Investigating long year gully erosion and its impacts on soil loss, land competition and crop yield reduction, north-west Ethoipia

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Abstract

This paper investigated the rate of gully formation and development, and its impacts on land competition and crop yield reduction in the Genbo Wonz Watershed, north-west highlands of Ethiopia. Geometrical gully dimension measurements, field observations and satellite imagery assessment have been performed selecting 22 gullies. As a result, road construction and design problems of soil and water conservation practices (SWCPs) were found to be important causes of gully formation and development. The total volume of soil loss from 22 gullies in three decades was ˜340, 957 t, changing ˜10 ha agricultural land to unproductive land. The annual rate of gully erosion was found to be ˜62 t ha-1 with an average gully density of 16.4 m ha-1. Gully erosion also results in loss of 24 t yr-1 Teff grain yield (Eragrostis teff, E. abysainica) and 14 t yr-1 animals forage. To arrest the problem, proper design of SWCPs within farmlands, appropriate runoff discharge mechanisms along roads and controlled grazing systems within the grazing lands ought to be executed.

Keywords: *Long Term Gully Erosion; Gully Density; Land Loss; Yield Loss; Satellite Imagery*

1.1 Introduction

Gully erosion is one of the major global problems confronting agricultural production. Although the problem is as old as the agricultural practices, its extent and adverse impact on crop production, land competition, groundwater depletion, etc. are getting worse year after year. In Africa ˜29 million ha of land was affected by gully erosion (Hurni et al., 2010) and productivity of agricultural lands had significantly declined (Osore & Moges, 2014; Mekonnen *et al.* , 2015; Rijkee, *et al* ., 2015; Mukai, 2017).

Gully erosion is the most prevalent form of soil erosion in Ethiopia, which dissects farmlands, impedes tillage operations, damaged agricultural and residential areas, and restricts the free movement of animals and humans (Daba *et al.,* 2003*;* Moges & Holden, 2008; Bewket & Teferi, 2009; Mekonnen et al., 2015). In the Ethiopian highlands, gullies covered ˜7.6 million ha (Poesen*et al.,* 2006; Frankl *et al* ., 2012) which severely affected soil productivity, reduced land size, damaged roads, and buildings (Daba et al., 2003; Avni, 2005; Nyssen et al., 2006; Rijkee et al., 2015), specifically estimated gully surface area coverage as 1.7 million m^2 over 30 years in the eastern highlands of Ethiopia. The rate of gully erosion was reported as 6.2 t ha^{-1} y^{-1} for northern Ethiopia (Nyssen et al., 2006) and the annual volume/mass of soil eroded only from four gullies was 1941.3 m^3 (2717.8 t) in the north-west highlands of Ethiopia(Mekonnen *et al.,* 2017).

In the north-west highlands of Ethiopia, gully erosion has also been identified as a major source of sediment for man-made reservoirs and natural lakes, which affects the water holding capacity of such water reservoirs and hence agricultural productivity by reducing irrigation water availability (Mekonnen *et al.,* 2017) and it significantly reduces both grazing lands (Tebebu et al., 2010; Mekonnen *et al* ., 2015), effective soil depth and groundwater availability thus hindering the free movement of moisture within the soil system (Moges &

Holden, 2007) and the sizes of farmlands (Poesen et al., 2003; Mekonnen & Melesse, 2011; Yitbarek *et al* ., 2012).

As part of the north-west highlands of Ethiopia, in this study area, Genbo Wonz watershed gully erosion is a priority problem and there was no study conducted to investigate the cause, rate of expansion and its impacts on crop production, except the district agricultural office reports explaining the severity (YDARDO, 2015). Since the causes of gully erosion are site-specific, many researchers recommended site-specific investigation on the causes of gully formation and development, its impacts in reducing agricultural lands and crop production(Tebebu et al., 2010; Zegeye, *et al* ., 2014; M. Mekonnen et al., 2015; Rijkee et al., 2015). Moreover, YDARDO (2015) reported the necessity of clear causal investigation to implement that could help to implement appropriate cause-based interventions. Therefore, the objectives of this study at Genbo Wonz watershed in the northwest highlands of Ethiopia were to; (i) identify site-specific real causes of gully formation and development for appropriate cause-based intervention planning and treatments; (ii) estimate long-term soil loss because of gully erosion, (iii) quantify land loss resulting from gully erosion and assess its adverse impact on crop production.

