Performance of Subsurface Water Drainage Technique on Gully Bank Stability in the Sub-Humid Highlands of Ethiopia

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Abstract

Gully erosion is the major sources of sediment in the watersheds. The lateral and upward retreat of gullies resulting mass failure of high, steep banks is one of the most serious forms of soil erosion. The risk of a given bank experiencing mass failure is a function of bank height, angle, and soil strength, which is governed by soil moisture. Therefore the objective of this research was to evaluate the applicability of a low-cost horizontal sub-surface water drainage technique for stabilizing a rapidly eroding gully banks in the (sub) humid Ethiopian highlands tested in the Debre Mawi watershed, about 32 km south of Bahir Dar. The study was conducted on the opposite sides of a gully (a total of two active gullies, one from Vertisol and one from Nitisol) that are hydrologically isolated from one another. The surrounding ground water tables were continuously monitored for two years at both sides of a gully: on the horizontally drained and control sections. Over the course of two wet seasons, average bank retreats for the control and drained plots were 0.62 and 0.15 m at Vertisols and 1.1 and 0.29 m at Nitisol, respectively. The average ground water table of the drained bank was 20% lower than the non-drained banks during the monitoring periods. This means that the drained banks displayed generally lower water table resulting lower pore water pressure. These results suggest that bank dewatering promoted lower rates of bank retreat and higher levels of stability of gully banks on both soil types. Initial cost of the dewatering treatments were significantly less than the conventional bank stabilization measures, but the former may require operational and maintenance costs. Bank dewatering could be one of the technologies for gully rehabilitation and its benefit could be maximized by integrating with other physical and biological protective measures.

Key words*: bank retreat, Debre Mawi, dewatering gully,*

Introduction

Gully erosion is one of the most damaging forms of soil erosion. Gully and riverbank failures and retreats are threats to agricultural land and infrastructure (Simon and Rinaldi, 2000). In the Ethiopian highlands, gullies are severely covering large tracts of areas and silting up rivers and reservoirs (Daba *et al*., 2003; Haregeweyn *et al*., 2013). Extensive areas of agricultural lands are affected each year leading to irreversible changes in soil productivity and the food security (Sonneveld and Keyzer, 2016; Zegeye *et al*., 2017).

Most gullies in Ethiopia have been advancing uphill (Tebebu *et al*., 2010, Zegeye *et al*., 2016). Previous research confirmed that the upward head migration is the most important factor in gully expansion and sediment production (Langendoen *et al*., 2013; Addisie *et al*., 2016). Controlling gully erosion is more difficult and expensive than sheet and rill erosion. Once formed, it requires a huge investment to rehabilitate. It also requires knowledge of the actual gully development processes in the targeted area. Simon *et al*., (1999) reported in his study that bank erosion is often caused by the interaction of hydraulic forces operating at the bank toe which result in undercutting and steepening, and gravitational forces operating on the bank mass. Rates of bank failure are governed by bank height, angle and the shear strength of the soil which is highly sensitive to pore-water pressure within the bank material (Zegeye *et al*., 2020). Soil saturation by a rising water table decreases the soil shear strength (Langendoen and Simon, 2008) and therefore destabilizes banks (Simon *et al*., 2000; Langendoen *et al*., 2013).

During the monsoon season, the negative pore water pressure will be lost due to bank saturation and hence, bank failures along incised channels occurs (Simon *et al*., 1999). Positive pore water pressures also increase the weight of the bank mass and contribute to bank failure (Wilson *et al*., 2007). Thus, maintenance of negative pore water pressure by artificial or other means could provide greater bank stability and reduced frequency of mass failure (Shields *et al.*, 2009). As discussed by Shields *et al*. (2009), maintaining lower levels of pore water pressures by dewatering may reduce the action of bank failure by hydraulic and geotechnical processes.

Figure 1. a) Inappropriate diversion of flowing water created another new gully, b) physical and biological headcut treatment by Zegeye et al. (2017) and the red circle shows the failure of planted material on the regarded bank due to wet bank, c) natural pipe dewatered the bank water and no failure was observed (Zegeye et al., 2016).

