Research Article

Gully controlling practices associated with soil geotechnical properties in the subhumid Ethiopian highlands

Meseret B. Addisie1*, Hailu M. Wassie1,2
1 Guna Tana Integrated Field Research and Development Center, Debre Tabor University, Ethiopia
2 Department of Natural Resources Management, Debre Tabor University, Debre Tabor, Ethiopia
*corresponding author: meseret.belachew21@gmail.com

Abstract

Check dams are business as usual practices used to avert gully erosion development and sedimentation in the downstream areas of the humid highlands of Ethiopia. We investigated the status of check dams and their relationship with geotechnical soil properties in the sub-humid Fogera floodplain. The density of gullies in the area was more sever having about 3.6 km km$^{-2}$ which shows the severity of gully erosion. Thirty-two dams constructed and monitored over one rainy season. In the beginning of the rainy season, all the dams filled up with sediments, and at the end of the monitoring period ninety five percent of them had destroyed and the remainings had partially destroyed and had sediments accumulated on one side of the gully bank. The longitudinal gradient of streams above the dams decreased due to sedimentation. The morphological change of the gully showed an increase in width-depth ratio, gully bank erosion, and sediment aggradation in the gully bed. We found that the amount of sediments deposited behind the dams were higher than the amount of eroded material. The higher clay content and Atterberg limits increased soil erodibility once the gully channel formed. The erodibility and saturation in these soils were highly contributing to gully development and reducing the effectiveness of check dams. In conclusion, it is better to adopt an integrated novel practice to control gullying than solely using check dams.

Keywords: erosion control measures geotechnical properties gully development soil erosion by water

Introduction

Gully erosion is the incision of the valley sides and beds by the erosive power of concentrated runoff. The incision and the development of gully networks in the landscape increase hydrologic connectivity and transport runoff and sediments downhill (Zegeye et al., 2018; Wang et al., 2019). According to Poesen et al. (2002), gullies contribute about 50 to 80% of the overall sediment production at the catchment outlet. Valentine et al. (2005) showed that most sediments in reservoirs might come from gully erosion. According to Tebebu et al. (2010), the 530 t ha$^{-1}$ year$^{-1}$ erosion rate produced from gully erosion in a 17.4 ha Debre-Mawi catchment. In addition, Nyssen et al. (2008) estimated that gully erosion accounted for 28% of the total soil loss in the semi-arid Tigray region, northern Ethiopia and gully sediment contribution reached up to 90% in the humid highlands of Ethiopia (Zegeye et al., 2018). Gullies in the sub-humid areas occur mainly in the saturated valley bottom lands used for grazing (Addisie et al., 2020). Currently, in the highlands of Ethiopia, deep gullies are common landscape features that severely threaten agricultural production (Yitbarek et al., 2012; Liao et al., 2019). Gullies sediment production and continuous development

To cite this article: Addisie, M.B. and Wassie, H.M. 2021. Gully controlling practices associated with soil geotechnical properties in the subhumid Ethiopian highlands. Journal of Degraded and Mining Lands Management 8(3): 2719-2729, doi: 10.15243/jdmlm.2021.083.2719.
associated with hydrology and soil properties (Valentin et al., 2005; Bruce, 2011). Soil texture is the dominant factor in the soil and water relationship for the hydrologic analysis (Saxton et al., 1986). Vertisols with high swelling characteristics in the dry season control gully development (Zegeye et al., 2016; Addisie et al., 2017). These soils experience soil piping during the rain phase as the flow of water through pipes washed the channel boundary and eventually, the pipe collapses and forms rills and open channels. Over time, the open channel forms a gully with eroded sides and the head could retreat up-slope. The incised gullies become deeper and deeper, creating a higher hydraulic gradient to the pipe on the side banks and then pipes lines develop up-slope (Frankl et al., 2013).

Soils differ in their susceptibility to erosion (erodibility) depending on natural properties and human factors (Lestariningsih et al., 2018). Erodibility expresses the soil's inherent resistance to particle detachment and transport by running water. Soil erodibility is directly proportional to an increase in aggregate stability. The determination of erodibility is by the cohesive force between the soil particles and may vary depending on the aggregate stabilities (Wischmeier and Smith, 1978). Soils containing over 20% of clay and organic matter improve aggregate stability and decrease surface crusting (Wakindiki and Benhur, 2002). Large sand grains having greater pore spaces reduce soil erodibility. In Ethiopia, the erodibility of different soil types range from 0 to 0.18, which is relatively low (Nyssen et al., 2007; Berhanu et al., 2013).

