; Yibeltal et al., 2019b), gully erosion rate (Muňoz-Robles et al., 2010) and land susceptibility index (Conoscenti et al., 2013), from several independent variables, including catchment geomorphology, land use/cover, rainfall, soil. These studies used present datasets to determine the present factors of gully formation. However, these studies involve some limitations because (i) the present land use/cover was not a decisive factor of gully erosion (Kompani-Zare et al., 2011; Frankl et al., 2013b; Mukai, 2017); (ii) the vegetation cover in the gully catchments at the time of incision explained the difference in threshold levels best (Vandekerckhove et al., 2000); or (iii) the rates of gully erosion was strongly correlated with land use/cover when the indicators of land use/cover were expressed in temporal variables (the rates of area changes in land use/cover items in the catchments between two periods; Mukai, 2017). The same goes for the topographic threshold studies. The topographic threshold levels and conditions for gully head development have been compared mainly between different land/use cover, soil, land management, flow conditions in different environments (Torri & Poesen, 2014). However, because most studies used present datasets, temporal interaction between environmental changes and gully head positions in the same catchments has not been assessed.

Some gully morphological characteristics have recently been used to determine temporal gully volume changes. Several studies have explored the relationship between the gully volume (V) and length (L) using a power equation $V = aL^b$ ($V-L$ relation; e.g., Frankl et al., 2013b). Li et al. (2017) proposed a relation between the gully volume (V) and gully area (Ag) using a power equation $V = aAg^b$. These models have advantages that the length and area of a gully can be easily determined from aerial photographs and high-resolution satellite images. These photogrammetric techniques were utilised to assess long-term changes in gully volumes (Frankl et al., 2013a) and to analyse the driving force of gully network expansion back to when gullies were initiated (Mukai, 2017). Thus, the combination of photogrammetric techniques and a simple $V-L$ relation may enable assessment of temporal interactions between environmental changes and gully erosion/gully head positions.

The objectives of this study carried out in semi-arid Ethiopian Rift Valley were, (i) to keep track of gully volumes and area-specific gully volumes in the catchments in two sub-areas; (ii) to analyse temporal dynamics in catchment geomorphology and topographical threshold of gully heads to explain the gully volumes and area-specific gully volumes specific to the sub-area; and (iii) to confirm that the combination of the $V-L$ relation and field measurements is feasible to assess the interactions between environmental changes and gully erosion/gully head positions.

MATERIALS AND METHODS

2.1 Study area

The Tebo and Geldia catchments (Figure 1) stretch from the northwestern Rift margin at ~2200 m asl to the southern lowland of the Rift Valley floor at ~1500 m asl. Most of the catchments are underlain by Quaternary lacustrine deposits intercalated with pyroclastic rocks, except the Rift margin sub-area and the Merko hillside where Tertiary sediments and Pliocene pyroclastic flow deposits prevail, respectively (Abebe et al., 2005). The catchments and permanent gullies in the catchments can be divided into two geographical sub-categories: the Rift margin sub-area (gullies) and the Valley floor sub-area (gullies; Billi & Dramis, 2003). The mean annual rainfall at the nearest rainfall gauge to the Rift margin sub-area is 881 mm (Ejere; 1976-2013) and that to the Valley floor sub-area is 874 mm (Welenchiti; 1992-2013). Rift margin gullies originate from either the Rift margin plateau or the southeastern cliff (Figure 2), whereas valley floor gullies originate from the vicinity of the Merko hillside (1500-1600 m asl, Figures 1 and 2). Soil and water conservation activities, such as soil and stone bund construction on farmland and trench construction on a hillside, have been occasionally implemented in minor parts of the catchments. No gully rehabilitation activities, e.g., check-dam construction, were implemented in both the sub-area before 2005. The soils in the Rift margin plateau are Cambisols or Vertisols (FAO, 1998), whereas those at the foot of the cliffs are Phaeozems or Kastanozems. Similarly, the Valley floor sub-area was divided into four sections: the main soil components of the Merko hill are Regosols and Leptosols, whereas Calcisols, Cambisols, and Vertisols dominate the downslope farmlands (Mukai, 2017).