Soil and water conservation (SWC) measures introduced by the Ethiopian government in 2010, under the Growth and Transformation Program (GTP), have positively impacted watersheds in northern Ethiopia (Dagnew *et al*., 2015). Related to gully erosion reduction, some of mitigation measures might include some combination of bank-toe protection to increase resistance to hydraulic forces (Simon *et al*., 2008, *2011*; Clark and Wynn, 2007), through the transpiration of vegetation (Simon and Collison, 2002, Langendoen and Simon, 2008), dewatering artificially by installing horizontal drains (Rahardjo *et al*., 2003;

Crenshaw and Santi, 2004) or regrading the bank slope to a flatter angle (Zegeye *et al.*, 2017).

In the case of the study area, Debre Mawi watershed, where gully erosion predominate the bottomlands, previous attempts to stabilize gullies are not very much successful (see Fig. 1b). Diversion of flow initiated new gully (Fig. 1a), vegetation has little effect for gullies up to 6 meters deep (Figure 1b), regrading bank angle and installing checkdams near the headcut significantly reduced the uphill migration of the headcut (Zegeye *et al.*, 2017) but the planted materials started to slide down and this is due to the saturation of the surrounding area of the bank (Fig. 1b). Therefore, stability might be increased by draining subsurface water out of the gully bank mass from within vertical wells or providing passive dewatering through horizontal drains (Shields *et al*., 2009). From the previous study (Zegeye *et al*., 2016), one of the monitored gullies was not eroded for two consecutive years and the reason was that the bank was dewatered through the natural pipes along the gully bank (Fig. 1c). Therefore, this research aimed at to evaluate the applicability of a low-cost horizontal drain for stabilizing a rapidly eroding gully bank in the (sub) humid Ethiopian highlands.

Materials and Methods

Area Descriptions: The experiment was conducted in the Debre Mawi watershed. The 608 ha Debre Mawi watershed, is near Lake Tana in the upper Blue Nile Basin at 11°20'13" N and 37°25'55" E (Figure 2b) with slopes ranging from 1 to 30%. It has a sub-humid region with an average temperature of 20°C and annual rainfall of 1,240 mm with more than 70% of the rainfall occurs through June to August. In the Debre Mawi watershed, gullies are expanding rapidly in the periodically saturated bottom lands (Fig. 2b) with a high regional groundwater table. On the cultivated slopes, sheet and rill erosion occur, but soil loss is much less than from the gullies (Zegeye *et al*., 2010; Amare *et al*., 2014).