2.1 Materials and methods

2.1.1 Study area

The study was conducted in Genbo Winze watershed, north-west highlands of Ethiopia. Geographically, it is located between 113025 and 111430 m N latitudes and 373128 and 373036 m E longitudes, Adindan_UTM_-Zone_37N (Figure 1). The study watershed covers an area of 553.7 ha with an elevation ranging between 2198 m at the outlet and 2316 m at its highest point on the watershed divide. The mean annual rainfall of the area was 1500 mm, which falls mainly from June to September, and the average minimum and maximum daily temperatures were 9.4°C and 24.6^{0}C, respectively (YDARDO, 2015). The dominant soil type in the watershed was Nitsols with a soil depth of greater than 1 m (MNREP, 1995).

Land use/cover of Genbo Wonze watershed includes cultivated land (81%), grazing land (9%) and the remaining 10% was mainly covered by eucalyptus trees, a small village, and roads. Land preparation was performed with the traditional Marsha pulled by a pair of oxen. The indigenous crop, Teff (*Eragrostis teff, E. abyssinica*) was the major crop grown in the study watershed during the main rainy season (June to September). Both asphalt and gravel road, and footpaths available in the watershed (Figure 1).

2.1.2 Materials and input datasets

A topographic map 1:50,000 scales (EMA, 1987) were used to delineate the boundary of the study watershed. ArcGIS 10.3 software was used for mapping and a GPS (Garmin 60, ˜2 m accuracy) was used to collect the outlet point of the watershed and gully locations. Satellite imageries were used to estimate the past and the current surface area coverage of the studied 22 gullies and to quantify the changes in gully dimensions. To measure the current annual development rate of gullies, one-year gully expansion measurement was done from eight gullies (i.e. three gullies on cultivated land, two gullies on grazing land and three gullies on both cultivated and grazing land) before and after the rainy season of the year 2017. Hand meter was used to measure gully geometrical dimensions (gully length, width, and depth). Erosion pins were installed around the studied gullies before the rainy season and the annual rate of expansion was determined after the rainy season calculating the difference in dimensions.

2.1.3 Field measurement

Gully cross-sectional geometry was surveyed by dividing the cross-section into trapezoidal segments at abrupt changes in gully banks and then measuring the width and depth of the gully at each segment (Figure 2).

To calculate the cross-sectional area (A), the surface area occupied by gullies (S), the volume of soil loss (V), dry mass of soil loss (Dm), gully density (Gd) and long term gully erosion (LTGE), Eq.1; Eq.2; Eq.3; Eq.4; Eq.5 and Eq.6 were used, respectively (Tebebu *etal* ., 2010; Gebreslassie *et al.,* 2014; Zegeye *et al.,* 2014; M. Mekonnen *et al* ., 2015).

The gully cross-sectional area (A; m^2) and the total surface area (S; m^2) occupied by gullies were calculated using Eq.1 and Eq.2, respectively. The volume of soil loss over the monitoring period was obtained by Eq.3. The dry mass of soil loss was calculated by multiplying the volume of soil loss with the average bulk density of the soils (Eq.4). Gully density (m; ha^{-1}) was calculated dividing gully length by watershed area using Eq.5.

A= $1/2 \sum_{i-1}^{N-1} (wi * hi + 1 - wi + 1 * hi)$..Eq. 1

Where A is the cross-sectional area of the gully; i is a trapezoidal segment index; w is gully cross-section width; h is the height of gully; N is the number of trapezoidal segment sides of height hi and located a distance w from the gully edge in a cross-section (Figure 3).

The total surface area occupied by gullies was calculated using Eq.2:

$S = \sum_{j-1}^{N-1} \quad Lj(\frac{(wj+wj+1)}{2})$..Eq. 2

Where S is the surface area of the gully; j is cross-sectional width index; w is cross-sectional width; N is the number of cross-sections; L is the length of the gully section between cross-sections j and j+1.

The total volume of soil loss was calculated using Eq. 3:

$V=\Sigma_{j-1}{}^{N-1} L_j(\frac{(Aj+Aj+1)}{2})$...Eq. 3

Where V is the volume of soil loss; j is the cross-sectional width index; A_j is the cross-sectional area of the gully at j; A_{j+1} is the cross-sectional area of the gully at j+1, and L_j is the length of the gully between A_j and A_{j+1}.

