Quantifying rill erosion by surface runoff on cultivated lands at Debre Mewi watershed in West Gojjam

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Abstract

In Ethiopia, rill erosion is commonly observed on agricultural fields with moderate and steep slope gradient conditions. It is considered as a predominant erosion feature that led to severe gullying and land degradation. A field study based on rill erosion survey was conducted at Debre Mewi watershed near Adet Agricultural Research Centre. The objective of the study was to determine the severity and rate of soil erosion and compare the results with erosion results predicted by USLE empirical erosion model. This paper, therefore, presented and discussed the field results of rill erosion processes on 33 surveyed agricultural fields (15 fields in 2008 and 18 fields in 2009). Individual rill dimensions were measured to determine the average rate of rill erosion for each surveyed field. The results from seasonal rill measurements showed that the average rate of erosion from rills and estimated sheet erosion on the surveyed fields (average of four crop types) was 36 t ha^{-1} in 2008 and 60 t ha^{-1} only from tef fields in 2009. Highest rill erosion rates were observed in early July which could be attributed to the higher erosivity of the rain, high erodibility of the soil surface after a warm and dry season, and the low soil cover. It was also found that agricultural fields located on foot slopes of the catchment and fields covered with tef crop were highly susceptible to erosion. Therefore, sustainable soil management practices must be developed to reduce further degradation and restore the productivity of the eroded land.

Key words: Crop cover, rill erosion, slope position, USLE.

Introduction

Debre Mewi watershed is recognized as one of the Ethiopian highlands suffers from severe visible erosion features, such as rills, gullies and concentrated accumulations that often indicate hot spots (parts of an area that are seriously affected by soil erosion). Rills are very shallow channels that are formed by the concentration of surface runoff along depressions or low points in sloping lands. Soil erosion that occurs in areas between rills by the action of raindrops (causing splash erosion) and surface runoff (causing sheet erosion) is called inter-rill erosion causing for about 30 % of soil loss (Gover, 1991; Bewket and Sterk, 2003). Compared to sheet erosion, rill erosion has entirely different characteristics. It removes a considerable amount of topsoil greater than sheet/inter-rill erosion. Through rills, eroded particles are transported quickly over a large distance. Large particles are more effectively transported. Rills differ from gullies in that they are temporary or seasonal features and can be easily destroyed during plowing, whereas gullies are more permanent features in the landscape (Stocking and Murnaghan, 2000). Rills and gullies constitute an “embryonic” drainage system (Mitiku *et al*., 2006), which, if unchecked, will develop eventually in to badlands. This may involve irreversibility of the land to return it back into crop production in agricultural systems that are based on animal-drawn implements for cultivating the land (Mitiku *et al*., 2006).

Without involving expensive instrumentation and sophisticated modeling of soil loss, field surveys of rills may yield more economical (and efficient) solutions in estimating field erosion and identifying severe local erosion areas than the application of the existing generation of erosion models (Herweg, 1996; Bewket and Sterk, 2003). It must also be treated as a means in itself to aid soil conservation (Herweg, 1996) and to inform catchment managers and decision/policy makers where to apply soil conservation. Hence, assessment of soil loss by surveying rill erosion plays a great role for soil and water conservation planning. Therefore, this study was aimed at estimation of the severity and rate of soil erosion in the Debre Mewi watershed. The specific objectives of the study were: To estimate the magnitudes of rill erosion based on crop cover types and slope positions; to compare the estimated rill erosion rates with the predicted erosion results using empirical USLE model; to recommend land management techniques that used to control rill erosion.

Materials and methods

The study area

This paper is based on a rill survey conducted on agricultural fields at Debre Mewi watershed located at 11°20’13’’ N and 37°25’55’’ E during 2008 and 2009. The watershed is located South of Lake Tana about 30 km from Bahir Dar Town, the capital of Amhara Regional State in the Northwestern Ethiopian highlands. The elevation ranges between 1950 and 2309 m above sea level. The total area of the watershed is estimated to be 523 ha. The slope gradient of the watershed ranges from 8 to 30%. The dominant soil types in the watershed based on FAO classification include Nitosols located in the upper part of the watershed covering about 24% of the watershed, Cambisols located in the middle part of the watershed covering about 40% of the watershed and Vertisols located in the lower part of the watershed covering about 21% of the watershed and the other soil type is Fluvisols (15%) mostly located near and along the water bodies of the watershed.

