

ASSESSMENT OF HYDROLOGICAL CONTROLS ON GULLY FORMATION AND UPLAND EROSION NEAR LAKE TANA, NORTHERN HIGHLANDS OF ETHIOPIA

Tigist Y. Tebebu, Anteneh Z. Abiy, Assafa Derebe Zegeye, Tilashwork C. Alemie, Students, Integrated Watershed Management and Hydrology Master Program, Cornell University at Bahir Dar, Ethiopia; Helen E. Dahlke, Seifu A. Tilahun, Research Assistants, Biological and Environmental Engineering, Cornell University, Ithaca, NY; Amy S. Collick, Assistant Professor, School of Civil and Water Resources Engineering, Bahir Dar University, Bahir Dar, Ethiopia, asc38@cornell.edu; Selemiyhun Kidnau and Farzad Dadgari, Soil Water Specialist and Consultant SWISHA, Bahir Dar, Ethiopia; Tammo S. Steenhuis, Professor, Biological and Environmental Engineering, Cornell University, Ithaca, NY 14853, tss1@cornell.edu

Abstract Over the past five decades, gullying has become more severe in the Ethiopian highlands. Besides negatively affecting soil resources, lowering crop yields in areas between the gullies and reducing grazing land available for livestock, gully erosion is one of the major causes of silting of reservoirs. Assessing the rate of gully development and the controlling factors of gullying will help to explain the causes for current land degradation and to design reliable conservation measures for already existed gullies and preventing strategies for those areas susceptible to further gullying. The study was conducted in the 523 ha of Debre-Mewi watershed south of Bahir Dar, Amhara region, Ethiopia, where active gullies were retreating upslope. Semi structured group interview and monitoring of gully development through time was made with profile measurements of contemporary gully volumes. Gullying started in the beginning of the 1980`s following the clearance of indigenous vegetation, leading to an increase of surface and subsurface runoff from the hillside to the valley bottoms. A comparison of the gully area estimated from 0.58 m resolution quick bird image with current gully area walked with a Garmin GPS, indicated that the total eroded area of gully was increased from 0.65 ha in 2005 to 1.0 ha in 2007 and 1.43 ha in 2008. The water levels measured with piezometers showed that in the actively eroding sections the water table was in general above the gully bottom and below it in stabilized sections. The elevated water table facilitates the slumping of the gully wall and their retreat. Water table height is decreasing after the gully has been formed. The gully erosion rate between 2007 and 2008 was $530 \text{ t ha}^{-1} \text{ yr}^{-1}$ in the 17.4 ha watershed, equivalent to almost 5 cm soil loss in the contributing area. Gully erosion rate was approximately 20 times the measured upland soil losses.

INTRODUCTION

Gully and upland erosion has become under increasing scrutiny in the Ethiopian Highlands during the since the nineteen eighties with the inception of the Soil and Conservation Research Program (Hurni, 1988; Moges and Holden 2008). Erosion negatively affects soil resources, lowers soil fertility and aggravates siltation of reservoirs. However, the gully process is not new and has been occurring over long periods of time. Carnicelli et al. (2009) examined gully formation since the late Holocene period. They found that besides tectonic events, gully entrenchment is triggered by increased stream transport capacity at the start of moist intervals, while gully entrenchment takes during transitions towards drier climate phases by decreased sediment transport and increased sediment supply. While mechanisms for upland erosion are

generally well understood (Haile et al., 2006), gully erosion is not. Better understanding of these gully erosion processes will result in more effective erosion control at less cost. Therefore, the objective of this study was to better understand erosion processes; in particular to compare erosion rates from an active gully to those of upland fields. This comparison will be used to determine the effect of landscape position and field wetness on erosion rates.

MATERIAL AND METHODS

The study was performed in the 523 ha Debre-Mewi watershed located: between 11°20'13" and 11°21'58" North and 37 ° 24'07" and 37 ° 25'55" East, 30 km south of Lake Tana, Bahir Dar, Ethiopia. The elevation is between 1950 and 2309 m and slope varies from 6-35%. Average rainfall falling mainly from June to September is 1240 mm. Land use consists of rain fed agriculture in a mixed farming system with scattered indigenous tree species, including *Cordia* sp. The soils are dominated by vertisols.

The historic rate of gully development was assessed through the AGERTIM method (Assessment of gully erosion rates through interviews and measurements, Nyssen et al., 2006) and by interpretation of air photos and satellite images. Gully hydrological processes were investigated by installing a weir to measure runoff. In addition to the weir, 24 piezometers (ranging in depth up to 6 m) were installed in the gully bottom as well as the gully's contributing area. The runoff and water depths were recorded manually during several storm events. Throughout the contributing area of the gully, soil bulk density was estimated and infiltration tests were performed. On July 1 and October 1, 2008, the volume and surface area of the entire gully system were estimated through measurements of width, depth and length of gully profiles.