By the nationwide efforts, gullies did not get sufficient attention similar to hillside treatments for rehabilitation particularly in the humid highlands (Bewket and Sterk, 2002; Nyssen et al., 2006). Conservation structures mainly check dams have been practiced averting the development of gullies (Nyssen et al., 2004). In the valley bottom gullies where saturation excess runoff dominates (Steenhuis et al., 2009; Addisie et al., 2020), the water table height is above the gully bottom, and the associated soil properties exacerbate bank failure. Check dams are not effective for controlling measures in these high rainfall areas and Vertisols with pipes because the flow bypasses the structure (Nyssen et al., 2004; Langendoen et al., 2014; Frankl et al., 2016; Addisie et al., 2017). However, gully control measures that are not effective in the humid Ethiopian highlands are successful using check dams in semi-arid regions (Nyssen et al., 2006). There is a need to understand better the effectiveness of check dams in controlling gully erosion and the associated soil properties in the sub-humid Ethiopian Highlands to design effective gully control measures. Therefore, the objective of this study was to understand the status of gully erosion controlling practices mainly check dams and the associated geotechnical property of the soil in the sub-humid Ethiopian highlands.

**Materials and Methods**

**Description of the study site**

The study area, Kuhar Michael in the sub-humid highlands of northwestern Ethiopia, located 40 km Northeast of Bahir Dar along the main road to Woreta (Figure 1). Geographically the study area is located at 37°39’43” to 37°39’59” E and 11°53’17” to 11°53’34” N. The altitude of the area is 1800 m a.s.l. The very downslope of the study area is the well-known Fogera flood plain saturated in the rainy season. Rainfall is unimodal, with a mean annual value of 1320 mm measured from 1986 to 2017 (Molla et al., 2020). The wet season extends from June to September, with high rainfall in July and August. There is a rain gauge stationed at 15 km to the south, owned by the National Meteorology Agency. The mean daily temperature is 20 °C. Soils are mainly Regosols in the uplands and Vertisols in the bottom slopes. The land use is characterized by dominantly cultivated and communal grazing land. The small indigenous shrubs predominantly found on the hill-slopes. Native vegetation entirely replaced by secondary forest, mostly eucalyptus trees used for fuelwood and construction. The soils on the steep slopes are too shallow to sustain crop growth, whereas, in the flat areas, deep soil systems potentially growing cash crops such as rice, maize, onion, and tomato.
in the communal lands, and gullies are overgrowing with no prevention in the last 7 years. This research focused on understanding the gully development processes in the short term, controlling mechanisms, and associated geotechnical soil properties in the study area.

**Data collection and analysis**

**Monitoring gully morphology**

We carried out gully morphology measurements at the beginning and end of the 2019 rainy season. Four gullies (GU1, GU2, GU3 and GU4) were randomly selected for the study (Figure 1). We divided the big gully into two because of the slope difference and length (GU1 and GU2; Figure 2). The measurement completed at reach lengths with varying intervals and gully dimensions (length, width and depth) were measured from the gully head inlet to the outlet. Erosion pins placed at each gully reach to monitor the rate of development. A 50 m long line tape, locally constructed ranging poles and pegs used during the measurement. The top and bottom width and length of the gully measured at each reach. The gully depth measured with another tape stretched from the above tape's surface to the gully bed with varying depths. The area affected by a gully and the volume of soil lost were calculated based on the measured dimensions. The surface area affected by the gully calculated using equation 1. The determination of the volume of soil lost as a product of the average cross-sectional area of the gully (equation 2) and each reach length (equation 3). The soil lost in tons per hectare of the catchment is the product of the volume of soil lost in meter equivalent and the average bulk density of the soil.

\[
S_a = \sum_{i=1}^{n} \left( \frac{L_i}{2} \right) (W_i - W_{i+1}) 
\]

\[
A = \sum_{i=1}^{n} \left( \frac{D_{av}}{2} \right) (W_i - W_{i+1}) 
\]

\[
V = \sum_{i=1}^{n} L_i \times A_i 
\]

Where \(S_a\) is the surface area of the gully; \(L_i\) is the reach length; \(W_i\) width of the reach; \(D_{av}\) is the average depth of the gully; \(A\) is the cross-sectional area of the gully: and \(V\) is the volume of soil loss at a section or reach.