Methodology

To assess and quantify the rill erosion magnitudes, rill erosion survey was conducted on agricultural fields. Fifteen agricultural fields covered by four major crop types (3.56 ha) in 2008 and 18 tef fields (5.38 ha) in 2009 were selected from the 523 ha land of the watershed. These fields are assumed to represent the cultivated slopes of the entire watershed. Rill survey measurements following transects were conducted on four major crop covers (tef, finger millet, wheat and maize) in the first year and one crop type (tef) in the second year along three slope positions in the catchment (upslope, mid-slope and down-slope based on their elevation). During the first year, rill magnitudes were compared across crop cover types and between the three slope positions where as in the second year (2009) rill magnitudes were compared only between the three slope positions: upslope, mid-slope and down-slope fields.

A series of transects across the slope with an average distance of 10 m between two transects was established; positioned one above another to minimize rill measurement errors and marked using sticks and stones (Hudson, 1993) as indicated in Figure 1. Traditional on-farm ditches constructed in the field for safe disposal of water were also used as transects, so that measurements of rills found between two consecutive ditches were undertaken.

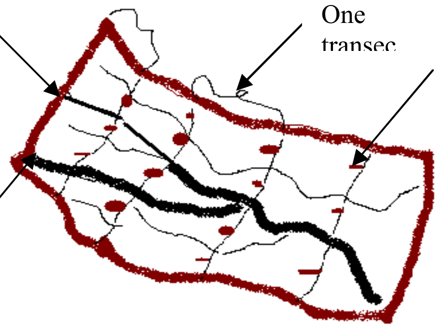

Figure 1. Transects across slope to show how rill dimensions were measured in a cultivated field.

During the months of July and August greatest rainfall amounts causing significant soil loss were recorded. And each survey field was repeatedly visited and measured immediately after rainfall storms had occurred. Rill measurements were not taken until rills were clearly noticed and thus only those rills with width above 25 cm were surveyed. Rill dimensions such as length, width and depth were measured in the surveyed fields. In each field, maximum development of rills, both in number and dimensions, was analyzed in this paper to estimate the total soil loss due to rills. Though continuous rill measurements were taken, their total soil loss rate refers to the maximum rill channel volumes. The eroded soil volumes, rill densities, areas of actual damage and other quantities were calculated from the measured rill dimensions: length, width and depth (Herweg, 1996).

The calculated volume is equivalent to the volume of soil lost from the formation of the rills. The total volume of soil loss from rills was obtained simply by summing the rill volumes (calculating as Length*Width*Depth) of all homogenous rill segments. The eroded soil volume was also expressed in terms of weight of eroded soil by multiplying the calculated volume by the measured bulk density of the soils at each surveyed fields in the site (Hagmann, 1996). The total soil loss was converted into per unit hectare of land to express the annual rate of soil loss after corrected for effective rill damage area. The area of actual damage per unit hectare was obtained from the product of length and width dimensions of each homogenous rill segment. The rill density was calculated by dividing the total rill lengths, obtained by summing up the length measurements of all the rills, by the total area of the surveyed fields. Some simplified formulae used to calculate rill magnitudes are indicated below.

$$X = \frac{\sum (L_i W_i D_i) N_i}{10000 \; A} \qquad AAD = \frac{\sum (L_i W_i) N_i}{100 A} \qquad D = \frac{\sum (L_i) N_i}{A}$$

Where, X is the volume of rills (m^3 ha^{-1}), L_i is the length of a rill (m), W_i is the width of a rill (cm), D_i is the depth of a rill (cm), AAD is the area of actual damage affected by rill erosion (m^2 ha^{-1}), D is the density of rills (m ha^{-1}), A is the field area (ha), and N is the number of rills. X is equivalent to the volume of soil lost due to the formation of rills. The eroded soil volume was also expressed in terms of weight of eroded soil by multiplying X with the soil bulk density of each of the 15 fields.

Parameters including average annual rainfall, slope length, slope gradient, soil color, land cover and management practices were collected in all the surveyed fields. Finally, soil loss was estimated in the surveyed fields using the Universal Soil Loss Equation (USLE) adapted for Ethiopian conditions according to Hurni (1985b) (cited in the guide of watershed management by Ministry of Agriculture (MoA, 2001).

$E = R * K * L * S * C * P$

Where, E is the mean annual soil loss, R is a rainfall erosivity index, K is a soil erodibility index, L is the slope length, S represents slope steepness, C is a crop factor, P is a conservation practice factor. Hence, the amount of soil loss was estimated by this equation and compared with the measured soil loss from rills and sheet erosion.

