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Research Article

Gully Morphology and Rehabilitation Measures in Different Agroecological Environments of Northwestern Ethiopia

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Gully erosion is a serious threat to the society and environment of the study, primarily caused by surface runoff and dramatically accelerated due to rugged topography and human induced factors. Intensive measurements of gully characteristics were undertaken to investigate the morphologies of gully, while aiming for sustainable gully rehabilitation; therefore, a total of 63 gully samples from three different agroecologies were randomly observed. The morphological variability of measured gullies was evaluated and the resulting CVs had been between 0.27 and 0.39 except for gully length, which had highest variability (CV = 1.10). The highest gully length (2,400 m) and highest lower width (6 m) were observed on Dembia district, which might be due to the loose and pulverized condition of the soil. The correlation matrices for many parameters of gully morphology in different districts of Semien Gondar showed several sets of significant relationships. Some of the assessed gullies showed that appropriate physical gully control structures integrated with vegetative measures have resulted in a significant reduction of soil loss and stabilized the gully from further enlargement. There could be various justifications for the success of these structures; however, the most important measures were vegetative management and exclusion of cattle.

1. Introduction

Soil erosion, in particular, gully erosion, perhaps remains one of the most challenging environmental problems in the globe [1–3]. Gully is the worst stage of all types of soil erosion and it is a highly visible form of erosion [4], which affects several soil functions (food and other biomass production, water storing, filtering and transformation, habitat and gene pool, physical and cultural environment for mankind, and source of raw materials) and hence soil quality [5]. Gully erosion is the removal of soil by runoff water and often persists in narrow channels and, over short periods, removes the soil from this narrow area to considerable depths [6] and cannot be smoothed out completely by normal tillage operations [7]. In many landscapes under different climatic conditions and with different land uses, one can observe the presence and dynamics of various gully types, that is, ephemeral gullies, permanent or classical gullies, and bank gullies [6]. Recently, gully erosion has attracted a growing interest and there is a need for concrete actions that directly address this issue at different spatial scales [8–10]. There are contradictory views about the share of gully erosion in the total amount of soil loss; however, gully erosion represents a major sediment producing process, generating between 10% and 95% of total sediment mass at watershed scale whereas gully channels usually occupy less than 5% of the total watershed [9]. Moreover, several literatures [5, 10–14] indicate that gully erosion is often the main source of sediments in water bodies and results in severe land degradation [3]. The shape of the gully is a product of processes of gully initiation [15], and many scientists believe that differences in gully shapes are due to differences among processes of gully initiation [15–18] and soil type.

The causes of soil erosion and its processes in the Ethiopia Highlands were adequately described in different studies [19–21]. Field scale soil erosion by [22] reported that 24 Mg ha^{-1} y^{-1} soil loss with soil bund and 50 Mg ha^{-1} y^{-1} soil

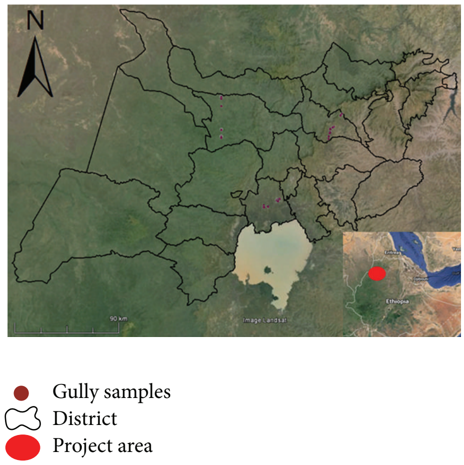


Figure 1: Overview of the study area in the northwest of Amhara region, Ethiopia, with the spatial distribution of observed gullies.

loss without soil bund in cultivated plots of the central Highlands of Ethiopia were measured, which was beyond the tolerance limit, as soil loss greater than 1 Mg ha^{-1} y^{-1} exceeds soil formation and leads to irreversible process [23]. Meanwhile, little has been done in practice to measure gully morphology and document effective and efficient mitigation measures in the Ethiopian Highlands. Therefore, the objectives of the present research were to measure gully morphological parameters and document gully rehabilitation methods in three different agroecological areas in the Ethiopian Highland.