The dry mass (Dm) of soil loss was calculated using Eq.4:

Dm = V*Bd...Eq.4

Where Dm is the dry soil mass; V is the volume of soil loss; BD is soil bulk density.

Gd = L/A...Eq.5

Where Gd is gully density; L is the length of the gully, and A is an area of the watershed.

The historical gullies' surface dimension was delineated using Google Earth Imagery and aerial photograph to quantify gully surface area coverage and assess changes. Since gully volume can't be obtained from the Google Earth Imagery/ aerial photograph, it was derived from the digitized gully surface area through a regression of the surface area measurements of gullies (Eq.8).

$V = 0.54S^{1.226}$...Eq.6

TSL =Vend*Bd - Vstart*Bd/ (Yend-Ystart)*A) Eq.7

Where V (m^3) is the volume of gully /soil loss; S is the gully surface area (m^2) obtained from Google Earth/ aerial photograph; TSL is total soil loss ($ha^{-1}yr^{-1}$); Vend is the volume of gully calculated at the end of the investigation year (2017); Vstart is the volume of gully calculated at the beginning of the investigation year (2007); Bd is Bulk density, and A is an area of the watershed; Yend is the final year of investigation (the year 2017) and Ystart is the starting year of investigation (the year 2007).

2.1.4 Crop yield loss calculation

The total loss of crop production in the watershed was calculated by multiplying the total surface area coverage of the gully (area of land devoid of production because of gully erosion) and the productivity of the Teff crop. To find the main causes of gully formation and development frequent field visits and observation during the 2017 rainy season, interview with farmers working in their fields using transect walks and discussion with development agents (DA) working with farmers in the watershed long years have been conducted.

2.1.5 Dry soil mass and bulk density calculation

To calculate the dry soil mass lost from volumetric measurements, soil density was required. Hence, soil samples were collected. The first sample was taken 50 cm below the edge of the gully, the second sample was taken at the middle and the third at 50 cm above the gully bed using cylindrical core sampler. The collected samples were oven-dried at 105^0C in the laboratory and density was calculated weighing the dried sediment and subtracting it from the wet sediment mass.

3.1 Results and discussion

3.1.1 Causes of gully formation and development

In the study area, construction of gravel and asphalt roads, footpaths, concentrated surface runoff from farmlands, overgrazing and improper design of soil and water conservation practices were found to be the causes of gully erosion (formation and development). However, the main asphalt and gravel roads passing through the study watershed were found to be the major causes for the formation and development of gullies (Figure 3), which is in line with many research findings, for instance: Montgomery *et al.* (1994); Wemple *et al* . (1996); *et al* . (1996) *and* Moyerson *et al.* (2000). In the highlands of Ethiopia, Birhane and Mekonen (2009); Rijkee *et al* . (2015) and Mekonnen *et al.* (2015) also reported that construction of roads and footpaths have a major role on the formation and development of gullies. Hence, an appropriate runoff discharge mechanism following roadsides that means stone-pave drainage lines along the roads should be constructed to arrest the problem.

Concentrated surface runoff from farmlands and inappropriately designed soil conservation practices (SWCPs), were found to be the second important causes for gully formation and development, which agreed well with different research results conducted in the northwest highlands of Ethiopia, for example; at Debre Mewi watershed (Tibebu *et al.,*2010; Mekonnen and Melesse, 2011; Zegeye *et al.* 2014) and Minizr catchment (Mekonnen *et al.,* 2017). Concentrated surface runoff from farmlands was also an important cause of gully formation and development in the southern part of Ethiopia (Gebreslassie *et al.,* 2014). After their formation gullies serve as soil/sediment transfer pathways and increase runoff connectivity between upstream and downstream parts of the watershed (Mekonnen *et al.,* 2017). Therefore, implementing properly designed SWCPs within fields that can reduce the energy of concentrated surface runoff and can increase water infiltration in the run-on area of gully head watershed is highly important. Constructing check dams that might reduce runoff concentration and disconnect the runoff transfer role of gullies will also be another important solution as recommended by Mekonnen *et al* (2017) in the northwest highlands of Ethiopia. Moreover, institutional integration is vital that means the road construction authority and ministry of agriculture have to work together. Principally, the road construction authority should construct stone-faced runoff discharging waterways along roads during road construction to discharge the excess runoff collected following roadsides, and the ministry of agriculture will construct check dams within the developed gullies and implement SWCPs within fields, which will enhance water infiltration and reduce surface runoff concentration.