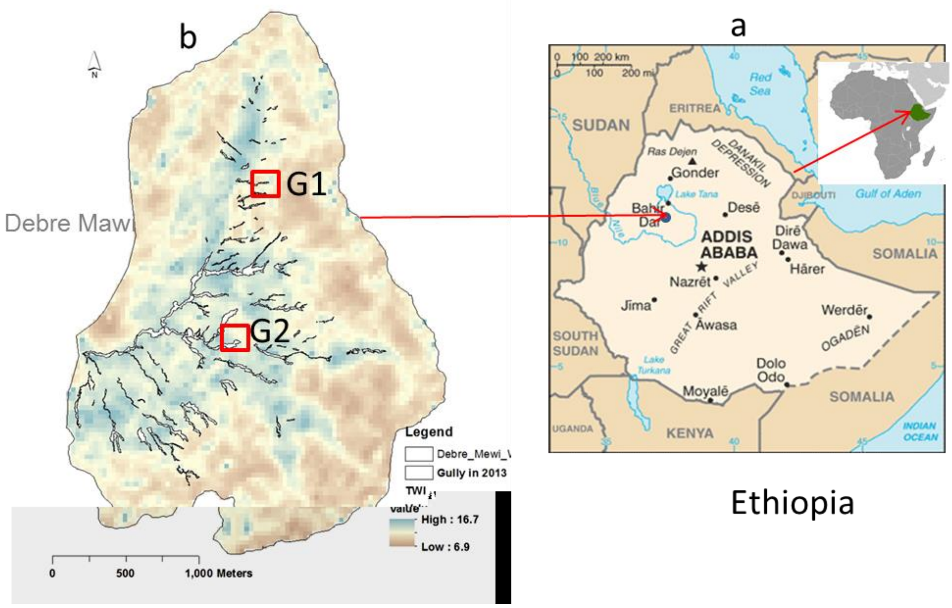

Figure 2. Location and gully network of the Debre Mawi watershed. (a) Ethiopia with neighboring countries; (b) the gully network in 2013, with a combined surface area of about 20 ha, superimposed on the topographic wetness index (TWI) of the Debre Mawi watershed (the study gullies (G1 is at Nitisol, G2 is at Vertisols) are located in the red rectangles).

Gully Geometry and Soil Loss: To compare the effect of dewatering over the control plot, cross-sectional geometry surveys were conducted twice a year, i.e., before and after the rainfall in a two-year study, by dividing the cross section into trapezoidal segments at abrupt changes in the ground profile, and measuring the width and depth of the gully at each segment (Zegeye *et al.*, 2016; Zegeye *et al*., 2017). Cross-sectional area (A) was calculated:

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where n is the total number of sides of the trapezoid with measured height *h* at a distance *w* from the left gully edge

The gully volume (*V*) was determined as:

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where the subscript, m are the total number of cross-sections, and L_j is length of channel between cross-sections j and j+1.

Experimental Setup: Two active gullies, one from Vertisol and one from Nitisol were selected in the watershed to represent gullies in similar agro-ecology. The left and right banks of a gully near the headcut that are assumed to be hydrologically isolated from one another were considered as experimental plots. The left banks are used as control plots with no dewatering, and the right banks were passively dewatering using horizontal drains. At the drained plot, a total of 24/36 perforated plastic pipes (i.e., two or three rows depending on the gully height spaced by one meter and rows spaced by 0.5m at similar elevation were installed as shown in the Figure 3.

Figure 3. Experimental designs that show piezometers, pivots for gully dimension measurements, Nitisol gully (a-left side), Vertisol gully (b-right side where the investigator photo is included).

In the first year, a 5 mm pipe covered with woven sock material was mechanically inserted (Fig. 3b); however, the woven socks that were supposed to prevent entrances of sediment in to the pipes were not effectively inserted and hence the subsurface water drainage was limited. In the second year (2019), the method was modified i.e., a 3 m long auger was used to dig a hole in which a 50 mm diameter and a 3 meter long plastic pipe covered with woven sock was inserted in to holes as shown in Figs. 3a & 4). On both years, pipes were installed perpendicular to the bank and extending up to 3m into the field (Fig.3).

Results and Discussion

Effect of Dewatering on Ground Water Table: The effectiveness of artificial dewatering was initially evaluated by comparing data from the piezometer readings at 3m and 6m away from both control and treated banks (Table 1). A lower water table level indicates lower pore water pressure translates to greater resistance to mass failure through its effect on apparent cohesion.

As indicated in Fig. 4, piezometers installed near the edge of the gully showed that the water table in these areas was deeper than elsewhere. On the other hand, the water table elevation (Fig. 4) was entirely above the gully bottom, indicating that the gully bank is highly saturated. This lowers the shear strength of the bank material destabilizing the gully banks. As Tebebu *et al*. (2010) and Zegeye *et al*. (2016) reported that saturation is the main cause of gully formation and gully bank sliding. Since the gully bank was saturated (Fig. 4), the pore-water pressure due to rising of ground water elevation has played a key role in triggering gully formation. This result is supported by several authors (e.g., Simon *et al*., 2008; Tebebu *et al*., 2010; Langendoen *et al*., 2013; Zegeye *et al*., 2016; Zegeye *et al*., 2020).