2. Materials and Methods

2.1. Location, Climate, and Topography of the Study Area. The study was conducted in Semien Gondar Zone which has an area of 45,944.84 km^2 and is located in the northwestern Amhara region, Ethiopia, between 1321569 and 1464599 north and 92444 and 473214 east (Figure 1). Semien Gondar Zone is bordered on the south by Lake Tana, Mirab Gojjam Zone, and Benishangul Gumuz Region, on the southeast by Debub Gondar Zone, on the west by Sudan, on the north by Tigray Region, and on the east by Wag Hemra Zone. The major crops grown in the rain-fed agricultural land use system of the study area include sorghum, sesame, teff (*Eragrostis tef*), fava bean, field pea, lentil, wheat, chickpea, linseed, fenugreek, and barley with scattered tree species, such as *Cordia* and *Acacia*.

The climate of Semien Gondar falls within Kola (warm semiarid, 500–1,500 m above sea level (a.s.l.)), Weyna Dega (cool subhumid, 1,500–2,300 m a.s.l.), Dega (cool to humid, 2,300–3,200 m), and Wurich (cool to moist > 3,200 m). The rainfall of the area is characterized by intensive rainfall events and average annual rainfall varies from 700 mm to 1200 mm. Rainfall events occur mainly between June and September with a dry spell from November to April. Traditional farming practices coupled with deforestation of native shrubs and/or forests for fuelwood and crop production in the steep slope area enhance the vulnerability of the soil for rainfall driven erosion [24]. The soil types in the landscape are predominated by Vertisol, Cambisol, and Leptosol.

2.2. Observed Data. Assessment of gully erosion has been long neglected because it is often difficult to collect data and predict [10], particularly for developing countries like Ethiopia where availability of data related to gully erosion processes and its hydrology across the different region of the country is scarce. The study area is characterized by scattered habitation pattern, small and fragmented land holdings which cover the whole range of the landscapes including the steep fragile slopes. In this research, historical documents and field surveying were conducted in three different districts, which are located at three distinct agroecology of Semien Gondar Zone (namely, Dembia, Dabat, and Tach Armachiho districts) and approximately 21 gully samples were randomly selected from each district. Gully depth and width were measured at the head cut, at 50% of gully length and at the lower side of each gully, while each gully slope was recorded. Physical characteristics (e.g., gully head cut shape and gully stage) of each gully and primary causes of gully initiation as well as mitigation measures were recorded. Natural characteristics such as rainfall, temperature, and topography of each gully site were collected. Extensive field observations and interviews with elders in the gullied regions have been carried out to record the most common and successful gully rehabilitation measures.

2.3. Gully Sampling and Measurements. A total of 63 gully samples of three different agroecological environments were randomly observed (21 gully samples from each agroecology) in May 2013. Most of the sampling sites were distributed on two different hillslope positions including middle slope (10–30%) and foot slope (0–10%) and two land use types including agricultural land and grazing land. The gully sampling sites are displayed in Figure 1. The geographical coordinates (Easting, Northing, and Elevation) of each gully sampling site were recorded using Garmin explorer global positioning system (±3 m).

2.4. Analysis Method. In this study, classical descriptive statistics was used to give an insight into the relationship between each gully morphological parameter. The summary of classical statistics and correlations between each measurement were analyzed using R statistical software [25].

2.5. Environmental Gully Erosion Controls. The work [6] documented the main factors controlling soil loss rates by gully erosion and some of the environmental controls are gully types, soil types, climate and weather, vegetation cover, and topography. Rainfall is one of the most significant factors affecting soil erosion [26]. Duration, intensity, and frequency of rainfall affect the rate and volume of runoff [27]. A longer duration and greater frequency rainfall increase both the total runoff and soil erosion [28]. Slope length and steepness are the two main features of topography that affects the rate of soil erosion [29]. The steepness of a given landscape influences the rate of soil loss because runoff over steeper slopes carries

Table 1: Summary of the descriptive statistics of the selected gully morphological parameters.