Results and discussion

Soil loss due to rill erosion

The amount of soil loss due to rills from the total surveyed fields in 2008 and 2009 was found at 26.6 t ha^{-1} and 45 t ha^{-1} respectively (Table 1) given the average soil bulk density of 1.21 g cm^{-3}. During the survey, the contributions of other erosion features were not considered. However, rills are not the only mechanisms for soil erosion; they are always accompanied by impacts of raindrops such as sheet or inter-rill erosion. According to Zachar (1982), rill erosion underestimates 10 to 30% of the actual soil loss. Govers (1991) also reported, as the contribution of inter-rill erosion can be more than 30% of the total soil loss in fields where rills are present. Bewket and Sterk (2003) also assumed 30% of the actual soil loss to calculate the contribution of inter-rill erosion to total soil loss. For this study, it was also assumed that the measured rill erosion rates underestimated soil loss by 25%. Therefore, having this assumption, the annual actual soil loss rates were estimated around 36 t ha^{-1} and 60 t ha^{-1} in 2008 and 2009, respectively.

Table 1. Classification of rills and their contribution in soil loss (2008).

Size of rills	Number of rills			Soil loss (t ha^{-1})			AAD (m^2 ha^{-1})			Rill density (m ha^{-1})		
	US	MS	DS	US	MS	DS	US	MS	DS	US	MS	DS
Small	103	376	865	7	12	24	107	334	610	686	2299	4424
Medium	2	74	94	1	9	11	69	271	274	21	543	522
Large		3			11			363			115	
Total	105	453	959	8	32	35	176	662	885	708	2860	4946

The widths of Small rills (<25cm), medium (25 to 200cm), Large (>200cm), AAD = Area of actual damage, US = upslope, MS = mid-slope, DS = down-slope.

Table 2. Rill erosion magnitudes in 2008 and 2009.

Year	Soil loss (t ha^{-1})				AAD (m^2 ha^{-1})			
	US	MS	DS	Total	US	MS	DS	Total
2008	8	23	35	27	256	662	884	717
2009	35	46	54	46	536	611	594	583

AAD = Area of actual damage US = upslope, MS = mid-slope, DS = down-slope.

This result has direct relationship with the Area of Actual Damage (AAD), the surface area covered by the rills themselves, which covered about 7.2% of the total surveyed areas. This was a significant amount, which lead to the decreasing or shrinking of size of crop producing farmlands. The productivity of the farmlands has also been decreasing due to loss of fine soil material by erosion. This result indicated that the survey area was under a high erosion risk.

Estimation of soil loss using USLE

According to Hurni (1985b), all the USLE parameters were adapted to the Ethiopian situation and corresponding values were described in the MoA watershed management manual (MoA, 2001). Using the adapted USLE the soil loss from the surveyed fields in 2008 and 2009 was predicted to be 39 t ha^{-1} and 43 t ha^{-1}, respectively. The correlation between the two results was 72 and 75% with R^2 value of 0.52 and 0.57, respectively (Table 3). The low R^2 value was due to the fact that there were differences in slope gradient, crop cover type and other factors among the surveyed fields.

Table 3. Comparisons of measured soil loss (SL) value and USLE predicted value in 2008 and 2009 in Debre Mewi watershed.

	2008			2009		
Field number	Field size (ha)	Total SL (rill + sheet) (t ha^{-1})	USLE predicted Soil loss (t ha^{-1})	Field size (ha)	Total SL (rill + sheet) (t ha^{-1})	USLE predicted Soil loss (t ha^{-1})
1	0.27	43.8	34.4	0.26	11.2	20.7
2	0.34	83.7	73.4	0.31	70.3	49.6
3	0.41	40.6	66.4	0.48	21.8	24.8
4	0.24	31.3	69.0	0.21	68.0	44.1
5	0.16	35.6	57.1	0.31	63.6	46.9
6	0.24	36.0	29.9	0.22	82.9	59.5
7	0.23	19.9	23.9	0.17	62.8	49.6
8	0.24	39.1	45.3	0.22	38.4	37.0
9	0.25	36.8	39.2	0.45	63.8	50.3
10	0.19	10.3	18.2	0.45	71.6	41.9
11	0.24	60.7	39.6	0.41	45.7	42.3
12	0.15	23.4	27.2	0.21	80.4	30.1
13	0.19	9.3	19.0	0.26	69.5	37.2
14	0.25	14.4	25.8	0.30	92.8	49.4
15	0.17	7.6	16.8	0.15	82.4	57.9
16				0.46	83.6	59.5
17				0.32	40.4	26.5
18				0.19	68.4	38.6
Mean	3.56	36.1	39.0	5.4	62.1	42.6