3.1.2. Land use and gully characteristics

Table 1 shows the gully characteristics of different land use/cover types. From the twenty-two gullies formed within the study watershed, three (13.6%) were formed on grazing land, fourteen (63.6%) were formed on cultivated lands and five (22.7%) were formed on both cultivated and grazing lands. Longer and deeper gullies were found on the cultivated lands. The most probable reason will be the nature of the soil that soils in farmlands were deep and can be easily eroded with runoff water at greater depth. From the total length of the investigated gullies, 70,523.89 m (74%) was found on the cultivated lands while 30,224.6 m (26%) was on the grazing lands. The average width of gullies in cultivated and grazing lands was 7.4 m and 9.4 m, respectively. Gully density was found to be 45.3 m ha^{-1} on grazing lands and 15.2 m ha^{-1} on cultivated lands. Higher gully density was found on grazing lands than on cultivated land, which was because of the lower area coverage of grazing lands than cultivated lands. Similarly, Belay & Bewket (2013) reported that a large percentage of gullies were located on cultivated and grazing lands.

Almost all of the gullies in grazing land were discontinuous (not actively expanding) because of treatments like area closure and grass plantation, whereas ~70% of the gullies found in cultivated lands were continuous which means gully depth, width and length were increasing in every direction. One important cause for the continuous development of gullies in cultivated lands was that gullies were serving as runoff discharging drainage channels or runoff transfer pathways coming from cultivated land. Farmers' are leading the runoff from their cultivated land into gullies considering gullies as waterways. Therefore, properly designed waterways within the cultivated lands are essential that will carry and transfer the runoff from cultivated lands to appropriate drainage channels like permanent rivers.

3.1.3. Gully surface area and gully to area ratio

The total length of the 22 gullies was 9,093 m. The longest gully length was 1,299 m and the shortest was 76 m with the mean length of 413 m, which was very long compared with previous findings in Ethiopia. For example, the longest and shortest gullies reported by Osore & Moges (2014) in Alalicha watershed, southern Ethiopia was 427.4 m and 108 m, respectively.

The total surface area occupied by gullies was 100,748.5 m^2 (~ 10 ha). This means gully erosion in the area is competing for productive agricultural lands by reducing the farmers' land size quantitatively. Different studies found that gully erosion is reducing the size of agricultural lands significantly in different parts of Ethiopia. For example, in the northwest highlands of Ethiopia Tibebu *et al (* 2010) found ~17.4 ha land loss at Debre Mewi watershed. In the southern part of Ethiopia, Belay and Bewket (2012) reported ~4.7 ha land loss at Bora watershed, Osore & Moges (2014) reported ~2.6 ha land loss in Alalicha watershed. Gully to watershed area ratio was found to be 0.02, which means for every 1000 units of land ~20 units of land was damaged by gully erosion and becoming out of production in the watershed. In the Kilie catchment central highlands of Ethiopia, Woldegiorgis *et al.* (2007) found 0.136.

3.1.4. Gully density and category

Gully density, total gully length divided by watershed area, was found to be 17.2 m ha^{-1}, which implies that the watershed was severely degraded because gully density between 10 and 25 m ha^{-1} was categorized as severely degraded (Valentin et al., 2005). Gully density reported by (Gebreslassie et al., 2014) in Huluka watershed, central rift valley of Ethiopia, was 16.1 m ha^{-1}, which agreed well with the finding of this study. In the northern highlands of Ethiopia, different studies found different results, for example; Osore & Moges (2014) found 8.9 m ha^{-1} in Alalicha watershed, and Belay and Bewket (2013) found 6.7 m ha^{-1} in Bonda watershed, and Tarekegn *et al.* (2010) found 67 m ha^{-1} in Kilie catchment, central highlands of Ethiopia.

Pathak *et al.* (2006) and Sargeant *et al* . (1984) classified gullies as small (< 1 m), medium (1-5 m) and large (> 5m) based on depth, and small (<5 m), medium (5-10 m) and large (>10 m) based on length. In this study, in terms of depth 91% of the investigated gullies were medium and 9% were large, and in terms of length, all gullies were under the large category.