**Figure 2. Cross-sectional surveys along the 400 m gully at each reach length and soil sampling locations in red dots. The red arrows indicated the point at which GU1 and GU2 were separated.**

**Gully control techniques**

Two gullies with 32 check dams (25 sandbag and 7 rock check dams) were identified and monitored since the 2019 monsoon phases. The minimum and maximum length of the gullies selected for the study was 128 and 412 m, respectively. Gully controlling practices were applied to shallow gullies with depth of less than 3 m since it is hard to treat gullies with depths greater than 3 m (Langendoen et al., 2014). Gullies classified as treated with sandbags and rock dams. The practice was started before the onset of monsoon rain in February by placing a series of check dams along the gully channel. The structures were placed in the middle of the gully channel with sandbags of the same size filled with locally available material. Whereas rock dams contain a mixture of stones having a size between 15 cm and 40 cm.

The shape of the rocks was more or less angular. The thickness of the sandbag and rock dam was about 1 and 0.5 m, respectively. The sandbag was thicker as the bag was double-faced and the width is equivalent to the channel width; and the sufficient height of both dams were about 1 m. Dam installation started by excavating the gully bed about 30 cm and the side keys of 30 cm for sandbags and 50 cm for rock dams. Larger stones were placed in the bed, keeping the base of the structure and side keys healthy to avoid side erosion. The final shape of the dam looks parabolic to allow...
free water flow. Dams spacing determined using the national catchment management manual with a formula considering the channel bed slope and sufficient height of a dam with 1 m (Desta et al., 2005). The spacing is the multiplication of effective height with 1.2 and divided by bed slope in percent.

Eight check dams (5 from the sandbag and 3 from rock check dams) were selected for a detailed study (Table 2). The product of longitudinal length and the average width of sedimentation was used to estimate the amount of sediment stored behind the sample dams. For these gullies, the channel had a U shape in cross-section. Hence, we assumed the width of the channel at the surface is more or less similar to the width of the previous channel depth. Therefore, the volume of sediment stored behind the dams was computed as a prismatic channel with rectangular section (equation 4) (Castillo et al., 2007):

\[
V = \frac{1}{2} L_s W_s D_a = \frac{1}{2} a D_a \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots 4
\]

where \( V \) is the volume of the sediments accumulated behind the sample dams (m³), \( L_s \) is the longitudinal length of the sedimentation (m), \( W_s \) is the average width of sediment wedge (m). The surface area of sedimentation \( (S_s) \) in m², \( w_s \) is the average width of sediment wedge (m). The surface area of Atterberg limits (\( S_s \)) in m² and \( D_a \) is the depth of the accumulated sediments measured from the basis of the check dam (m). The gully depths measured using pins installed behind each check dams.

**Soil sampling and analysis**

The soil sampling sites were identified at three surveyed gully locations. Before the sampling, the field observation was done to determine the surface colour and subsurface gully soil. After knowing the soils in the gully depth, both undisturbed and disturbed samples were collected. Four soil cores and another four disturbed samples were collected from the area. These disturbed samples were used to determine the particle size distribution and Atterberg limits. The samples were collected from exposed active gullies and a composite sample of surface and subsurface soils at the gully bank. The soil cores were sealed immediately after collection in the field and were transferred to the laboratory for analysis. The core samples were oven-dried at a temperature of 105°C to a constant weight to calculate the soil bulk density using the mass-volume relationship as the mass of dry soil (g) divided by the total volume of soil (cm³). Particle size distribution analysis was performed using sieve and hydrometer analysis to determine the soil particles distribution within a given sample. The analysis was performed following USDA D422 method and the soil texture class was determined using the USDA Soil Texture Triangle based on the percentage of sand, silt and clay. Atterberg limits (liquid limit (LL), plastic Limit (PL) and plasticity index (PI)) were determined using the ASTM D4318 method. Soil hydraulic conductivity was determined according to Saxon et al. (1986) and Saxon and Rawls (2006) where conductivity is a function of soil texture. Therefore, the SPAW (soil plant, air and water) standalone soil and water relationship model was used to estimate hydraulic conductivity of the soil.