Upland erosion was assessed as well. Fifteen representative fields were selected according to slope positions. The dimension of each rill was carefully measured after major storms to determine the volume of soil loss (Herweg, 1996; Hagmann, 1996; Bewket and Sterk, 2003). Soil samples were collected in three typical slope positions in four locations of each field for determining the moisture content. Additionally, farmers' perceptions about soil loss and soil conservation were gathered by interviewing 80 farm households from the four surrounding villages and by holding focus group discussions with groups of watershed community members.

RESULTS

The Debre-Mewi gully (Figure 1) is an actively eroding gully system with a contributing area of 17.4 ha. According to farmers' interviews, the gully erosion started in 1980, which corresponds to when the watershed was first settled and the indigenous vegetation on the hillsides was converted gradually to agricultural land. Erosion rates for the main stem and two branches are given in Table 1. The increase in main stem erosion rate can be explained by the recently enlarging and deepening of the gully at the lower end (Figure 2). In 2005, gully extent was estimated from the 2005 Quick Bird image (0.58 m resolution). Gully boundaries were determined before the rainy season in 2008 (indicated as 2007 measurement) and after the rainy season on October 1 (the 2008 measurement) by walking the gully with Garmin GPS with 2 m accuracy. These measurements showed that from 2005 to 2007, the gully system increased from

0.65 ha to 1.0 ha, respectively, a 43% increase in area. The following year, it increased by 60% to cover 1.43 ha in 2008.

Once gully size was determined, the rates of erosion were then calculated by determining the change in dimension of the different gully segments. The average gully erosion rate from the period from 1981 to 2008 was equivalent to 31 t ha^{-1} per year in the contributing watershed. The gully erosion rate has accelerated significantly in the last few years and in the 2008 rainy season the erosion rate was 530 t ha^{-1} (Table 1) which is equivalent to nearly 4 cm of soil in the contributing watershed. These values are very high for the region compared to the results from other studies (Daba et al., 2003 and Nyssen et al., 2006).

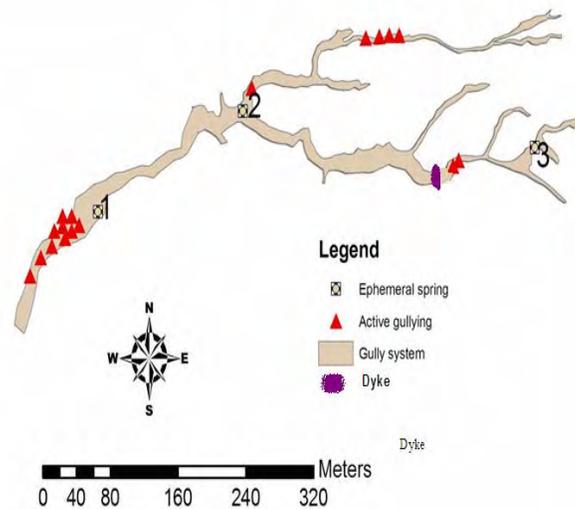


Figure 1 Drawing of the Debre-Mewi gully generated by handheld GPS tracking. Active erosion areas are indicated by triangles. Ephemeral springs are shown as well.



Figure 2 Actively forming gully at the most downstream end. Just below “1” in Figure 1.

The Debre-Mewi gully is very active in a few areas as indicated by the red triangles in Figure 1. Our measurements with the piezometers show that at these locations the water table is above the bottom of the gully. An example is given in Figure 3 for the actively forming gully shown in Figure 2. In figure 3 the distances are measured from the branch with another river. The depths of the gully (Figure 3a) and the corresponding widths (Figure 3b) before and after the 2008 rainy season show that the gully is most active at distances less than 200m from the outlet. The gully advanced backward past the 187 m mark (figure 3a) and increased up to 20 m in top width (Figure 3b). In this region the water table was near the surface and approximately 4 m above the gully bottom (Figure 3A). Upstream of the 187 mark the water table is below the gully bottom (Figure 3A) and the gully is stable as can be seen from Figure 3B since the width is not increasing.

Table 1 Gully erosion losses calculated as uniformly distributed over the watershed.