In the study gullies, the piezometer readings show that the untreated left gully banks were wetter than the treated (drained) right banks during the testing periods (Table 1, Fig.4). This means that gully banks in which draining pipes were installed were relatively stable as water drains out through the pipes resulting in water table drawdown resulting lower pore-water pressures. In this case, the shear strength of the bank materials increases and reduces bank failure which is in line with the studies of Simon *et al*. (2011) and Zegeye *et al*. (2020).

Table1. Ground water table (GWT) and calculated gully geometry.

Parameter	2018				2019			
	Vertisols		Nitisols		Vertisols		Nitisols	
	Control	Drained	Control	Drained	Control	Drained	Control	Drained
GWT(m)	0.73	1.1	2.36	2.54	0.49	0.84	2.46	2.76
ABR(m)*	0.42	0.2	1.7	0.48	0.83	0.13	0.53	0.1
ACSA (m^2)	1.4	0.6	6.3	2.0	3.75	1.62	3.14	0.03
V, m^3	7.1	3.3	17.7	5.6	12.7	4.87	9.43	0.09

*ABR stands for average bank retreat, ACSA is average cross sectional area and V is change in volume.

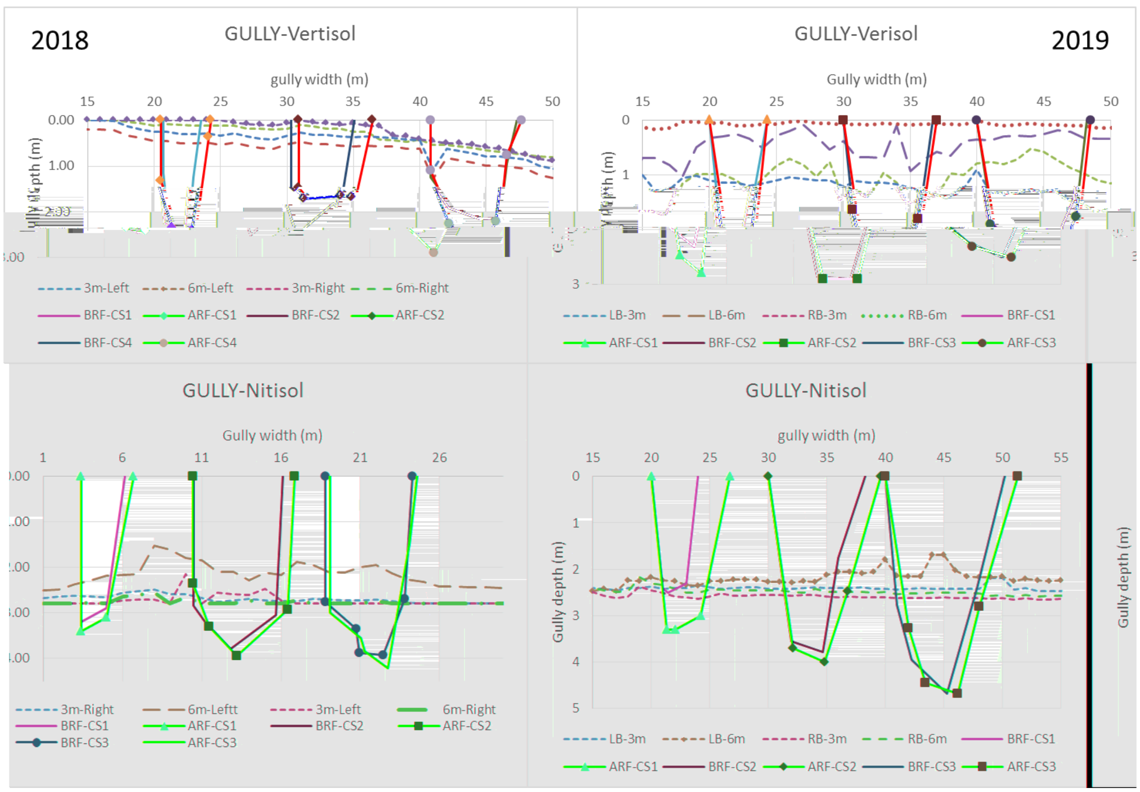

Figure 4. Observed changes in gully geometry and ground water table at 3 m and 6 m from the

Gully Bank and Volumetric Retreat: Bank edge monitoring demonstrated that both banks initially experienced similar retreat rates, associated with wetting up after the first rainfalls in June until the treatment began the last weeks of July on both study years. However, retreat slowed and stopped sooner on the drained banks, and thus total retreat was much less (Table 1). The drained banks experienced much slower retreat, with only minor sloughing off the bank face.