Five catchments (Boruamba, Telilo, Adare, Gebruamba, and Koka) from the Rift margin sub-area and seven catchments (Hadaware, Merko, Goro, Abharo, Kawa adami, Aware, and Odalega) from the Valley floor sub-area were selected as study catchments (Figure 1).

2.2 Field measurements

Aerial photographs from 1957 and 1972 at a 1:45,000 scale (ground resolution of 1.25 m, scanned at 1200 dpi) were obtained from the Ethiopia Mapping Agency. Aerial photographs (1:50,000) of the study area (~25 km×20 km) were also taken in 2005 with high-resolution panchromatic film. Geometric rectification and photogrammetric restitutions were performed using ground control points, and a digital elevation model (10 m pixel size) for the 2005 orthophotograph with positional accuracy in terms of root-mean-square errors ($RMSE_{xyz}$; 2.4, 3.7, and 3.5 m) was constructed. For the 1957 and 1972 aerial photographs, the geometric rectification was performed by co-registration with the 2005 orthophotograph, which resulted in root-mean-square errors ($RMSE_{xy}$; 3.7–3.8 and 3.2–3.4 m) for the 1957 and 1972 aerial photographs (Mukai, 2017).

In the field surveys conducted in 2005 and 2009, gully networks were divided into homogeneous morphological sections of similar width and depth (Mukai, 2017). The dimensions of gully cross-sections and the length of each gully section were measured by using a tape and laser distance meter (Leica DISTO A5, Leica Geosystems; with a measurement accuracy of 1.5 mm), and then the area of the gully cross-section was calculated by using Microsoft Excel. In total, 266 gully sections were selected (127 and 139 sections from the Rift margin and Valley floor catchments, respectively).

Based on the ground measurement values in the 12 study catchments, relationships between the volume of a gully network (V , 10^3 m^3) and the length of the gully network (L, km) (a V-L relation) in 2005 was calculated as $V = 0.870L^{1.406}$ ($n = 12, r^2 = 0.963$; Mukai, 2017). This power function was used to estimate the volumes of gully networks in 1957 and 1972. For each catchment and period, the area-specific volume of a gully network (V_a , 10^3 $m^3 km^{-2}$) was estimated by the equation of $V_a = V / A$ where V(10^3 m^3) and A(km^2) are the volume and catchment area of the gully network, respectively. For each catchment and period, a gully erosion rate in a mass unit (EM ; 10^3 Mg y^{-1}) was estimated by the equation of $EM = (V_{end} BD_{end} - V_{start} BD_{start}) / (Y_{end} - Y_{start})$ where BD (Mg m^{-3}) is the approximation of soil bulk density (Mukai, 2017) and Y is year; the subscripts *start* and *end* represent the starting and ending years of estimation. Similarly, an area-specific gully erosion rate in a mass unit for each of the catchments (AEM ; Mg $ha^{-1}y^{-1}$) was estimated by the equation of $AEM = (V_{end} BD_{end} / A_{end} - V_{start} BD_{start} / A_{start}) / (Y_{end} - Y_{start})$. Information on land use/cover in the 12 catchments was collected from interviews with villagers, from aerial photos of 1957 and 1972 and from a 2005 field survey (Mukai, 2017).

Some geomorphic indices were used to analyse the temporal changes in areal and relief aspects of the study catchments: (i) compactness coefficient (CC ; Gravelius, 1914);where Pe (km) is catchment perimeter. (ii) Form factor (FF ; Horton, 1932);$FF = A / HL^2 \pi$. (iii) Relief ratio (RR ; Schumm, 1956); $RR = HDC / HL$ where HDC (km) is a height difference between the outlet (H_{min}) and the highest point in the catchment (H_{max}). (iv) Lemniscate ratio (LR ; Chorley, Malm, & Poaorzelski, 1957); $LR = HL^2 \pi / 4A$ where HL (km) is maximum catchment length. (v) Hypsometric integral (HI ; simplified equation of the elevation-relief ratio proposed by Pike & Wilson (1971) was used; $HI = (H_{mean} - H_{min}) / (H_{max} - H_{min})$ where H_{mean} is the mean height in a catchment. The lower values of LR and CC and the higher value of FF indicate the more compact shape of the catchment and hence the lesser time of concentration for runoff and the more soil erosion (Morgan, 1996). Schumm (1956) found that sediment loss per unit area is closely and positively correlated with RR . Strahler (1952) found that a catchment at a younger evolutionary stage is highly susceptible to erosion and has a large HI value, but it decreases as the landscape is denuded towards a stage of maturity and old age. The HI value can be used as an estimator of erosion status of catchments (Singh, Sarangi, & Sharma, 2008), such as the watershed is old and fully stabilized (HI [?] 0.3); equilibrium or mature stage (0.3[?] HI [?]0.6); and disequilibrium or young stage (HI [?] 0.6), in which the watershed is highly susceptible to erosion (Strahler 1952).

