Assessment of Hydrological and Landscape Controls on Gully Formation and Upland Erosion near Lake Tana

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Abstract

Gully formation and upland erosion were studied in the Debre-Mewi Watershed in the Gilgil Abay Basin south of Lake Tana. Gully erosion rates were found to be equivalent to over 500 tonnes/ha/year for the 2008 rainy season when averaged over the contributing watershed. Upland erosion rates were twentyfold less. Gully formation is accelerated when the soils are saturated with water as indicated by water table readings above bottom of the gully. Similarly, upland erosion was accelerated when the fields were close to saturation during the occurrence of a rainfall event. Height of the water table is an important parameter determining the amount of erosion and should, therefore, be included in simulation models.

Introduction

For the past five decades, gully and upland erosion has been the dominant degradation process in the Ethiopian Highlands. Erosion negatively affects soil resources, lowers soil fertility and aggravates siltation of reservoirs. 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^{o}20'13" and 11^{o}21'58" North and 37 ^{o} 24'07" and 37 ^{o} 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 rainfed 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 (**A**ssessment of **g**ully **e**rosion **r**ates through **i**nterviews and **m**easurements, 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 and Discussion

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 a 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.

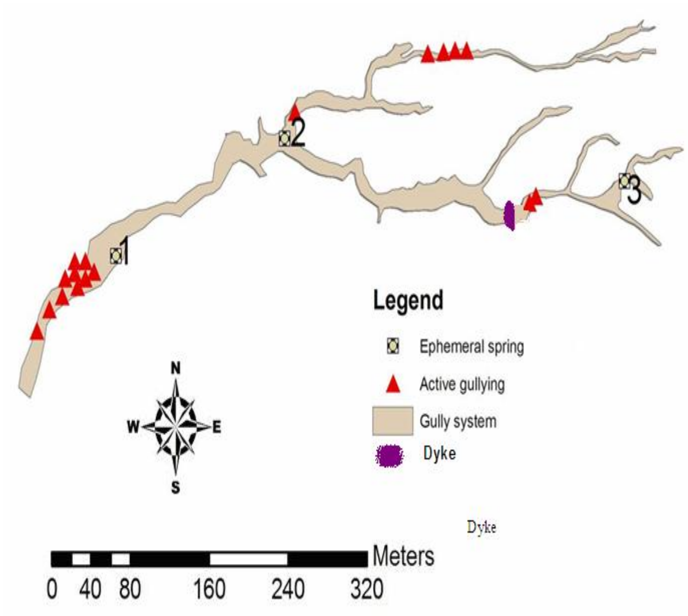

Figure 1: Drawing of the Debre-Mewi gully generated by handheld GPS tracking. Active erosion areas are indicated by triangles. Ephemeral springs are shown as well

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 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**

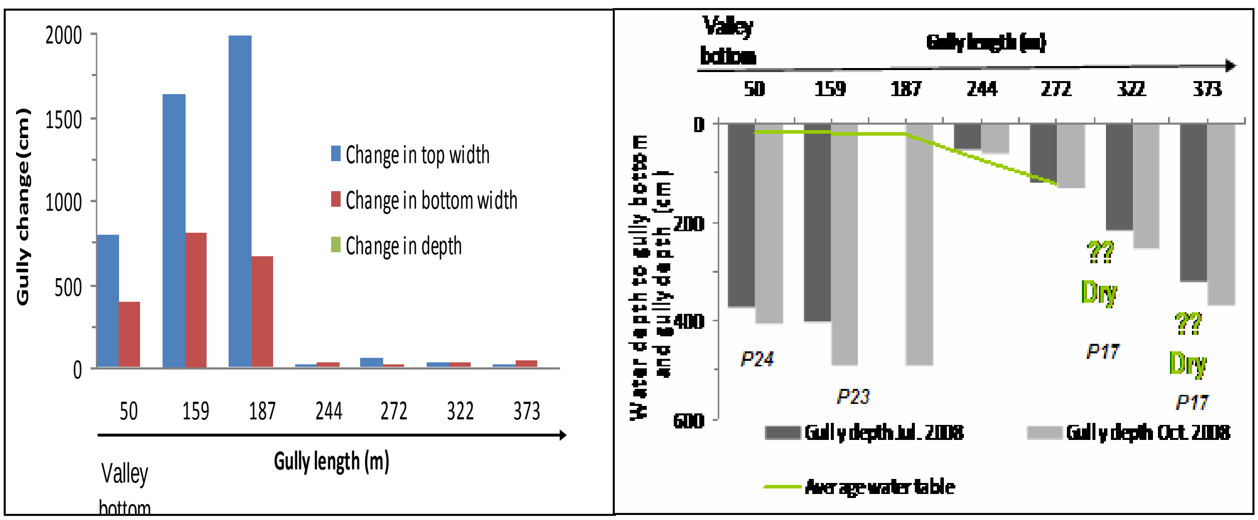

Figure 3: Gully dimensions before and after the 2008 rainy season for the main stem. a) Depths and average groundwater table; b) change in top and bottom width and depth of the gully

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 d cribed above, 61% used soil bunds and 47 % used contour plowing.