Gully morphology (m)	Min.	Max.	Range	Mean	SD	SE (mean)	CV
Length	25	2400	2375	373.78	412.01	51.91	1.10
Head cut depth	0.45	2.50	2.05	1.21	0.43	0.05	0.36
Depth (50% of gully length)	0.53	2.90	2.37	1.46	0.55	0.07	0.38
Lower depth	0.12	0.35	0.23	0.23	0.06	0.01	0.27
Head cut width	0.80	3.00	2.20	1.33	0.41	0.05	0.31
Width (50% of gully length)	1.20	8.70	7.50	4.06	1.52	0.19	0.37
Lower width	1.10	6.00	4.90	2.89	1.12	0.14	0.39

SD: standard deviation; SE (mean): standard error of mean; CV: coefficient of variation.

more soil than runoff over gentle slopes [28]. The soil properties (texture, structure, infiltration capacity, organic matter content, permeability, and depth) greatly affect soil erosion and runoff [30]. When rainfalls on a surface are covered with dense vegetation, the effects of rainfall velocity and its erosive power can be nearly avoided and most of the water either quickly infiltrates into the soil or moves over the surface with slight erosive velocity [28]. The human induced factors (cleaning of vegetation, poor farming system, removal of crop residue and animal dung from farm fields, badly designed and constructed roads, and conservation measures) can increase soil erosion danger. Gully development reduces agricultural productivity and land availability [29, 31], and it is one of the major causes of reservoir siltation in the Nile River Basin [3].

3. Results and Discussions

3.1. Variability of Gully Morphologies. Understanding gully morphology is the first step in the evaluation of processes of gully initiation [16]. Therefore, a systematic compilation of the different types of gully morphological characteristics (e.g., length, depth, and width) and their controlling factors (e.g., topography, land use, soil type, and hydrology) in a wide range of environments is necessary [6]. Variability of gully morphology can be described by classical statistics (e.g., minimum, maximum, standard deviation (SD), and coefficient of variation (CV)). Among them, CV is the most decisive descriptive statistical factor as it is a useful statistic for comparing the degree of variation from one data series to another, even if the means are drastically different from each other [32]. The morphological characteristics of gully such as length, head cut depth and width, lower depth, and width were analyzed and presented in Table 1. In the study area, all the CVs of gully morphology are between 0.27 and 0.39 except for gully length. This indicates that lower depth, lower width, head cut depth, head cut width, depth at 50% of gully length, and width at 50% of gully length have moderate variability, but gully length has high variability (CV = 1.10). According to the gully measurements, 57 of the measured gullies have U-shape cross sections and located around gentle slope (0–10%) while 6 of the observed gullies are V-shaped near hilly side (greater than 10%) and most of the gullies are medium depth class that ranged from 0.5 m to 3 m. Meanwhile, 56 of the observed gullies were active (actively eroding) and only 7 of the measured gullies were inactive (stabilized). Active gully can occur where the erosion is actively moving up in the landscape due to head cut retreat [9]. The slope of the study gullies ranges from nearly flat (less than 4%) in Dembia district to exceptionally steep (greater than 28%) in Dabat district and the average gully slope in this study is 13.44%.

Despite a number of significant trends revealed by the gully morphological data, there were also obvious random distributions. This could probably be due to the fact that the study covers various agroecological and geologic conditions as well as a range of different land management and topographic characteristics. There is clear difference of climatic and geologic conditions among the study districts; therefore, vegetation composition changes dramatically among these districts. Gully study cannot be conducted at plot level or in smaller and more homogenous areas because parts of a single gully might be located at different soil-landscape features (soil, vegetation, and topographic and geologic conditions). Whether gully morphologies are controlled by the vegetation covers and climatic and geologic conditions or not, detailed investigation of gully morphologies is helpful for further study. However, these kinds of large scale gully databases are mainly intended to be summarized at different agroecological level. Results of gullies morphological data in the three districts illustrate distinct differences between gully morphologies (Table 2). Gully measurements at the selected agroecologies were averaged to obtain location based estimation of each morphological parameter (Table 2). Comparisons of gully morphologies by agroecologies (Table 2) revealed that significant differences in length, head cut depth, lower width, depth, and width at 50% of gully length were found. In contrast, head cut width and lower depth have no statistical differences among the three districts (Table 2). The highest average gully length (638.69 m) and average lower width (3.55 m) were observed in Dembia district which might be due to the loose and pulverized condition of soil in the site while the highest average head cut depth (1.43 m) was recorded in Dabat district which could be due to the highest gullies gradient in the district.