3.1.5. Rate of gully development

Based on the measurement of eight gullies in the year 2017 rainy season (June to September 2017), average gully depth was 3.26 m and 3.59 m before and after the rainy season respectively, and gully width was 12.18 m and 12.68 m before and after the rainy season, respectively (Table 2). Within a rainy season, gully depth increased by 0.33 m and gully width increased by 0.5 m.

Figure 4 shows gully depth and width before and after the rainy season and Figure 5 shows the relationship between gully depth and width expansions. Gully depth increment and gully width expansion showed a positive correlation using a linear model. That means as gully depth increases, and gully width also increases (Figure 4) with a correlation coefficient of 0.88 (Figure 5). Gully length, surface area, and volume showed, respectively, 64 m, 2727 m2 and 23,553 m^3 increment in a rainy season (Table 5).

3.1.6. Soil loss and land competition

In four decades (~40 years) the volume of soil loss from 22 gullies was 235,532 m^3 or 340,956.7 t with surface area coverage of ~100,748.5 m^2 or ~10 ha. Within a rainy season from the investigated eight gullies, ~23,553 m^3 or 34,387.4 t soil was lost with an average bulk density of 1.46 g cm^{-3} that means bulk density was found to be 1.34 g cm^{-3} (upper), 1.46 g cm^{-3} (middle) and 1.57 g cm^{-3} (lower) parts of the gully depth. The result shows that ~10 ha of productive land was lost. Loss of land and reduction of crop production were found as the major impacts of gully erosion (Desta et al., 2012; Yitbarek et al., 2012).

The rate of gully erosion was found to be ~62 t ha^{-1} yr^{-1}. Different studies found different results, for example, in the semi-arid rift valley of Ethiopia, (Mukai, 2017) found 16·2 t ha $^{-1}yr^{-1}$; in Debre Mewi watershed, northwest highlands of Ethiopia Tibebu et al. *(* 2010) found 530 t $ha^{-1}yr^{-1}$, and Nyssen et al. (2006) reported 6.2 t ha^{-1} yr^{-1}. According to Zegeye et al. *(* 2014), in Debre Mewi watershed, northwest highlands of Ethiopia, the rate of gully erosion was 127 t ha $^{-1}yr^{-1}$. In Alalicha watershed, southern Ethiopia Osore and Moges *(* 2014) reported ~2.12 t ha^{-1} yr^{-1}. All the above study results show that the rate of gully erosion was different, which will be due to the difference in land use/cover, rainfall, soil type, etc.

3.1.7. Impact of gully erosion on crop production

The main crop grown in the study watershed was the native crop Teff (*Eragrostis teff, E. abyssinica*) with a productivity of 2400 kg ha^{-1}. Taking into account this productivity and the area lost (10 ha) due to gully erosion, on average ~24,000 kg of Teff grain yield was being lost annually. The total grazing land lost was 30,225 m^2 and ~14 t animals feed (grass) was lost annually with an average animal forage productivity of 4.5 t ha^{-1}. In the Dangila district, northwestern highlands of Ethiopia, Belay, and Bewket (2012) reported that 46,265 m^2 lands were damaged due to gullies, from this, 1,401 m^2 was cropland showing 502 kg of crop yield reduction annually. In Alalicha watershed, southern Ethiopia ~25,761 m^2 land was a loss due to gullies (Osore and Moges 2014). Such research results indicated that gully erosion is significantly reducing the limited resource that is land and farmers' income in Ethiopia.

3.1.8. Treatment practices

Gully erosion is becoming a priority agenda in Ethiopia. It is damaging all resources available on land and hence affecting human existence. Based on this study, the investigators recommended possible preventive and remedial measures as follows: (i) Institutional integration-ministry of road construction and agriculture should work together. During constructing roads the ministry of road construction is not bothering about soil erosion/gully erosion occurring because of road construction and it is pushing the responsibility to the ministry of agriculture. Hence their integration is vital; (ii) technical standards of soil and water conservation practices (SWCP) - experts/ professionals should properly put the design/ layout of SWCP since inappropriate designs are leading to surface runoff concentration and hence formation and development of gullies; (iii) immediate action – immediate actions like removing the young gully at its rill stage through plowing is a best remedial measure; (iv) constructing check dams - for large and deep gullies, constructing check dams combining with vegetative practices will help to rehabilitate the gully or at least it helps to stop its development (Mekonnen et al. 2015).