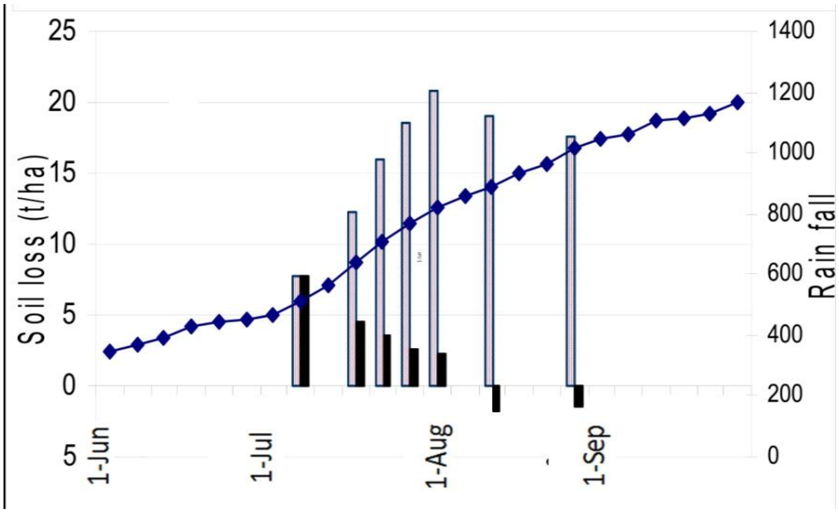

Figure 4: Average soil loss for the 15 upland agricultural fields in the Debre-Mewi watershed, the light shaded columns is the cumulative soil loss for the season. The black boxes are the soil losses for the individual storms; the line with diamonds is the cumulative precipitation for the rainy season.

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.

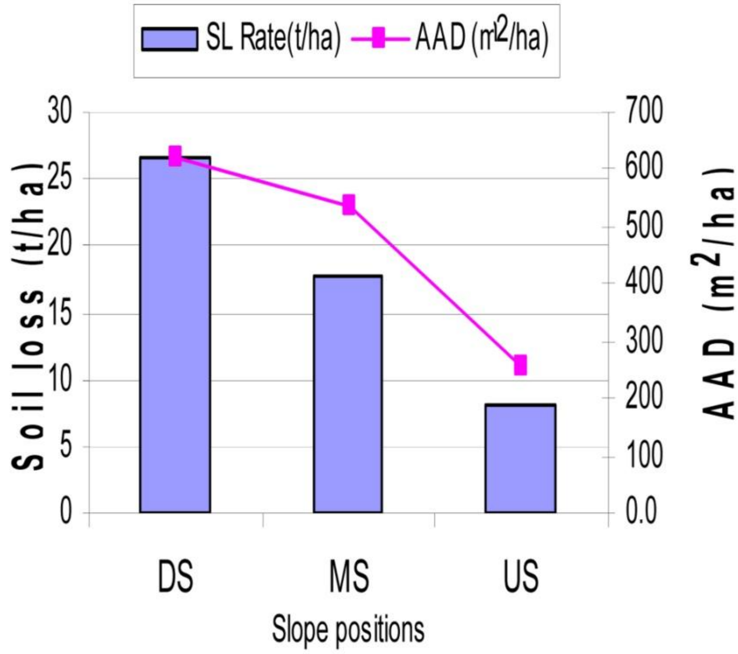

Figure 5: Erosion rate in tons /ha over the growing season as a function of slope position; where DS is down slope, MS is middle slope and US is upper slope. AAD is area actual damaged due to rill formation in m^2/ha.

Comparing the gully and upland erosion rates, 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.

A final question that needs to be answered is 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. 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. 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 groundwater 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

Bewket W. and Geert Sterk, 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

Hagmann Jurgen, 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.

Herweg, K. 1996. Field manual for assessment of current erosion damage. Soil conservation research programme (SCRP), Ethiopia and Centre for Development and Environment (CDE), University of Berne, Switzerland

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 TX . 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.

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