3.2. Correlations among Gully Morphologies. The correlation matrices for many measurements of gully morphology in different districts of Semien Gondar Zone indicate several sets of significant relationships (Table 3), although not all correlations were strong. The morphological parameter that correlated most strongly with gully length was depth at 50%

Table 2: Comparison of mean values of gully morphological parameters of the three different districts using R statistical software.

District	Agroecology	Gully morphology in meter (m)						
		Length	Head cut depth	Depth (50% of gully length)	Lower depth	Head cut width	Width (50% of gully length)	Lower width
Tach Armachiho	Kola (warm semiarid, 500–1,500 m)	133.43[b]	0.94[b]	1.17[b]	0.22[a]	1.47[a]	3.4[b]	2.4[b]
Dembia	Weyna Dega (cool subhumid, 1,500–2,300 m)	638.69[a]	1.25[a]	1.77[a]	0.24[a]	1.27[a]	4.83[a]	3.55[a]
Dabat	Dega (cool to humid, 2,300–3,200 m)	349.24[b]	1.43[a]	1.43[ab]	0.23[a]	1.25[a]	3.94[ab]	2.71[b]

Values in each row with the same letter are not significantly ($P < 0.05$) different among gully morphologies.

Table 3: Pearson correlation coefficients between gully morphological characteristics in the three different districts.

Gully morphology (m)	Lower depth	Lower width	Depth (50% of gully length)	Head cut depth	Head cut width	Length	Width (50% of gully length)
Lower depth							
Lower width	0.01						
Depth (50% of gully length)	0.24	0.22					
Head cut depth	0.33^{**}	0.29^{*}	0.39^{**}				
Head cut width	0.09	0.01	0.21	0.15			
Length	0.13	0.47^{***}	0.52^{***}	0.37^{**}	0.16		
Width (50% of gully length)	0.37^{**}	0.24	0.31^{*}	0.34^{**}	0.07	0.49^{***}	

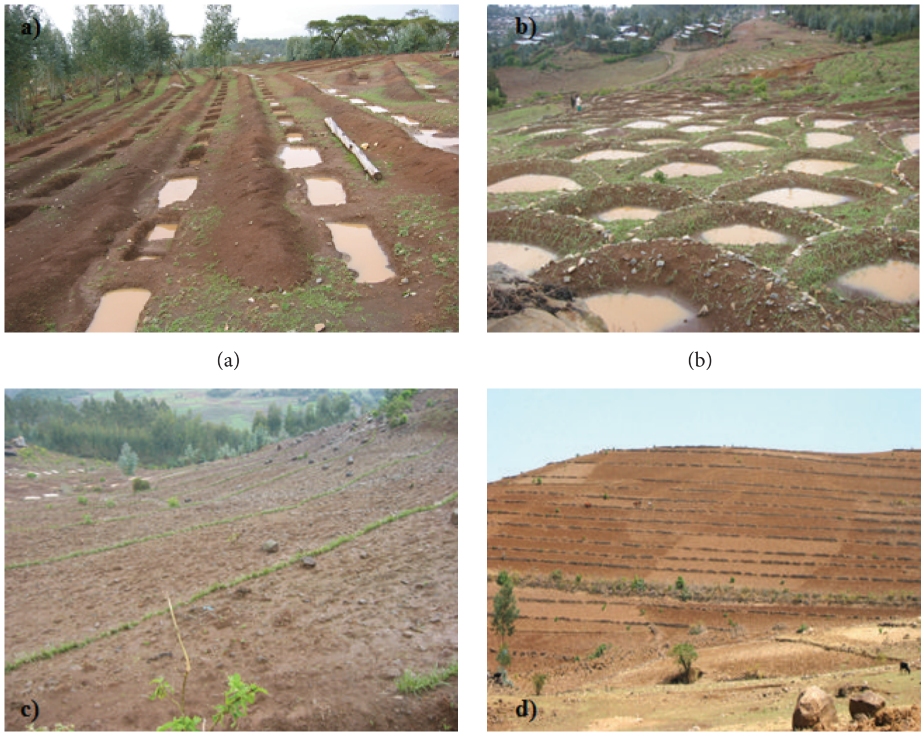
*,**,***Correlation at $P < 0.05$, 0.01, and 0.001, respectively.