Gully topographic thresholds, the relationships of the slopes at the gully heads (s) that were formed before 1957, between 1957 and 1972, and between 1972 and 2005 and the upslope drainage areas of the gully heads (a) were investigated for the main gully channels in the sub-areas.

2.4 Statistical analysis

The geomorphic parameters (HL , A , Pe , and HDC) and indices (CC , FF , RR , LR , and HI) of the catchments were grouped according to the Rift margin and Valley floor derivations. Normality of each soil parameter in each group was tested with the Kolmogorov-Smimov test ($\alpha = 0.05$) and the Shapiro-Wilk test ($\alpha = 0.05$), and homogeneity of variance was tested with the Levene test ($\alpha = 0.05$). For the parameters and indices that were tested for normality and homogeneity of variance, a t-test was applied to detect differences in the mean values between the two groups; otherwise, a non-parametric test was applied. SPSS ver. 20 (IBM) was used for the statistical analyses.

RESULTS

3.1 Long-term gully volume change

Changes in both mean volume of the gully networks (V) and mean area-specific volume of the gully networks (V_a) for the two sub-areas from 1957 to 2009 were well (R^2= 0.98–0.99) approximated by exponential functions (Figure 3), which were continuous trends shown for the same gully networks between 1957 and 2005 (Mukai, 2017). The mean area-specific gully erosion rate (AEM) for the 12 catchments from 2005 to 2009 was 73.3 Mg ha^{-1} y^{-1}; 116.3 Mg ha^{-1} y^{-1} for the Rift margin and 51.9 Mg ha^{-1} y^{-1} for the Valley bottom. The AEM for the Rift margin was comparable to those measured in sub-humid Ethiopian highlands. The AEM for the 12 catchments from 1957 to 2009 was 21.2 Mg $ha^{-1}y^{-1}$, which increased from that from 1957 to 2005, 16.2 Mg ha^{-1} y^{-1} (Mukai, 2017).

3.2 Temporal changes in catchment geomorphic characteristics

All values of the catchment geomorphic parameters (HL , A ,Pe , and HDC) showed increasing tendencies as the gully networks expanded over time (Mukai, 2017). Over the three periods, 1957, 1972, and 2005, no areal aspect of catchment geomorphic parameters,HL (maximum catchment length), A (catchment area), andPe (catchment perimeter) showed any significant differences ($p > 0.05$) between the two sub-areas (Mukai, 2017). The same was true for the catchment areal aspect indices, LR(lemniscate ratio), CC (compactness coefficient), and FF(form factor; Table 1). Besides, no notable tendencies in LR ,CC , FF , and RR were observed over the three periods. The relationships between HL and A (Figure 4 (a)) and Pe and A (Figure 4 (b)) showed the same spatial and temporal trends; (i) regardless of the period and sub-area, all the data appeared to be positioned on the linear lines that represent the relationships between each pair of the two parameters; and (ii) the Vallley bottom main gullies largely extended the HL -A andPe -A relationships over time, whereas the temporal changes were limited for the Rift margin main gullies.

