Rehabilitating gullies with low cost methods, in the sub humid Ethiopian highlands

Meseret B. Addisie [1] , Getaneh K. Ayele [1], Azalu A. Gessesse [1], Seifu A. Tilahun [1], Mikael M. Moges [1] , Assefa D. Zegeye[2], Wolde Mekuria[3], Petra Schmitter[3], Eddy J. Langendoen [4], Tammo S. Steenhuis [1,2]

(1) Faculty of Civil and Water resource Engineering, Bahir Dar University, Bahir Dar, Ethiopia

(2) Department of Biological and Environmental Engineering, Cornell University, Ithaca, NY

(3) International Water Management Institute (IWMI), East Africa and Nile Basin Office, Addis Ababa, Ethiopia

(4) USDA, Agricultural Research Service, National Sedimentation Laboratory, Oxford, MS, USA

Abstract*—Gully erosion in the highlands of Ethiopia has reduced agricultural productivity and degraded ecosystem services. To better understand the processes controlling gully erosion and design effective control measures, a study was conducted in the headwaters of the Birr watershed for three consecutive years (2013-2015). Fourteen gullies with similar morphology were studied in three adjacent sub-watersheds. Stabilization measures were applied to 5 of the 14 gully heads. Three gully control measures were compared: a) reshaping gully banks and head to a 45 degree slope with stone rip rap on the gully heads, b) controlling gully bed grade, and c) planting grasses and trees on shallow gullies (i.e., < 3 m deep). Results demonstrated that gully control measures were effective in controlling the expansion of gullies as no further retreat was observed for the 5 treated gully heads, whereas the average retreat was 3 meters with a maximum of 22.5 m for the 9 untreated gullies. The migration of untreated gully heads produced an average soil loss of 38 tons per gully. Compared with simple reshaping of gully heads, the additional integration with stone rip rap was an effective and low cost measure. Vegetative treatment by itself could not stop the upslope migration of gully heads, though it had the potential to trap sediments. Re-vegetation at gully heads stabilized with stone rip rap occurred faster than at unprotected, reshaped heads and banks. From the fourteen rehabilitation treatments, gully head protection integrated with plantation showed the largest potential in decreasing gully development in terms of labor, time and material it requires.

Key Words: **Ethiopian highland, Erosion, gully head advancement, gully stabilization**

I. INTRODUCTION

In Ethiopia soil erosion has led to severe environmental problems affecting the livelihood of its population [3]. In the study area, Amhara National Regional State, 2.6 million hectares of land is considered as degraded and about 200,000 – 300,000 hectares of land is covered with gullies [13]. Wide and deep gullies are now common landscape features and severely damage croplands and grazing lands [5],[15],[32]. These gullies in the sub humid areas occur when the soil is saturated in the valley bottom land [27],[29].

Several case studies have reported the amount of soil loss, loss of productive areas, and reduction in crop yield due to gully erosion [5],[20],[27],[32]. For example [28] indicated that, 530 ton ha^{-1} year^{-1} was lost due to gully erosion in a 17.4 ha Debre-Mawi watershed, south of Lake Tana. [20] estimated that gully erosion accounted for about 28% of the total soil loss in Tigray in the semiarid northern Ethiopia, whereas the contribution of gully erosion to the total soil loss reaches about 96% in the humid highlands of Ethiopia [33]. [31] showed that gully erosion contribute the largest proportion of sediment deposited in reservoirs. A study conducted in south Gondar, Ethiopia, [32] has also reported considerable loss of crop due to gully erosion (ranges from 11 to 36 quintal ha^{-1} per gully area per year) which translates to loss of about 2744 ETB per annum. A study conducted in two rural villages in the northwestern Ethiopian highlands showed that the livelihood of over 3% of the their population was affected due to losses of soil and crop yield caused by gully erosion [2].