gully length ($r = 0.52$) (Table 3). The value of depth at 50% of gully length was positively correlated with most selected gully morphologies, such as gully length, width at 50% of gully length, and head cut depth. Meanwhile, width at 50% of gully length and lower width were positively related to length. Head cut depth is of course directly correlated with length and width at 50% of gully length and some of nonsignificant correlations were found for lower depth with lower width and head cut width with lower width (Table 3). The observed relationships of gully morphologies are expected to become much stronger if spatially intense observations would be used for each district. In general, due to the large variability of environmental conditions high correlations coefficients cannot be expected; however, the correlations found may still have a physical meaning.

3.3. Gully Erosion Control and Rehabilitation. Inappropriate agricultural land management practices coupled with deforestation and overgrazing of pasture have resulted in severe erosion, which is a major challenge to keep a stable and productive ecosystem in the study area. Semien Gondar Highland is one of the most soil erosion vulnerable parts of Ethiopia, as the area has a high erosive force of rainfall, intense land uses and land cover change, and high population pressure and it is inescapable fact that agricultural land productivity in the area is declining quickly; at the same time the population proliferates. Early studies showed innumerable example of horrible consequences of soil erosion in the northern Highlands of Ethiopia [33, 34]. Therefore, adoption of soil and water conservation measures is a survival for populations in these Highlands, which have been settled for millennia and agriculture has a matching history [35].

Soil erosion rates are partially controlled by soil and water conservation (SWC) measures, such as stone and soil bund terraces, grass strips, trenches, and microbasins (Figure 2) which are installed along the contour lines [19, 21], supported with water harvesting practices (e.g., contour tillage, mulch covering, and earth bunds), and have been widely used in the Ethiopian Highlands during the last few decades [36, 37].

In the study area, the successful gully erosion control measures so far tested and which significantly reduced surface runoff and erosion, while improving soil fertility, forage, and fuelwood production along gully lines, were through implementing integrated vegetative management and physical measures (check dams). Vegetative materials such as grass (e.g., *Chrysopogon zizanioides* (vetiver grass) and green gold and elephant grass) which can grow in a shallow soil with high tolerance to drought are utilized throughout the area. A check dam is a small, often temporary structure, constructed across gully lines (aligning perpendicularly to flow direction) to counteract soil loss by reducing the energy of runoff [38, 39]. A check dam placed in gully interrupts and minimizes the runoff velocity, thereby inducing infiltration rather than eroding the channels [38]. During visual observation, a system of several check dams situated at different intervals was implemented across gully lines; however, the most prominent types of check dams in Semien Gondar Zone were sandbags supported with brushwood check dams, stone check dams, bamboo check dams, and gabion check dams. If the check dams are well constructed, the local community could



(a) (b)