As observed in Fig. 4, the second cross section of vertisol in 2018 showed that the saturated untreated (control) bank failure debris filled the gully channel that reduced the channel depth until moved by the flowing water downstream. The positive change in cross section area ($0.6m^2$) was due to the sidewall retreat that compensated the area filled by the bank debris. Generally, the average cumulative bank retreat and soil losses on the drained banks are reduced by 72% and 60% on Vertisol and 74% and 80% on Nitosols, respectively, as compared to the control banks (Table 1). Over the entire period of the experiment, the drained bank lost about 14 m^3 which is 70% less than the control. The results show that dewatered banks retreated about one-fourth as fast as the control. This is because; the pore-water pressure in the drained bank is reduced resulting increase of the shear strength of the bank material which increase stability. This result is supported by Le´onard and Richard (2004) and DeBeats *et al*. (2008) who reported that there was a significant linear relationship between saturated soil shear strength and critical shear stress (defined as the stress at which soil detachment begins or the condition that initiates soil detachment). If the critical stress is higher than the effective stress, the erosion rate is considered zero (Clark and Wynn, 2007).

Figure 5. Observed discharges during installing the horizontal drain pipes in Vertisol gully at Debre Mawi watershed (2019). The man is installing pipes using auger of similar diameter.

As shown partially in Fig. 5, the discharge was observed on the five pipes with different amount of which two were in the upper row that were quickly stopped because of the lower row discharges. The upper banks went to dry after two days of installations. Differences in the volume of water discharged among all installed pipes suggest that movement of groundwater through the site was heterogeneous, probably as a result of the lenses of coarser and finer bed material that compose the bank materials and the presence of macropores (Wilson *et al*., 2007).

Clearly, precise comparison of bank dewatering between the two gullies is not possible due to the site-specific conditions at each gully. Nevertheless, the result demonstrated that the comparison is still possible within the gullies between left and right banks.

From our field observation, although the water table was near the surface in vertisol gully banks, the pipes installed in these banks drained very slowly as compared to nitisol banks. This could be associated with the difference in soil hydraulic conductivity, permeability and stratigraphy between the two soil types. It has scientific explanation that the verisols is a deep clay material which has relatively poor hydraulic conductivity (lower porosity and permeability) than the bank material at nitisol. The smaller the size of the sediment grains, the larger the surface area the water contacts that increases the frictional resistance to flow, which reduces the permeability as also reported by Norris and Fidler (1965) as the intrinsic permeability is proportional to the grain size of the sediment.

This dewatering treatment was relatively inexpensive compared with other methods of bank stabilization; total initial costs were 400 Ethiopian Birr for drained plots. Each plot stabilized about 4 m of bank at a cost of 100 Ethiopian Birr m^{-1}. This compares with costs of approximately 300 Ethiopian Birr m^{-1} for gully stabilization using re-grading and riprap, though there are recurrent costs associated with maintenance for dewatering system (Shields *et al*., 2009). Bank dewatering may be practical to protect critical infrastructure and also provides a potential means of temporarily stabilizing a bank till vegetation is established. Therefore use of passive drains was shown to have an effect on bank retreat, and showed promising indications that drainage could improve bank stability under bank saturated conditions. Performance of the drains could have been improved by modifying drain design parameters (depth and spacing) using better information regarding soil permeability and hydrologic loading than we had available.