In response to the negative effects of soil erosion and the severe 1973-74 famines, the

Government of Ethiopia began major efforts to implement both structural and vegetative soil and water conservation measures since 1975 [4],[11],[26]**.** Despite a lot of emphasis on soil and water conservation measures, erosion continues to be a major concern [4],[18]. In many cases the soil and water conservation measures are not effective [4],[12] or practices such as terraces, fail after construction [24]. Often conservation techniques are new or unfamiliar for the people that have to implement them, and extension is lacking to transfer the knowledge for technology adoption [10]. The conservation techniques are also rarely adopted by farmers because they are not commonly associated with initial benefits [6] as farmers often rely upon incentives [31]. Further, the installed structures are often unsustainable due to improper designs [19] top-down approaches that do not assess needs [4] and lack of maintenance [8],[24]. Although gullies are primary sediment sources, they did not get sufficient attention for rehabilitation compared to hillside treatments, especially in the humid areas [22].

Different mitigation measures, such as check dams, were installed in the Ethiopian highlands to prevent the development of permanent gullies in grazing and crop lands [21]. However, check dams are not effective control measures in high rainfall areas because flow can by-pass the structure [21]. Installation of dewatering techniques may be used to remove excess ground water near banks by burying perforated pipes beneath ground surface [23]. But for the local farmers it is expensive to install pipes. Vegetative treatments on gully head and banks increase the cohesive strength of the bank soils, thereby providing additional resistance against mass failure [25]. Planting vetiver grasses as hedges across the bed of the gully retards the flow and protects gully bed and bank toe from erosion [7]. The occurrence of bank failure and mass wasting events could be reduced by regrading gully head and banks, which is affordable for the farmer.

This study seeks to answer the following questions: (1) How much does the magnitude of gully soil loss change when conservation measures are installed?; and (2) What are effective gully control measures, are these measures affordable, and what lessons can we learn from their implementation?

II. MATERIALS AND METHODS

A. Study area Description

The study was conducted in the 414-ha Birr watershed in the Northwestern Ethiopian highlands. The average elevation of the watershed ranges from 2001 to 2410 m above sea level. The topography at the upper, hilliest part has an average slope of 37%, and is dominated by rock out crops and cultivated fields. The middle portions have an average slope of 25%, and are used for cultivation and homesteads. The lower slopes are periodically-saturated open grazing lands with an average slope of 12%. Generally, the terrain is susceptible to erosion. The area receives a mean annual rainfall of 1200 mm, mainly during the rainy season that extends from April to October with highest intensity rainfall during July to August. The average temperature is 23 ^{o}C. The farming system of the watershed is a mixed farming system of both crop production and domestic animal raring. The major crops grown in the area include maize (*Zea mays*), Teff (*Eragrostis tef*), Chickpea (*Cicer arietinum*), wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*). Woody vegetation mainly consists of eucalyptus plantations around homesteads with some natural growing bushes in the hilly areas. Gullies are primarily located on the lower slopes at grazing lands where the black soils are Vertisols.

B. Gully control approaches

Field experimental design

Fourteen gullies were identified and monitored during the 2013-2015 rainy monsoon phases for studying the effects of different gully erosion control measures. Three gully erosion control approaches were assessed (more details are provided below): a) reshaping gully heads and banks to a 45 degree slope with stone riprap (GH3, GH4, GH5, GH6 and GH7) and without rip rap (GH2) on gully heads b) stabilizing gully beds by overlying bamboo sheets (GB7), and c) planting of grasses and trees (GB4, GB6, GB7, GB13 and GB14). These techniques were applied to shallow gullies less than 3 m in depth. Gully head protection consisted of regrading the head at an angle of 45 degree, when the factor of safety indicating slope stability is near unity under saturated conditions [16], and placing stone rip rap on the reshaped bare surfaces. A graded type of riprap containing a mixture of stones which vary in size from 20-30 cm was used. Graded riprap is preferred over uni-size riprap, because graded riprap provides a flexible self-healing protection when stones shift. The selected size of the riprap was based on the diameter of the stones rather than their weight, because the void space was used to establish grass species that could reinforce the stones and hold them in place. The thickness of the riprap layer was about 15 cm. The shape of the stones was more or less angular. The placement of the stones was started by excavating the toe of the gully head and placing larger stones first to prevent any local gully bed and toe erosion. Gully bank conservation measures consisted of regrading to a 45 degree slope (average observed bank slope is about 80 degrees) and plantation.