In contrast, the catchment relief aspect parameter HDC (height difference for catchments) showed a significant difference (p< 0.01) between the two sub-areas (Mukai, 2017). The same was true for the catchment indices, RR (relief ratio) and HI(hypsometric integral; Table 1). Over the three periods, the Rift margin showed higher RR values than the Valley bottom, showing the catchments of the Rift margin had higher sediment loss per area. TheHI values of the Rift margin shifted from 0.37 in 1957 to 0.33 in 2005, indicating the catchments were always at the equilibrium or mature stage, whereas those of the Valley bottom shifted from 0.60 in 1957 and 1972 to 0.47 in 2005, indicating the catchments recently have developed from disequilibrium/young stage to equilibrium/mature stage. The relationship between HL and HDC (Figure 4 (c)) showed a contrasting trend between the two sub-areas; (i) regardless of the period, all the data appeared to be positioned on the linear lines representing the HL-HDC relationships that are specific to each sub-area; and (ii) the Valley bottom main gullies largely extended theHL-HDC relationship over time, whereas the temporal changes were limited for the Rift margin main gullies.

3.3 Temporal changes in topographical thresholds of gully heads

All the s -a relationships for the 12 main gully channels were approximated by power functions (Figure 5); the coefficients of determination were 0.39-0.85 (the mean 0.65) for the Rift margin and 0.65-0.98 (the mean 0.84) for the Valley bottom.

Besides the threshold lines for each main gully channel, the topographical thresholds of the gully heads for each period (before 1957, 1957-1972, and 1972-2005) in a sub-area can be approximated by a line representing a power function (Figure 5). It appeared that 2 data for the Rift margin and 3 data for the Valley bottom were outliers (rounded by solid red lines in the figures). All of these gully heads were formed at lower threshold levels than those of each corresponding year. According to aerial photo interpretation and field observations, it was evident that the formation of these gully heads was influenced by roads (cattle passageway). Nyssen et al., (2002) found that the slope gradients of the gully heads influenced by the road were lower than those of without influence of the road (not statistically significant); lowering topographic threshold levels. Thus, these outliers were excluded from the subsequent analysis.

For both the sub-areas, 3 threshold lines for before 1957, 1957-1972, and 1972-2005 appear to be parallel with each others, and as time passes, they shift towards the origin, i.e., in equation (1), the exponent b values are rather static, whereas the threshold coefficient k values decrease over time. Univariate analysis of variance for the 6 sets of the s -a data of the threshold lines, such as (i) before 1957, (ii) 1957-1972, and (iii) 1972-2005 for the Rift margin, and (iv) before 1957, (v) 1957-1972, and (vi) 1972-2005 for the Valley bottom, found the hypothesis of no interaction between the factors (6 datasets) and covariate (upslope drainage area; a) was rejected ($\alpha = 0.05$), i.e., they cannot be paralleled. However; the analyses for (i), (ii), and (iii) and for (iv), (v), and (vi) proved that the s -a threshold lines of each sub-area could be parallel with each other. Thus, the threshold lines representing gully head positions in the three periods in each sub-area maintained almost the same exponent b specific to each sub-area while the threshold coefficient k decreased as time passed.

DISCUSSION

In the evolutionary processes, the values of the catchment geomorphic parameters generally increased; however, the main gully channels of both the sub-areas expanded maintaining almost the same risk of soil erosion hazard specific to each sub-area. The difference in dynamic movements of the catchment geomorphic indices observed between the sub-areas is likely to be reflected by the gully evolutionary processes specific to each of the sub-areas. In the Valley floor catchments, gully incision started within the uppermost dense forests before 1957, and then they extended downwards to flat farmlands via steep slope hillsides and gentle slope farmlands as a fierce land use/cover changes occurred during the subsequent periods by 2005. In contrast, no distinctive trend was observed in the starting points of gully incisions in the Rift margin catchments. In some catchments, gullies were found at the farmland close to the outlet of catchments in 1957. Thus, the catchment areas of the Rift margin sub-area showed a slight increase over the three periods (Mukai. 2017).

The steeper slopes inherent in the Rift margin catchments have contributed to a higher risk of soil erosion hazard in the sub-area since gully incision, which is likely to affect more rapid change particularly in area-specific gully volumes (V_a) in the sub-area. It is because areal aspect of the catchment morphological parameters had a relatively strong or strong correlation with only V , whereas relief aspect of the catchment morphological parameters had a relatively strong or strong correlation with both V and V_a (Tamene et al., 2006; Haregeweyn et al., 2008; Mukai, 2017).