4.1. Conclusion

In this study, even though construction of gravel and asphalt roads, footpaths, concentrated surface runoff, overgrazing and inappropriate design of soil and water conservation practices were the causes of gully formation and development, road construction (both gravel and asphalt) and concentrated surface runoff from farmlands were found to be the main causes. Most of the gullies located in farmlands were active (expanding in all directions/dimensions) compared with the gullies located in grazing lands. Gully formation and development was different for different land use/cover type, which was serious on farmlands than grazing lands.

Gully erosion also played an important role in soil and land losses. About 340, 956.7 t of soil was lost and ~10 ha of land damaged (became out of production). The annual rate of soil loss due to gully erosion was found to be 62 t ha^{-1} with an average gully density of 16.4 m ha^{-1}. Gully erosion also greatly reduced crop production (Teff grain yield) and livestock forage due to land competition. Farmers are losing ˜24,000 kg Teff grain yield and ˜14 t animals' forage annually.

Gully erosion is competing for the agricultural land, reducing farmers' income affecting crop production and animals forge in the study area. Therefore, properly designed biological and physical soil and water conservation practices, maintenance of roads and properly diverting runoff generated along the roads to nearby natural waterways were found to be possible solutions to rehabilitate the developed gullies and protect new gully formation.

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Table1: Shows the characteristics of the investigated 22 gullies on different land use/cover types at Genbo Wonz watershed, north-west highlands of Ethiopia from 1977 to 2017

Gully characteristics and dimensions.	*Gully characteristics and dimensions.*	Land-use type Farmland	Land-use type Grazing land
Total area covered of gullies, m^2	100,748.5	70,523.89	30,224.6
Total gully volume, m^3	233,532	175,149	58,383
Total gully length, m	9,093.4	6836.5	2,257
Runoff contributing watershed, ha	553.7	448.5	49.8
Average gully depth, m	3.6	3.66	3.21
Average gully width, m	8.22	7.4	9.4
Gully density, m/ha	16.4	15.24	45.3
Gully to area ratio	0.02	0.016	0.06

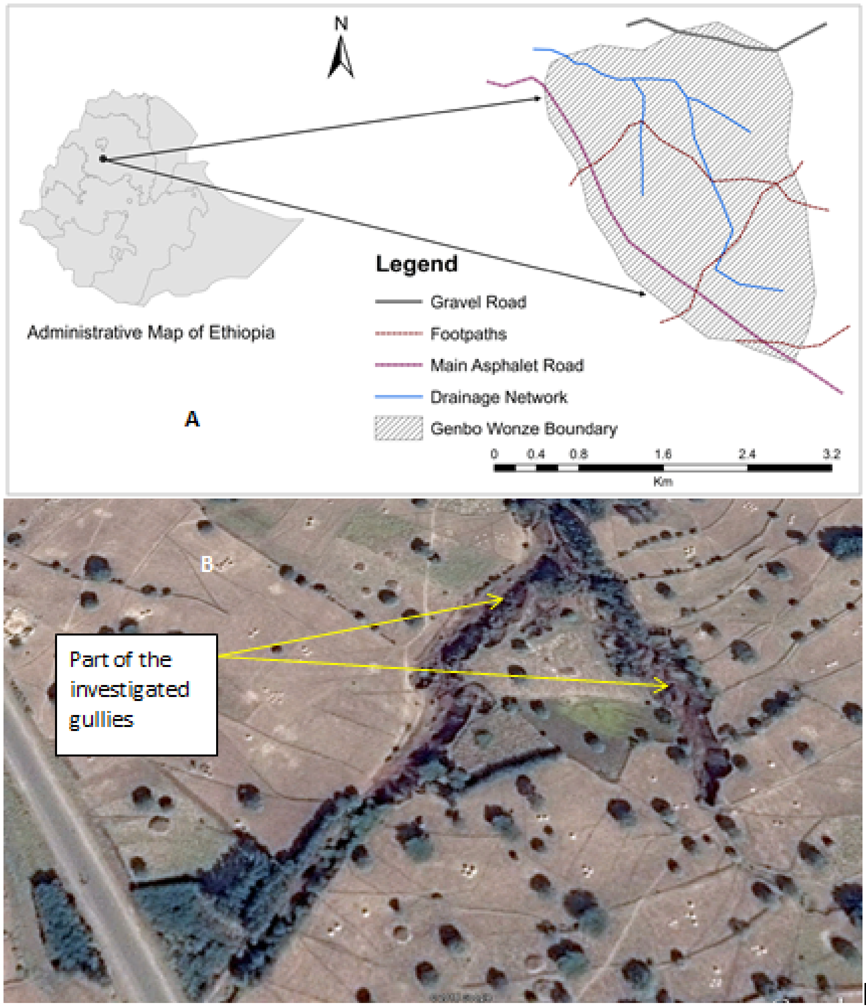
Table 2: Average depth and width of the eight investigated gullies before and after the rainy season in 2017