The gully bed erosion control measure consisted of reducing slope and surface cover. The soil materials left from bank regrading were used as fill to construct the design slope. The design channel slope was based on the bed slope of a nearby naturally stabilized gully. The fill material was compacted manually using locally available load like big stone. To protect the disturbed surface from eroding, bamboo sheets were laid over the soil surface and reinforced with stones and wood pins along the edges of each bamboo sheet.

Three gully banks were vegetated with vetiver grasses with a vertical spacing of 25 cm. Averages of 5 rows were planted on both gully banks. The spaces between the rows were seeded with fast growing plants such as *Sesbania Sesban* as vetiver grass needs time to establish. The other two big gullies completely treated with *Sesbania Sesban* and *Pennisetum purpureum.*

The gully rehabilitation work was started in 2013 by planting shrub and grass species such as *Sesbania Sesban* and *Pennisetum purpureum* and check dams in a 0.71-ha gully [1]. In 2014, one gully was treated with vegetation, and three active gully heads were regraded and protected with rip rap, and one gully bed was protected with over laid bamboo sheet. In 2015 three additional gully heads and banks were treated with head and bank protection measures (Fig.1). Sediment trapping check dams were installed at the end of each gully branch. Gullies were classified as treated or untreated over the three monitoring years. The minimum and maximum protected gully length for the study was 22 m and 160 m, respectively. Furthermore, 0.71, 0.62, and 1.9 ha of gully surface area were enclosed in 2013, 2014 and 2015, respectively, with community agreement. This allows the area to revegetate and be a source of grass for the cattle.

Fig. 1. Gully head protection: a) before gully control structure in place; b) immediately after regrading and placement of stone riprap (June 2015); and c) after 4 months of the rainy season (October 2015) well stabilized and covered with vegetation.

Data Collection

The amount of sediment deposited behind each check-dam was determined by placing erosion pins. A cylindrical core sampler was used to collect undisturbed soil samples at each gully to determine the bulk density of the soil. Also, gully cross sections were surveyed annually before and after rehabilitation. The gully cross section measurement was made in May before the start of the rainy season and in October at the end of rainy season. Finally, to measure the change in channel morphology (depth, width and length) erosion pins were installed at regular intervals at each sides of the gully system.

Sediment concentration data were collected from July to September for two years (2014 and 2015). Discharge and suspended sediment concentration monitored at the outlet weir (day and night). Sediment samples were taken using a 1-L plastic bottle at 15 min intervals during a storm event. Samples were collected until the runoff water becomes clear of sediments or is not turbid anymore. The samples were filtered using Whatman filter paper with a pore opening of 2.5 μm, oven dried, and weighed to determine the mass of sediment taken at each bottle.

Data analysis

Comparison of the gully treatments were made against two identical nearby untreated gullies having almost similar characteristics (soil, land use, head slope, depth, and width). For example between gully head 6 (GH6) and gully head 7 (GH7); GH3, GH4, and GH6 before and after gully head protection. Bank protection measures comparison made between gully branches 3 (GB3) and GB4; GB6 and GB7 based on the change in pins at each depth, width and length.

The volume of trapped sediment was calculated by multiplying the average change in pin height by the width of the gully bed and the length of the deposited material in the channel. The mass of trapped sediment was then calculated by multiplying the soil bulk density with the volume of sediment trapped [30]. Further, a non-parametric test using SPSS (Statistical Package for Social Sciences) was used to observe whether there is a significant difference before and after implementation of gully head control measures.