In contrast, the rates of land use/cover changes in the catchments between the two periods significantly and relative strongly or strongly correlated with only V (Mukai, 2017). Torri & Poesen (2014) examined 63 reported s -a relationships data from various parts of the world and found the exponent b varied slightly with land use while the median coefficient k increases from cropland to forest via grazing land/pasture. Examination of land use/cover at the gully heads formed before 1957, 1957-1972, and 1972-2005 found that, in both the sub-areas, forest had the highest frequencies (94% for the Rift margin and 62% for the Valley bottom) among the land use/cover items in 1957 for the gully heads that began incision before 1957 (Table 2). Similarly, grazing land had the highest (similarly, 100% and 71%) in 1972 for the 1957-1972 gully heads, and cropland had the highest (97% and 100%) in 2005 for the 1972-2005 gully heads. Thus, the null hypotheses that the gully heads created before 1957, 1957-1972, and 1972-2005 had land use/cover of the forest, grazing land, and cropland, respectively, were tested by Mann-Whitney U tests. All the tests failed to reject the null hypotheses ($\alpha = 0.05$). Thus the high threshold levels for gully heads incised before 1957 and 1957-1972 in both sub-areas can be best explained by the relatively high resistance to erosion due to the protective vegetation cover (Torri & Poesen, 2014). In both the sub-areas, land use/cover has continuously changed in the direction of reducing vegetation cover in the catchment since the initial gully incision. That induced reductions in the gully topographical threshold levels in the sub-areas, which can significantly influence further increase in gully volumes (V).

Muňoz-Robles et al. (2010) stressed the importance of a quantitative analysis that assessed past land use/cover when gullies were initiated. Vandekerckhove et al. (2000) stated that, in rangelands, vegetation cover at the time of incision appears to be the most critical factor differentiating between topographical thresholds. In the study area, this principle can be applied to a wider land use/cover items, from forest to cropland. Thus, the combination of photogrammetric techniques, the $V - L$ relation, and field measurements and interviews is probably one of those methods that enable to assess temporal interactions between environmental changes and gully erosion/gully head positions.

Nyssen et al. (2004) found that the s -a relationship can be a guideline where structural measures, such as loose-rock and gabion check dams, are effective for gully control. This indicates that more than a certain topographic threshold level in a catchment, a gabion check dam should be selected. In the study area, the gully points formed earlier, e.g., before 1957, have higher topographic threshold levels. Thus, a historical survey on gully head formation guided from an on-site interview or aerial photo interpretation might provide a rough idea of what types of physical structures will be required on the spot; i.e., the site of a gully formed earlier have a higher level of topographical threshold and, therefore, more reliable structural measures will be needed.

CONCLUSIONS

As gully networks expand, catchment geomorphic parameters and indices change. The areal aspect catchment morphology showed a similar scale and pattern of temporal changes between the sub-areas. In contrast, relief aspect catchment morphology varied between the sub-areas, influenced by temporal evolutionary processes of the gully networks specific to each sub-area. Higher slopes inherent in the Rift margin sub-area represent the higher risk of soil erosion hazard and affect its higher area-specific gully volume in particular.

Besides the topographic thresholds of gully head positions for the study catchment, the topographic thresholds observed during the same individual period in each sub-area were approximated by a single power function. Transitions in these gully topographic threshold lines showed clear temporal and spatial patterns: the threshold lines maintained almost the same exponent b specific to each sub-area while the threshold coefficient k decreased as time passed. The land use/cover changes occurred in agroecology can influence these phenomena. The expansion of gully network induced by land use/cover changes lowered the gully topographic threshold levels in agroecology, which accelerated further gully expansion and influenced the exponential temporal increase in gully volumes in particular.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the cooperation of Boset woreda Bureau of Agriculture and both Merko Odalega and Koka Gifawasen villagers. Part of this study was financially supported by the Ministry of Agriculture, Forestry and Fisheries, Japan. The authors declare no conflict of interest.