Gully location	Soil loss		
	1980-2007 t/ha/year	2007-2008 t/ha/year	2007-2008 cm/year
Branches	17.5	128	1.0
Main stem	13.2	402	3.0
Total	30.7	530	4.0

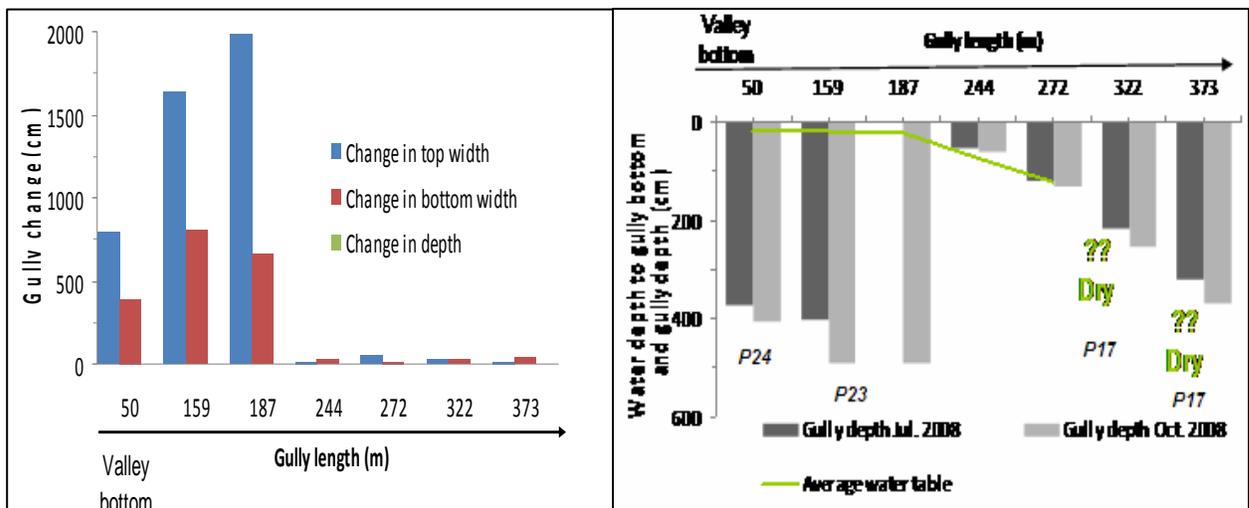


Figure 3 Gully dimensions before and after the 2008 rainy season for the main stem. a) Depths and average ground water table; b) change in top and bottom width and depth of the gully.

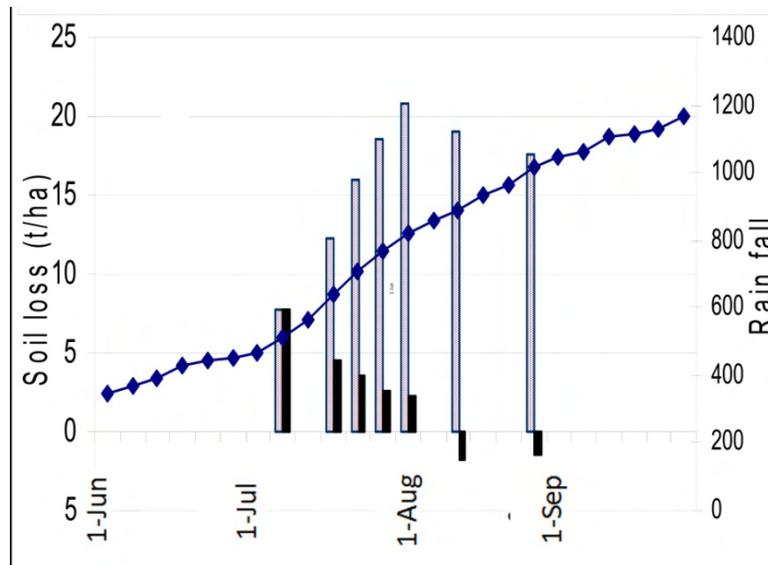


Figure 4 Average soil loss for 15 upland agricultural fields in the Debre-Mewi watershed. The light shaded columns are the cumulative soil loss for the season. The black boxes are the soil losses for individual storms. The line with diamonds is the cumulative precipitation for the rainy season.

The average upland erosion of the 15 agricultural fields for each storm is depicted in Figure 4. These erosion rates are with traditional soil conservation practices in place, which consist mainly of small, hand dug, 10 cm deep drainage channels, which direct water to the field's edge. Over the whole watershed, 75% of the farmers used the traditional ditches described above, 61% used soil bunds and 47 % used contour plowing.