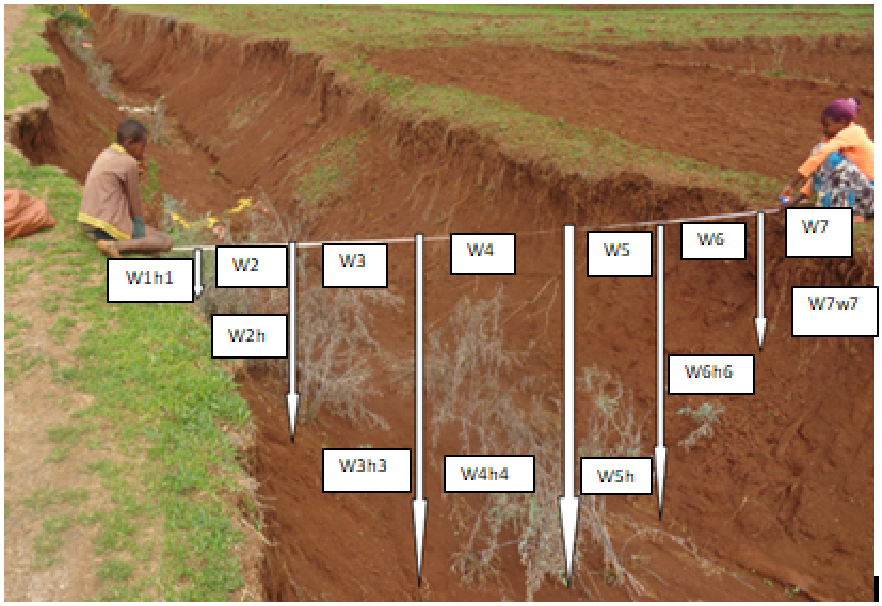
Gullies	Gully depth, m Before rainy season	Gully depth, m After rainy season	Difference	Gully width, m Before rainy season	Gully width, m After rainy season	Difference
G1	4.2	4.6	0.4	13.7	14.4	0.7
G2	7.9	8.7	0.8	21.5	22.4	0.9
G3	1.5	1.7	0.2	4	4.3	0.3
G4	1.4	1.6	0.2	3.6	3.86	0.26
G5	2.5	2.6	0.1	8.5	8.53	0.03
G6	3.3	4	0.7	18.55	19.8	1.25
G7	3.1	3.2	0.1	17.1	17.2	0.1
G8	2.2	2.3	0.1	10.5	10.7	0.2
Average	3.26	3.59	0.33	12.18	12.65	0.5