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TABLE 1 Topographical indices of the study catchments in 1957, 1972, and 2005

Study catchments	2005	2005	2005	2005	2005
	LR	*CC*	*FF*	*RR*	*HI*
Boruamba	4.0	1.5	0.20	0.12	0.33
Telilo	5.3	1.5	0.15	0.10	0.43
Adare	7.8	1.8	0.10	0.11	0.33
Gebruamba	4.7	1.4	0.17	0.10	0.34
Koka	5.7	1.5	0.14	0.13	0.22
Hadaware	4.9	1.8	0.16	0.03	0.52
Abharo	6.5	1.4	0.12	0.03	0.36
Kawa Adami	7.3	1.7	0.11	0.04	0.49
Aware	7.4	1.7	0.11	0.02	0.49
Odalega	6.6	1.6	0.12	0.03	0.47
Merko	9.5	2.1	0.08	0.08	0.42
Goro	6.8	1.7	0.12	0.07	0.56
Rift margin Valley bottom *P*-value Mean	5.5 7.0 *n.s.* 6.4	1.5 1.7 *n.s.* 1.6	0.15 0.12 *n.s.* 0.13	0.11 0.04 ** 0.13	0.33

Lemniscate ratio (*LR*); compactness coefficient (*CC*); form factor (*FF*); relief ratio (*RR*); hypsometric integral (*HI*). *n.s.* , not significant; $^{**}P < 0.01$

TABLE 2 Land use/cover of the gully heads in 1957, 1972, and 2005

Gully head incision period	*n*	1957	1957	1957	1972	1972
		Forest	Grazing land	Cropland	Forest	Grazing la
Rift margin	Rift margin	Rift margin	Rift margin	Rift margin	Rift margin	Rift margi
Before 1957	17	**16 (94)**	1 (6)	0 (0)	11 (65)	6 (35)
1957–1972	6	2 (33)	4 (67)	0 (0)	0 (0)	**6 (100)**
1972–2005	36	6 (17)	6 (17)	24 (67)	1 (3)	6 (17)
Valley bottom	Valley bottom	Valley bottom	Valley bottom	Valley bottom	Valley bottom	Valley bot
Before 1957	13	**8 (62)**	1 (8)	4 (31)	7 (54)	2 (15)
1957–1972	14	1 (7)	6 (43)	7 (50)	0 (0)	**10 (71)**
1972–2005	10	0 (0)	3 (30)	7 (70)	0 (0)	3 (30)

The numbers are frequencies followed by percentages in brackets. The bold numbers indicate the land use/cover items that had the highest frequencies in the period when the gully heads began incision

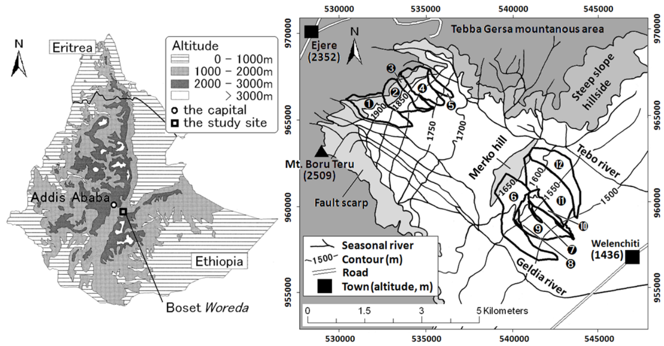

FIGURE 1 Ethiopia (left) and the study catchment (right). Sample catchments in the Rift margin sub-area (1. Boruamba; 2. Telilo; 3. Adare; 4. Gebruamba; and 5. Koka) and Valley floor sub-area (6. Hadaware; 7. Merko; 8. Goro; 9. Abharo; 10. Kawa adami; 11. Aware; and 12. Odalega)