The erosion is greatest at the end of June when the soil is loose and dry making it easy to erode as rills (Bewket and Sterk, 2003). After the initial rain storms, the soils wet up and plant cover is established; decreasing the rate of erosion. In late August, the rills degrade giving an apparent negative soil loss. The average cumulative soil loss is 26.6 tons/ha provided that the average bulk density of all surveyed fields was 1.21g/cm^3 and compares well with the measurement of the nearby erosion plot. By assuming the erosion caused by raindrop impact is 25% of the actual soil loss, the rate of soil loss is going to be estimated around 36 tons/ha. The tef plots had the greatest density of rills, which is likely caused by the repeated cultivation of the field and grinding of the soil by livestock traffic before sowing.

There was a greater soil loss from the fields at lower elevations than higher up the slope (Figure 5). The lower fields were either at saturation or close to saturation before the rain storm occurred; the upper fields were better drained. The erosion mechanisms for the upland agricultural fields are consistent with the mechanisms for the gully formation, because the soils near or at saturation have the least amount of adhesion between the soil particles and therefore, have the highest erosion rates. For the gullies this results in bank failure in which the soil loses its stability causing the slumping of the gully walls and the surrounding soil (Zhu, 2003), while for the upland fields deeper rills form. When the soil is dry, the soil has no strength either, and

high soil losses results. Although not observed in this study, gully banks erode easily by any disturbance such as grazing animals.

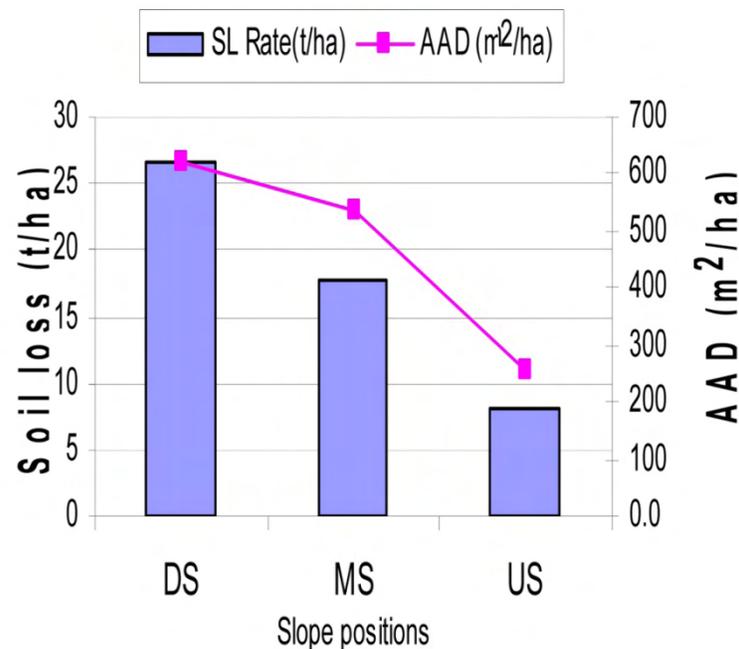


Figure 5 Erosion rate in tons /ha over the growing season as a function of slope position; where DS is down slope, MS is middle slope and US is upper slope. AAD is area actual damaged due to rill formation in m²/ha.

DISCUSSION

Thus both for the upland erosion and the gully formation there is a clear link between moisture content and rate of erosion. In the gully area where the water table is close to the surface, gully formation occurs by sliding of the gully wall (both at the end and from the sides) into the bottom of the gully and subsequently the soil is taken out by the flowing water during rainstorm when high flow occurs. Slumping occurs because of the pore water pressure above the gully bottom pushes the soil out and at saturation the soil does not have any strength. Thus the high water table is the cause of the rapid traveling uphill of the gully head as shown in Figure 3. When the water table is below the gully bottom the soil is more cohesive and the menisci in the unsaturated soil keep the soil together. If the gully widens when soil is unsaturated, it is caused by overland flow entering the gully, but this occurs at much less rapid rate than when the soil is saturated (Figure 3).

It is of interest to examine why the Debre Mewi active gully is being formed. According to a formal and informal survey carried out in the watershed, gully formation started in the beginning of the 1980's following the clearance of indigenous vegetation, leading to an increase of surface and subsurface runoff from the hillside to the valley bottoms. This increased flow then likely increased saturation at the bottom of the slope and a small disturbance forms an initial small gully and once formed it proceeds rapidly uphill. Thus our results agree in part with those of Mogus and Holden (2008) who indicated that gully formation is human induced. However it is not in direct way but likely indirectly through the following mechanism: When forests are

replaced by agricultural land, the evaporative term in the water balance becomes smaller, making the soils wetter and the extra water flows towards the watershed outlet resulting in wetter and sometimes saturated soil soils leading near in some cases to saturated soil that then can trigger gully formation.