**Results**

**Gully development and morphology**

A survey on gully morphology was conducted at each reach length considering the meanderings or abrupt change in the gully profile. Forty gully reaches were surveyed at GU1 (12), GU2 (13), GU3 (7), and GU4 (8), respectively. We surveyed at the same location as the pins installed early at each reach lengths. Therefore, we used the same number of reaches per gully to minimize measurement errors. The total length at GU1, GU2, GU3 and GU4 was 191, 221, 129 and 117 m. The average width and depth of these four gullies before and after treatment was 3 and 0.85 m, respectively (Table 1). The growth rate of gully length over the monitoring season was insignificant for all gullies except 3.6 m at GU3 and 2.3 m at GU4. The change in average width was +0.9 m, while the depth decreased by 0.3 m. The increment in gully length for GU1 and GU2 was zero since the head was stable with shallow depths. The change in average gully width and depth before and after the rainy season was more significant. This change was more remarkable at the beginning of the rainy season and the trend changed with rainfall progression and the erodibility of the bed material at the end of the monitoring period (Figure 3). In similar areas, rainfall progression significantly affects soil erosion, especially in bare and less vegetated lands. Besides, human activities played an essential role in gully development. The total surface area damaged by gullies was 0.35 ha and the surface area at the end of the survey increased by 550 m² per year. In contrast, after the installation of dams, the volume of soil loss decreased by 114.6 m³. The reason was the decrease in the average gully depth from 1m to 0.7 m (Table 1). In the monitoring period, the width-depth ratio (WDR) increased from 3.4 to 4.7. The WDR is an indicator of the activity of the gully. The WDR at GU3 was more significant than the other gullies because of gully bank erosion and sediment aggradation.

**Gully controlling practices**

Thirty-two check dams at two big gullies (GU1 and GU2 from the long gully and GU3) were installed. These were twenty-five sandbags and seven rock dams used to check sediment transport along with the gully system (Figure 3). The effective height of the dams varied from 0.5 to 1 m. Seventy-five percent of the rock dams had depths from 0.5 to 0.75 m, while the remaining 25% had 1m around the head. Whereas 90% of the sandbag dams had depths of 1m. At the beginning of the rainy season in July, all the dams were completely captured sediments. At GU1 and GU2 with...
sand dams, the dam stored water over seven weeks upstream of the structure. The livestock consumed the stored water. On the rock dams, for the consecutive two months (July and August), dams were filled up with sediments. Sediment accumulation behind the check dams was started in the upstream of the gully and then continue to downslope after the dam filled up with sediments. Sample dams were selected to determine the amount of sediment accumulated behind each dam.

Table 1. Morphological characteristics of the gully in the study area.

| Gully ID | Number of Measured Reaches | Total length (m) | Average Width (m) | Average Depth (m) | Width-Depth Ratio | Surface Area (m²) | Total Volume of Soil Loss (m³) |
|----------|---------------------------|-----------------|------------------|-----------------|------------------|------------------|-------------------------------|
|          |                           |                 |                  |                 |                  |                  |                               |
| Before Check dams |                       |                 |                  |                 |                  |                  |                               |
| GU1      | 12                        | 191.0           | 3.9              | 1.4             | 2.8              | 1139.0           | 1057.2                        |
| GU2      | 13                        | 220.6           | 3.3              | 1.2             | 3.3              | 1027.1           | 751.3                         |
| GU3      | 7                         | 128.9           | 3.0              | 0.7             | 5.1              | 561.7            | 300.5                         |
| GU4      | 8                         | 117.2           | 1.2              | 0.6             | 2.4              | 177.0            | 71.4                          |
| Total/Ave. | 40                       | 657.7           | 2.6              | 1.0             | 3.4              | 2904.8           | 2180.4                        |
| After Check dams |                     |                 |                  |                 |                  |                  |                               |
| GU1      | 12                        | 191.7           | 4.8              | 1.0             | 4.1              | 1393.3           | 1127.5                        |
| GU2      | 13                        | 220.6           | 3.7              | 0.5             | 6.9              | 1096.0           | 410.5                         |
| GU3      | 7                         | 132.5           | 3.5              | 0.7             | 5.1              | 666.8            | 395.4                         |
| GU4      | 8                         | 119.5           | 1.9              | 0.6             | 2.8              | 298.6            | 132.4                         |
| Total/Ave. | 40                       | 664.3           | 3.5              | 0.7             | 4.7              | 3454.7           | 2065.8                        |