The average suspended sediment concentrations (SSC) for a storm events were determined by dividing the total event sediment load by the total storm runoff (R) [30]. Instantaneous sediment load was calculated as the product of discharge and sediment concentration.

III. RESULTS AND DISCUSSION

A. *Effect Of Gully Treatment On Gully Head And Bank Retreat*

The results from the untreated gully heads indicated that, the average head retreat was 3 m with a maximum of 22.5 m in 2014 (Fig. 2). In 2015 this average value decreases to 0.26 m. The decrease in retreat was due to the treatment of additional three active gully heads (GH3, GH4 and GH6) in 2015. The other reason may be due to the decrease in rainfall amount from 761 mm in 2014 to 552 mm in 2015. Gullies treated with stone riprap (GH3, GH4, GH5, GH6 and GH7) did not retreat while regraded gullies treated without riprap retreated (GH2) 0.3 m and 0.8 m in 2014 and 2015 respectively (Fig. 1). Gullies regraded without stone rip rap shows minimal temporary retreat in the 2014 but it increases in the second rainy season (2015). The regrading at this GH2 in 2014 was able to reduce the extent of retreat but after a continuous over flow, the edge of the head gets steeper and that creates fast retreat in 2015. The non-parametric test result indicates that, there was a significant difference in gully head retreat before and after installing head protection measures ($p<0.04$).

The comparison between treated gully (GH7) and untreated (GH6) in 2014 shows, the treated head had never show any advance while the untreated head moves up slope by 2.5 m. Further the comparison between GH3 and GH4 both untreated in 2014 and treated in 2015 indicates, GH4 retreated by 22.5 m and GH3 by 11 m without treatment but in 2015 after implementation of head protection measures both heads keep in place with zero retreat (fig. 1, 2).

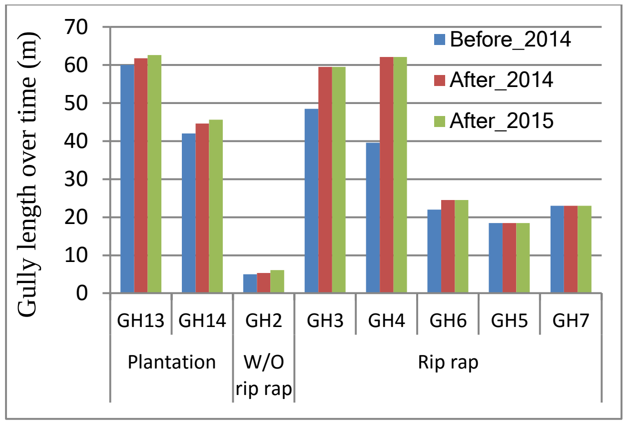

Fig. 2. Change in gully length for the treated gullies before and after protection and the untreated gullies GH1 GH8, GH9, GH10, GH11 and GH12. W/O is without.

The maximum head retreat measured at GH4 that is because of the implementation of improperly designed draining structure by farmers to dispose excess runoff up stream of the gully heads.

Figure 3 shows the change in gully width before and after implementing gully bank protection measures. At the regraded gully bank there was no any retreat observed. After regrading the bank width increased by 1.1 m. The zero measurement was used without considering the increased in width due to reshaping that is equal to 1.1 m.

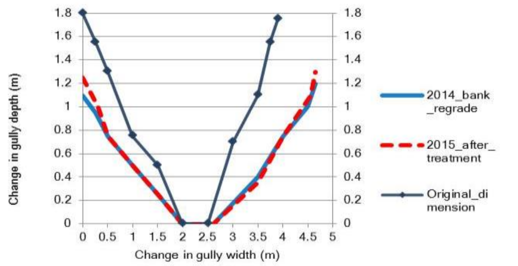

Fig. 3. Gully treatment at gully branch 7, where both the bank and bed protected with regrading and bed with bamboo sheet cover. The figure shows before and after protection measures installed.