The result obtained from the survey indicated that erosion in the study area was severing. As described above soil loss due to rill and sheet/inter-rill erosion, for example, in 2008 was estimated to be 36 t $ha^{-1}yr^{-1}$, which is equivalent to 3.6 mm per year, provided that 1 t ha^{-1} was equivalent to 0.1 mm per year (Morgan, 1996; Tadesse, 2001). According to Basic *et al*. (2004), the erosion risk in the watershed can be estimated by the following formula:
Erosion risk = [Erosion rate] ÷ [Soil loss tolerance]

Assuming the mean soil loss tolerance be 10 t ha^{-1}, which was accepted as appropriate for moderate thickness of soil (Morgan, 1996; Tadesse, 2001), then the soil loss obtained from this study increased by 70% (approximately four fold of soil loss tolerance). This is also greater by 97% to soil formation, assuming the average soil formation worldwide is 0.1 mm per year (the range is from 0.01 to 7.7 mm yr^{-1}) taken from the book of Morgan (1996). According to this assumption, the Debre Mewi watershed can be characterized as high erosion risk area. Taking the top soil depth as 20 cm thick, after 50 years all the top soils with their nutrients that contain organic-rich topsoil, which was used to improve crop production in the watershed, will fall under high risk unless special attention is given to construct appropriate conservation measures to decrease this threat.

Characteristics of rill erosion on different crop cover types

Tef is the dominant cereal crop in the watershed followed by maize, finger millet and wheat. Local farmers sow tef from early July to early August, Finger millet from late may to late June, maize from late April to mid June and wheat in June. This timing has an implication on the contribution of ground cover of the croplands in reducing erosion. Tef and finger millet fields need five to seven times plowing, four times for wheat and barley, and three times for maize.

The result of the study indicated that the number and dimensions of rills were higher on tef. Hence, the erosion rate was exceptionally peak in the field plots covered with tef. From the surveyed mid-slope position fields (where the four crop cover types found), the soil loss rate on tef fields was three times greater than the rate in finger millet and wheat, and twice in maize covered fields. On the other hand, the soil loss rate on tef fields was increased by

70% from finger millet fields, 68% from wheat fields and 40% from maize fields. Soil loss in all crop cover types, except millet and wheat, showed significant difference to each other. In the case of area of actual damage by rills, only tef fields showed significant difference with all surveyed crop cover types ($p<0.01$).

Table 4. Multiple comparisons to show significant differences of soil loss among crop cover types in 2008.

		Soil Erosion (t ha^{-1})		AAD (m^2 ha^{-1})	
(I) CT*	(J) CT	MD (I-J)	Sig.	MD (I-J)	Sig.
Maize	Wheat	6.4*	0.00	51	0.13
	Millet	6.8*	0.00	44	0.23
	Tef	-4.7*	0.02	-340*	0.00
Wheat	Maize	-6.4*	0.00	-51	0.13
	Millet	0.4	0.84	-7	0.84
	Tef	-11*	0.00	-391*	0.00
Millet	Maize	-6.8*	0.00	-44	0.23
	Wheat	-0.4	0.84	7	0.84
	Tef	-11.5*	0.00	-384*	0.00
Tef	Maize	4.7*	0.02	340*	0.00
	Wheat	11*	0.00	391*	0.00
	Millet	11*	0.00	384*	0.00

**CT is crop type, AAD is area of actual damage, MD is mean difference, Sig. is significance (P), * denotes significant difference at P<0.05.*

One reason why tef fields scored this amount of soil loss was that the land was prepared by plowing repeatedly (5-7 times) before sowing. This was because, the farmers believed that it overcomes weeds and gives better crop yields. This number of plowing resulted the soil on tef fields becomes loose, poor in structure and hence more susceptible to soil erosion. The other reason was that the period of land preparation for tef is during high rainfall season, which increased the vulnerability of the land for erosion.

Furthermore, it should be considered as one reason that the activities practiced to decrease the roughness of tef fields while sowing. From field observation and personal interview, the well prepared rough surface of tef field due to repeated plowing was trampled by animals (mostly by farm animals and donkeys) just before sowing. This activity is also common on finger millet fields except, in this field, the activity is done twice just before and after sowing. This was because the farmers believed that unless it is packed and compacted enough, the crop would dry before the expected crop calendar. Moreover, as it was observed during the survey, the root of tef crop was neither strong nor deep enough to protect the soil from high surface runoff. According to Hurni (1985a), the annual average crop cover factor (C-factor) of the Universal Soil Loss Equation (USLE) is 0.25 for Ethiopian tef field and others have less than this value. All the above reasons confirmed that tef fields were very susceptible for soil erosion process compared to other crop cover types.