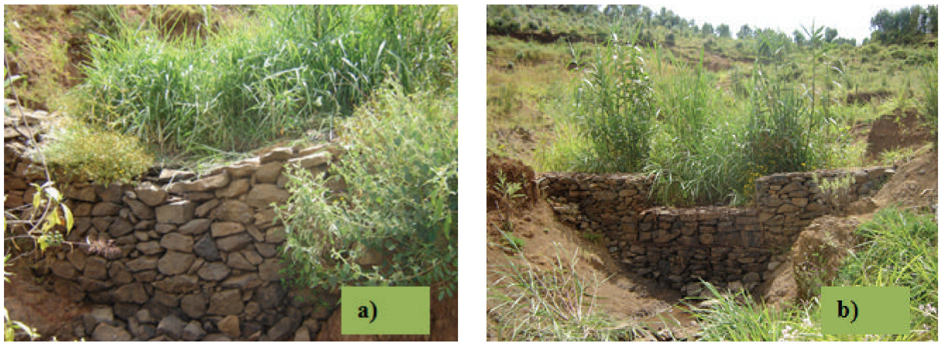
(c) (d)

Figure 2: Overview of soil and water conservation measures in the steep sloped area for reducing erosion and recharging the groundwater. (a) Trenches, (b) microbasins, (c) grass strips, and (d) stone bund terraces.

(a) (b)

Figure 3: Gully erosion control with sandbags and vegetative measures (a) before and (b) after a rainy season.

probably prefer them because such check dams have a faster implementation timeline, are cost effective, will not displace communities, and will not affect natural resources. Moreover, these check dams are simple to construct and do not rely on advanced technologies as it was documented by [40]. As an illustration, the most successful check dams for controlling gully erosion in the study area are displayed in Figures 3–6. Each of these check dams was integrated with different technologies and practices (e.g., awareness creation, exclusion of cattle through fencing, and vegetation managements) as described by [41]. Typically, such check dams were built on gully courses to decrease the original bed gradient and thus to reduce the erosive power of runoff. There might be various reasons for the success of these gully erosion control measures; however, the most important was integration with vegetative managements and area closure.



(a) (b)

Figure 4: Loose stone check dam supported with green gold grasses: (a) arc spill way and (b) rectangular spill way.

Figure 5: Properly constructed gabion check dam which is strong enough to resist the force of the runoff.

(a) (b)

Figure 6: Combination of different technologies: (a) bamboo box and loose stone check dams and (b) bamboo box.

4. Conclusions

Gullies are distributed in all agroecological zones of the study area and this research has examined the morphological characteristics of gullies and documented efficient and effective gully stabilization techniques. The major causes of gully initiations in the area were man induced factors, which include overgrazing, clearing of vegetation cover, poor farming system, removal of crop residue and animal dung for fuelwood, badly designed and constructed culverts, canals, drains, and soil conservation measures. Therefore, it is important to emphasize that once the erosion problem is detected, the actions taken to reverse the process must be based on a multidisciplinary approach which considers all factors at work in the erosion feature, its surroundings, and necessary restorative structures and vegetation.

In the study area, gullies have medium depth class that ranged from 0.5 m to 3 m and their cross sections are dominantly U-shaped in plains and V-shaped in hilly and mountainous areas. The morphological variability of measured gullies was assessed and the resulting CVs are moderate variability except for gully length which had the highest variability (CV = 1.10). The highest average gully length (638.69 m) and averaged lower width (3.55 m) were observed on Dembia district which might be due to the loose and pulverized condition of Vertisol in the site; therefore, prior attention should be given to this area. Our analysis also showed that, at 50% of gully length, gully depth has a positive correlation with most of the measured gully morphologies. Meanwhile, at 50% of gully length, gully width has a strong positive relationship with the gully length and head cut depth. Despite some expected nonsignificant correlation due to heterogeneity in the gully morphological datasets, which includes data from three distinct districts with differing climates, geology, vegetation, and land management, it was possible to find correlations between observed morphological parameters and obviously this study depicts larger generality than that of researches conducted at farm scale.

Appropriate physical gully erosion control practices coupled with biological measures have resulted in a considerable reduction of soil loss and stabilized the gully from further enlargement, which is a major success to keep a stable and productive ecosystem in the region. In general, the study shows the potential of agroecology as a factor for gully morphological variation and also the need for further studies. Therefore, different approaches which include land management, land use, and topographic conditions might help for better understanding of gully morphology.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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