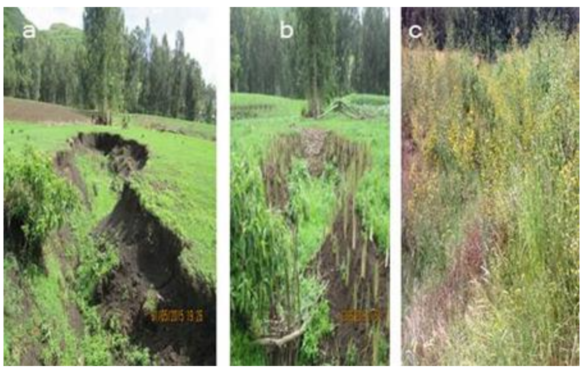

Fig. 4. Gully bank protection with regrading, vetiver grass plantation and sediment trap check dam at the end of the gully branch in the case of gully branch GB6, the figure shows the bank protection before and after implementation of bank protection measures.

B. Gully Treatment With Bed Stabilization

Gully bed was redesigned to keep flatter slope using infillings and surface cover. The initial slope of the channel was 12% and after redesign it reduced into 6%.

During the implementation of gully bed stabilization, soil compaction was done in June 2014. The soil was not strong enough to compact due to its wetness. Once the cover or sheet over laid, in July when the flow concentrated, the soil gets more wet and looser. As a result, the bamboo sheet starts to lower and remain in the center of the channel.

The overlaid biological material (bamboo sheet) could not resist the internal (soil wetness) and external (sun and rain) fluctuation. In the first three weeks of the rainy season the bamboo sheet were kept in place with effective protection. But at the end of the rainy period in September, 2014, the sheet had broken down. However, the residues were not washed out rather used as a geotextile with grasses grow at the gully cannel that retard the flow and trap sediments. The channel depth was increased from 1.05 m to 1.25 m (Fig. 3). Time of intervention for regrading and compaction was significant. It was difficult to cut the black soil column into a proper angle since the reshaping started early before rain falls. Waiting until the soil gets moist keeps the reshaped well but it is difficult to compact the soil because of its wetness. This less compacted underlying soil leads to failure of the overlying bamboo sheet and it may aggravate gullying. Application of infillings and overlying sheet may be successful in areas where gullies developed other than black soils.

C. Gully Treatment With Plantation

One big gully, gully branch 13 (GB13) treated with plantation and the amount of sediment deposited behind the check dam was, 2200 and 3000 ton $ha^{-1}yr^{-1}$ in 2013 and 2014 respectively [1]. But at these gully heads the retreat was continuing. Hence both grow by 3 m in 2013 and 1.5 m in 2014. Plantation without integrating with physical measures at gully heads could not stop the upslope migration. This result agree with the findings in china that vegetation has little effect on gully head protection [9]. The monitored vetiver grass growth status shows, an increase in length by 35 cm after three months and 60 to 75 cm after five months of plantation. A comparison result between vegetated gully branch GB4 with 63 m length and GB3 without vegetation having 48 m length shows, the amount of sediment trapped at each branch was 63 kg and 610 kg of soil respectively. This indicates that gullies treated with vegetation could have the potential to reduce sediment loads emanating from gullies. At the beginning of the 2015 rainy monsoon 1.9 ha of gully location enclosed from animals and people interference. The effectiveness of the enclosure [17] allows fast revegetation of natural grasses and the people could harvest grasses for their livestock consumption.

D. Effect Of Gully Rehabilitation On Sediment Concentration

The comparison result between GH7 treated and GH6 untreated show, the untreated head had recorded 20 ton of soil loss. In addition at the gully branch The comparison result between two gullies with a length of 60 m (treated) and 48 m (untreated) in 2015 shows that, 5 cm depth of sediment deposited behind a sediment trapping check dam from the treated bank as compared with 60 cm depth of sediment from the untreated bank both heads protected. This is equivalent to 50 and 610 kg of soil loss with a bulk density of 1.13 g/cm^3 respectively. In the other comparison gully branch 6 (GB6) with 22 m length compared before and after implementation of bank protection, shows a change in gully average width of 0.75 m (equivalent to 360 kg of soil with a bulk density of 1.15g/cm^3) without treatment in 2014 and 0 m after treatment in 2015 (Table 1).