Conclusion and Recommendation

Only few studies worldwide have documented the relationship between dewatering gully banks and bank stability. The ground water table monitoring during the study periods demonstrated that dewatering gully banks lowered the level of the surrounding groundwater table. The results suggest that bank dewatering promoted lower rates of bank retreat and higher levels of stability of gully banks on both soil types with relatively minimum initial cost. Bank dewatering could provide a potential means of temporarily stabilizing a bank till vegetation is becoming established. The discharge from the draining pipes should be safely disposed and join to the main channel, may be advisable to install an apron at the water-falling area of each drain to dissipate the falling discharge energy that could scour under the pipe. Generally, integrating bank dewatering with other gully rehabilitation measures including physical and biological measures should be considered on future gully rehabilitation packages. Further research on improving the performance of the drains by modifying drain design parameters (depth and spacing) using better information including soil permeability and hydrology are important.

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References

Addisie, M., G. Ayele, A. Gessess, S. Tilahun, A. Zegeye, M. Moges, P. Schmitter, E.

Langendoen E.J., Simon A., 2008 modeling the evolution of incised streams. II: streambank erosion. Journal of Hydraulic Engineering 134: 905 915. DOI: 10.1061/(ASCE)0733 9429(2008)134 : 7(905).

Langendoen, E., T. Tebebu, T. Steenhuis and S. Tilahun., 2013. Assessing gully widening and its control in the Debra-Mawi watershed, northern Ethiopia. **In**: *Proceedings Conference on Science and Technology Towards the Development of East Africa (ICST 2013), eds N. Gabbiye, E. Kaba, KK Monocha Singh, and S. Sharma (Bahir Dar University Institute of Technology: Ethiopia)*.

Le´onard J., Richard G., 2004. Estimation of runoff critical shear stress for soil erosion

World Environmental and Water Resources Congress 2008 Ahupua'a [CD-ROM], edited by R. W. Babcock Jr. and R. Walton, Am. Soc. of Civ. Eng., Reston, Va.

Simon A., Pollen-Bankhead N., Thomas R.E., 2011. Development and application of a deterministic bank stability and toe erosion model for stream restoration. Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools, AGU, Washington, DC, A. Simon, S.J. Bennett and J.M. Castro Editors, pp. 453-474.

Simon A, Collison AJC., 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth Surface Processes and Landforms 27(5): 527 546.

Sonneveld B. and Keyzer M., 2003. Land under pressure: soil conservation concerns and opportunities for Ethiopia. Land Degradation & Development. 14(1): pp. 5-23.

Tebebu T.Y., Abiy A.Z., Zegeye A.D., Dahlke H.E., Easton Z.M., Tilahun S.A., Collick A.S., Kidnau S., Moges S., DadgariF.,Steenhuis T. S., 2010. Surface and subsurface flow effect on permanent gully formation and upland erosion near Lake Tana in the northern highlands of Ethiopia, *HESS* 14, 2207-2217.

Wilson GV, Periketi R, Fox GA, Dabney S, Shields Jr FD, Cullum RF. 2007. Soil properties controlling seepage erosion contributions to streambank failure. Earth Surface Processes and Landforms 32:447 459.

Zegeye A.D., Langendoen E.J., Stoof, C.R. Tilahun, S.A., Dagnew, D.C., Zimale, F.A., Guzman, C.D., Yitaferu, B., Steenhuis, T.S. ,2016. Morphological dynamics of gully systems in the sub-humid Ethiopian Highlands: The DebreMawi watershed. Soil **2016**, 2, 443 458.

Zegeye A.D., Steenhuis, T.S., Mekuria M., Dagnew D.C., Addisie M.D., Tilahun, S.A ,Tadele A.K., 2017. Effect of gully headcut treatment on sediment load and gully expansion in the sub-humid Ethiopian highlands, Environment and ecology Research, 5(2): 138-144. DOI:10.13189/eer2017.050208

Zegeye A.D., Langendoen, E.J. Steenhuis, T.S, Tilahun, S.A., 2020. Bank stability and toe erosion model as a decision tool for gully bank stabilization in sub humid Ethiopian highlands, Ecohydrology & Hydrobiology, https: //doi.org/10.1016/j.ecohyd.2020.02.003