Once the gully is established, it forms a passage for the ground water to drain and the soil becomes unsaturated and regains its strength and the gully is stabilized in the reach where the soil is unsaturated. The gully formation stops when the gully has proceeded uphill to a location where the soil becomes steep and where there is no long-term water table (the increase driving force) in the gully without saturating the soil.

CONCLUDING REMARKS

Comparing the gully and upland erosion rates in the Debre Mewi watershed, we find that in 2008, the soil loss rate of the upland plots (rill erosion) is approximately 20 times less than that transported due to gully erosion. While significantly less than gully erosion, rill erosion is still nearly four times greater than soil loss tolerance and thus cannot be ignored in any planning for erosion control to save fertility on the field. On the other hand, if reservoir siltation is the primary impetus for soil conservation, gully erosion should be addressed before upland erosion. Thus it is important that the soil erosion rates and especially those of gullies is being reduced. It is therefore important to see what can be done (based on the information above) to stop the advance of gully formation.

It is obvious that lowering the water table below the gully bottom would be most effective to slow down gully formation. This can be accomplished with drainage lines which, in theory, are practical. Application under Ethiopian conditions, however, may be cumbersome due the relatively high cost and lack of mechanized equipment. An additional way that the water table can be lowered is by planting eucalyptus trees on locations where the original forest was removed. It is generally known that eucalyptus trees reduce the flow (Lane et al. (2004). However it should be tested before it is implemented.

Finally gully formation can be stopped by stabilizing the gully as soon it is initialized for the first time and is still small. This requires continuous attention of the farmers and soil and water specialists and likely will be too time consuming for it to be practical.

It should be noted that buffer strips around the gully (which is sometimes advocated by engineers) do not address the basic problem, which is the fact that ground water is too close to the surface. Once gullies are stabilized, buffer strips could be more effective, however more research needs to be done before such a conclusion can be drawn with confidence.

REFERENCES

Aerts R., Finneran N., Haile M. and Poesen J. 2010. The Accumulation of Stone Age Lithic Artifacts in Rock Fragment Mulches in Northern Ethiopia. *Geoarchaeology-an International Journal* 25: 137-148

- Bewket W. and Sterk G, 2003. Assessment of soil erosion in cultivated fields using a survey methodology for rills in the Chemoga watershed, Ethiopia. *Agriculture, Ecosystems and Environment* 97, 81–93
- Carnicelli S., Benvenuti M., Ferrari G., and Sagri M. 2009. Dynamics and driving factors of late Holocene gullying in the Main Ethiopian Rift (MER) *Geomorphology* 103, 541–554
- Hagmann J., 1996. Mechanical soil conservation with contour ridges: cure for, or cause of, rill erosion? *Land Degradation & Development* 7, 145-160
- Daba, S., Rieger, W., Strauss, P., 2003. Assessment of gully erosion in eastern Ethiopia using photogrammetric techniques. *Catena* 50, 273-291.
- Haile M., Herweg K. and Stillhardt B., 2006: *Sustainable Land Management: A New Approach to Soil and Water Conservation in Ethiopia by Land resources Management and Environmental Protection Department*. Mekele Ethiopia.
- Hurni, H., 1988. Degradation and Conservation of the Resources in the Ethiopian highlands. *Mountain Research and Development* 8: 123-130
- Herweg, K. 1996. Field manual for assessment of current erosion damage. Soil conservation research programme (SCRIP), Ethiopia and Centre for Development and Environment (CDE), University of Berne, Switzerland
- Lane, P. N. J., Morris, J., Ningnan, Z., 2004. Water balance of tropical Eucalyptus plantations in southeast China, *Agricultural and Forest* 124, 253-267.
- Moges A. and Holden N.M. 2008. Estimating the rate and consequences of gully development, a case study of umbulo catchment in southern Ethiopia. *Land Degradation & Development* 19: 574-586
- Nyssen, J., Poesen, J., Veyret-Picot, M., Moeyersons, J., Haile , M., Deckers J., Dewit, J., Naudts, J., Teka, K., Govers, G., 2006. Assessment of gully erosion rates through interviews and measurements: a case study from northern Ethiopia. *Earth Surface Processes and Landforms* 31, 167-185.
- Zhu T.X. 2003. Tunnel development over a 12 year period in a Semi-Arid catchment of the loess plateau, China. *Earth Surface Processes and Landforms* 28, 507-525.