The sediment concentration (SC) result shows, there exist a variation in SC between 2014 and 2015 in the watershed out let. The average sediment concentration was 15.1 g/l in 2014 which decreases into 10.6 g/l by 2015 (Table 1). The measured erosion rate significantly decreases from 7.5 t ha^{-1} yr^{-1} in 2014 to 0.96 t ha^{-1} yr^{-1} by 2015. This is equivalent to the reduction in sediment load by 87%. The likely reason for the lower erosion in 2015 was, gully control measures installed on the upper active part of the gully system. Field observation result confirms that, the downstream part of the gully is relatively discontinuous or inactive than the upstream parts where the large proportion of sediment source. The other reason may be due to the lower rainfall in 2015 (552 mm) than 2014 (761 mm). Because the cumulative rainfall has a strong positive correlation with the gully head retreat ($r = 0.95$). As observed in the field monitoring and repeated photography the control measures were efficient in trapping sediments due to plantation and free drainage of surface flow over the rip raped gully heads (Fig. 4). Similar results were reported in the Debre-Mawi watershed that, the implementation of rehabilitation techniques can reduce downstream sediment concentration [8].

E. Evaluation Of Low Cost Gully Treatments

The tested gully rehabilitation measures were low cost, especially compared to the cost of other gully reclamation measures such as gabions. Locally available materials such as stones and grasses were used. The cost was mainly payments for daily labor and grass seedlings. In addition, local communities, considering their financial and technical capacities, can easily manage the tested gully rehabilitation measures. Farmers construct traditional draining structures to reduce the upstream over land flow effect but it had the potential to create other gully if safe disposal sites are located wrongly. Due to cultivated land scarcity, farmers always face conflicts each other on locations where draining structures constructed. This misunderstanding among farmers can be resolved by implementing low cost measures such as by placing gully head protection measures to drain excess water following the existing natural flow paths. Unlike the study in Northern China, gully head drainage measures needed higher costs, and difficult to build in less developed regions [14]. But this study result demonstrate the way of implementing gully head protection measures using low cost measures and it was promising (Fig. 2). Finally the study brought a change in farmer's attitude regarding the possibility of reclaiming gullies with low cost locally available materials.

IV. CONCLUSION

The comparison made between gullies of treated and untreated over the gully heads and banks result shows a significant change in sediment production. The installed grading structures with stone rip-rap at heads could safely dispose the runoff over the head surface without causing damage and stop gully head advancement. Heads with rip rap integrated with plantation control erosion as compared with heads protected by reshaping without stone rip rap. Bank protection with regrading is also effective for gully erosion control. Bed stabilization with bamboo sheets could not stay longer because it is susceptible for damage. Enclosure of the surrounding gully area plays a role to revegetation and self-stabilization of gully beds than banks. Finally, these gully treatment experiments were effective to be replicated by the local farmers with low cost inputs. For sustaining the structures and minimize failure, proper attention to engineering design, time of intervention, and long-term maintenance are essential.

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Appendix

Table 1: Monthly average suspended sediment concentration (SSC) in grams per liter and sediment load (SL) in ton per hectare at the outlet weir for the two years, 2014 and 2015.

Year	2014				2015			
Months	Min	Max	Average	SL	Min	Max	Average	SL
Jun	0	0	0		5.4	24.27	15.42	0.05
July	4.58	32.95	15	1.32	4.99	26.04	11.39	0.56
August	5.01	31.2	17.12	3.94	2.39	18.73	10.67	0.33
September	2.3	17.97	12.4	0.51	0.79	1.13	0.99	0.02
October	9.7	24.8	15.7	1.68	0	0	0	
Total	2.3	33.0	15.1	7.5	0.8	26.0	10.7	0.96