In finger millet crop lands, at the beginning of rill survey the numerous very-shallow rills were observed. However, after one month (up to the middle of August) almost all rills were disappeared. This might be because of the redistribution of sediments as the rill dimensions were very small due to highly compacted area by animals. The highly dense cover effect of finger millet was also another major factor to the disappearance of rills.

Rill erosion hardly exists in wheat field since the surface, before and after sowing, was rough. This increases infiltration, which in turn decreases runoff that was considered to be the major source of rills and sheet erosion in the area. The growth cover of wheat was faster than other surveyed crop covers before the roughness became smooth due to high rainfall and runoff sealing effect. Soil loss rate in maize crop fields was also higher next to tef fields. This may be due to scattered and sparse plantation and may be the plant area coverage was slowly increased. At weeding time, the maize cover again decreases until the leaves become dense to decrease the rainfall erosivity by the interception process.

Characteristics of rill erosion on different slope positions

Rill erosion is the most visible mechanism of soil loss from sloping cultivated land (Herweg, 1996). The results of the ANOVA indicated that the soil loss from rills, the area of actual damage and rill density were significantly different among the three slope positions ($p = 0.0008$, $p = 0.0001$, $p = 0.0004$) at 5% probability level. Since all surveyed fields were cultivated with the same crop type (tef), the rate of erosion in the down-slope fields was increased by 15% from that of mid-slope fields and by 35% from that of the upper slope fields.

Table 5. Rill erosion magnitude on tef fields at three different slope positions in 2009.

Slope positions	Soil Loss (t ha^{-1})	AAD (m^2 ha^{-1})	RD (m ha^{-1})
Down slope	54^{a*}	594^{a}	19434^{a}
Mid-slope	46^{b}	611^{a}	17555^{b}
Upslope	35^{c}	536^{b}	11446^{c}

*AAD = area of actual damage, RD = rill density. *Means in a column followed by similar letters are not significantly different at P<0.05.*

The mid slope fields scored relatively higher area of damage (Table 5). This was because all of the rills occurred in this position are found and classified as large that were caused by surface runoff coming from the upland fields. In down-slope fields, most of the rills were initiated within fields. Hence, the widths of rills were smaller compared to the mid-slope tef fields.

The slope lengths in the down and mid-slope fields showed significant difference with upslope fields'. Statistically, no significant difference of slope length and slope gradient was observed between down slope and mid-slope fields, and between mid- and upslope fields, respectively. However, the slope gradient in the down slope fields showed significant difference with the mid- and upslope fields. Hence, the average critical distances, the length from the upper field boundary to the place where the rills began, were a bit longer than the fields in the down-slope field positions as the slope gradient of mid-slope fields was less than down-slope fields. This slope distance influenced the length of the rills in the fields.

Conclusions and Recommendations

Land in the Debre Mewi watershed suffers from severe erosion. Gullies and their effects are increasing at alarming rate and threatening the watershed inhabitants. Basic natural resources like soil, water and vegetative cover in the watershed are deteriorating. Based on field observations, the intensity of the rainfall coupled with poor vegetation cover has aggravated the soil erosion in the watershed. Hence, crop production and soil productivity have been decreasing overtime. So far, farmers hardly undertake action to reduce erosion. Only few soil conservation structures accompanied with poor management practices at household level were observed during the field survey. If nothing is done to correct the existing situation of the area, the adverse effect of erosion will jeopardize the efforts of the community and in the near future, the farmers will remain with severely degraded lands.

Therefore, sustainable soil and land management practices must be developed to reduce further degradation and restore the productivity of the eroded land. The management options to reduce soil erosion are to implement effective and efficient soil conservation measures and/or to change the cropping system from inappropriate to more sustainable and appropriate farming practices. Soil conservation measures including terraces and bunds as well as semi-permeable structures like grass strips are used as barriers to holdback runoff and the sediment carried with it. Agronomic measures like contour plowing have the advantage to reduce runoff and soil loss. Changing to cropping systems that need less tillage and improve the soil structure can reduce the problem of erosion. Especially the soil conservation designers should find a mechanism in such a way that farmer can plant tef to get high profit while its contribution to erosion should be minimized. Traditional ditches are not recommended as an important option to conserve soil. Moreover, extension workers and land use planners can use the rill survey method to assess and quantify soil loss and identify erosion risk areas at field level in a simple way and shortest time, and then after to plan effective and site dependent soil and water conservation measures.

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