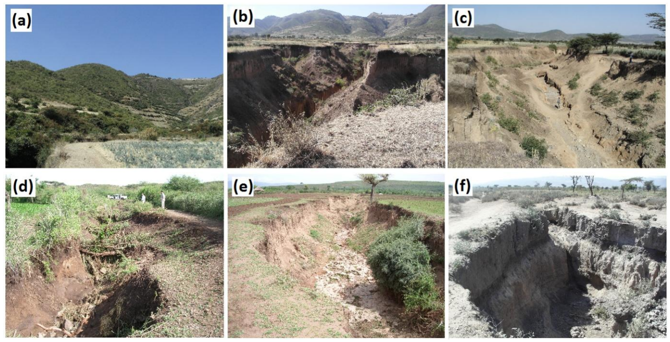

FIGURE 2 Examples of gully cross-sections in the rift margin ((a), (b), and (c)) and the valley bottom ((d), (e), and (f)) sub-areas. All photos were taken in 2005 or 2006. (a) The southeastern cliff of the Rift margin plateau, which is located in the most upper reaches of the Rift margin gullies, (b) Boruamba main gully channel 0.7 km downward from the foot of the southeastern cliff (10.9 m top width and 10.3 m depth), (c) 2.3 km downward from (b) (12.5 m top width and 9.2 m depth), (d) Abharo main gully channel 0.3 km downward from the southern foot of Merko hill (4.7 m top width and 2.8 m depth), (e) 1.2 km far from (d) (9.6 m top width and 5.6 m depth), (f) 3.7 km far from (e) (8.1 m top width and 4.6 m depth)

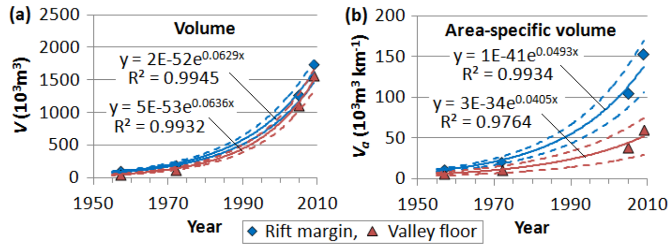

FIGURE 3 Transitions in (a) mean volumes of the gully networks (V) and (b) mean area-specific volumes of the gully networks (V_a) over 1957, 1972, 2005, and 2009. Solid lines are fitted lines (exponential functions), whereas dotted lines are 95% confidence intervals

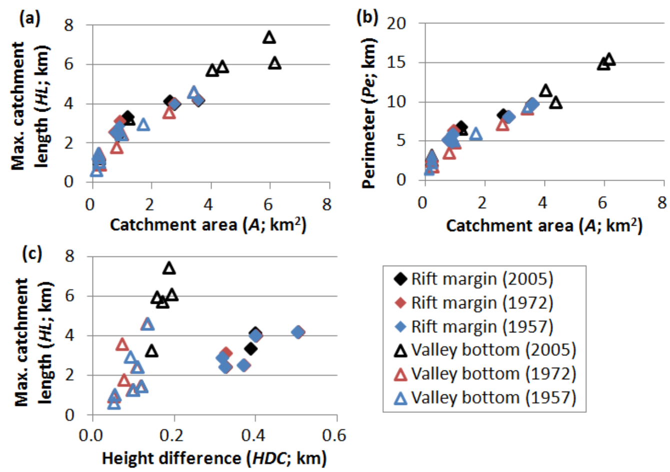

FIGURE 4 Transitions in the relationships between catchment topographical parameters over 1957, 1972, and 2005: (a) the maximum catchment length (*HL*) and catchment area (*A*); (b) the catchment perimeter (*Pe*) and catchment area (*A*); and (c) the maximum catchment length (*HL*) and height difference for the catchment (*HDC*)

1

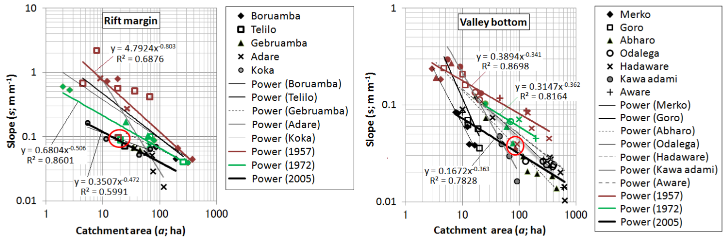

FIGURE 5 Gully topographic thresholds, the relationship between the slope at the gully head (*s*) and the upslope drainage area (*a*) at 1957, 1972, and 2005. For the Rift margin and Valley bottom main gullies, 62 (19 for 1957, 7 for 1972, and 36 for 2005) and 39 (15 for 1957, 13 for 1972, and 11 for 2005) points (cross-sections) were selected, respectively. Outliers (2 data for the Rift margin and 3 data for the Valley bottom) were rounded by red solid lines

1