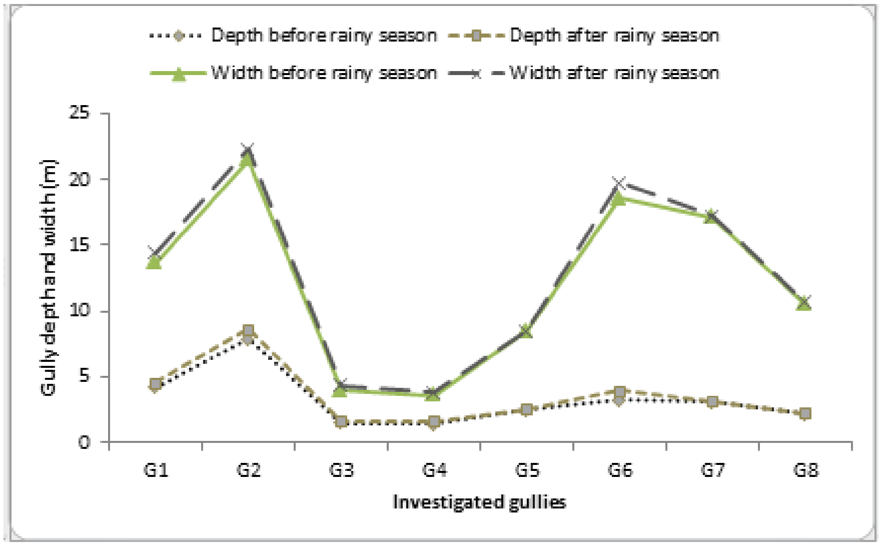
Table 5: Length, surface area coverage and volume of the investigated eight gullies before and after the rainy season in 2017

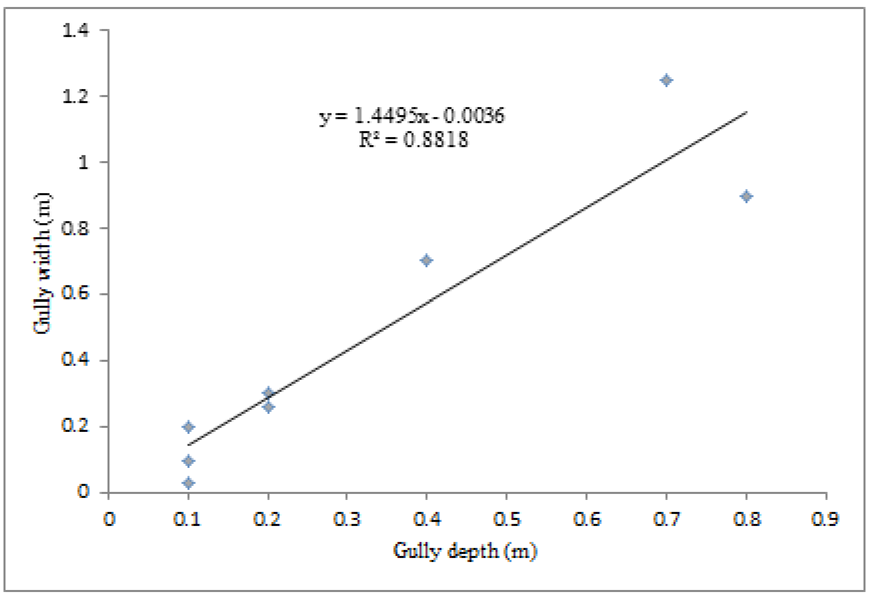
Gullies	Gully length (m) before rainy season	Gully length (m) after rainy season	change	Gully area (m^2) before rainy season	Gully area (m^2) after rainy season	change	Gully volume (m^3) before rainy season	Gully volume (m^3) after rainy season	Gu vol (m cha
G1	1275	1299.2	24.2	18161	18983	822	48027.7	53390.7	53
G2	167	171	4	3815	4004.9	189.9	18158.6	19636.7	14
G3	410.5	412.6	2.1	1679	1816.6	137.6	1933	2252.59	31
G4	697.6	700.8	3.2	2447	2626.5	179.5	2767.94	3018.48	25
G5	1054	1065.4	11.4	9088	9404.6	316.6	13169.3	14184.5	10

G6	370.5	381.8	11.3	6486	7078.7	592.7	14423.7	17380.5	295
G7	949	953.6	4.6	16617	16814	197	34351.6	35072.8	72
G8	1240	1243.5	3.5	13099	13391	292	18734.2	30183	11
Total	6163.6	6227.9	64.3	71392	74119	2727.2	151566	175119.3	235
Av	770.5	778.5	8.04	8924	9264.9	340.9	18945.8	21889.9	165




W1h1
W2
W2h
W3
W3h3
W4
W4h4
W5
W5h
W6
W6h6
W7
W7w7


Depth before rainy season
Depth after rainy season
Width before rainy season
Width after rainy season
Gully depth and width (m)
25
20
15
10
5
0
G1
G2
G3
G4
G5
G6
G7
G8
Investigated gullies


y = 1.4495x - 0.0036
R² = 0.8818
Gully width (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Gully depth (m)