Figure 3. Sample gully reaches treated with check dams and failure of the structure at the end of monitoring; (a), (b) and (c) were sandbag check dams well in trapping sediments, and then running water bypasses the structure as indicated with a red arrow and finally failed; (d), (e) and (f) were rock dams had a similar history like sandbag dams.
Eight sample dams, five from sandbags and three from rock dams were identified. The five sandbag dams were considered at each 80±6 m gully length. The sampling process used rock dams selected randomly at the head, middle, and downslope. From the average sediment deposited at the sample dams, the total sediment accumulation was determined. Table 2 shows the total amount of sediment deposited behind the sample dams at the end of monitoring. The volume of sediment trapped by the check dams ranged from 7.50 to 17.46 m³. The total sediment trapped by the 32 structures was about 387 m³ of which the average sediment trapped by the sandbag and rock dams were 12.63 and 11.20 m³, respectively; transported sediment was originated from the gully bank and the contributing area. Sediment from the contributing area was low as confirmed by field measurement that the slope was minimum (2.4%) and lower runoff limits the eroded materials (Figure 3). However, gully bank sides eroded by forming rills. 

**Soil geotechnical properties**

**Soil particle-size distribution (PSD)**

For further analysis of the gullies; gully Ga is divided into two sections with the most upstream GU1 and the downstream levelled as GU2. Determination of the PSD is one of the most important physical attributes in the soil system that affects the soil properties and the movement and retention of water. The highest and the lowest clay contents were 74.0 at Ga and 54.0% at Gd. The brown soil colour at GU4 showed the weakest in sand content (8.0 %). The sand percentage varied from 8 to 36% in GU4 and GU3, respectively. The results indicated that coarse soil particles increased from the downslope gully to the upper slope and the finer soil particles increases at the fourth gully with soil colour of brown. The GU4 and GU1 had the greatest clay content of 74 and 64%, respectively. Clay particles have an essential role in soil aggregate stability. If clay content is over 40% in gullies, soil aggregate formation is small and soil erosion is quicker. Soil texture was the highest in clay content from the four gullies.

**Bulk density (BD)**

The mass of a unit volume of dry soil with both solids and pore spaces indicates the compaction of the soil and it is a function of soil aggregates, the nature of the mineral and organic matter content. The average BD obtained in this study was 1.51, with a maximum of 1.73 g cm⁻³, indicating that these soils were fair. Soils at GU1, GU2 and GU3 had similar values, whereas GU4 had a higher bulk density 1.73 g cm⁻³. Natural root growth is restricted as BD becomes greater than 1.5 g cm⁻³ in fine-textured soil. According to Mukhopadhyay et al. (2019), BD of less than or equal to 1.3 g cm⁻³ is good, between 1.3 and 1.55 g cm⁻³ is fair, and greater than 1.8 g cm⁻³ is considered extremely bad. The relative increase in Bd may be related to land management practices.

Table 2. The amount of sediment deposited behind the sample dams located at a different location along the gully (Ds = sand dam; Dr = rock dam).

| Sample Dam | Reach location | Surface area (m²) | Ave. Depth (m) | Sediment accumulated (m³) |
|------------|----------------|------------------|----------------|--------------------------|
| Ds1        | upper          | 21.00            | 0.23           | 24.15                    |
| Ds2        | upper          | 9.63             | 0.27           | 13.00                    |
| Ds3        | middle         | 15.0             | 0.50           | 7.50                     |
| Ds4        | middle down    | 17.30            | 0.45           | 8.50                     |
| Ds5        | down upper     | 20.10            | 0.40           | 10.00                    |
| Dr1        | upper middle   | 16.50            | 0.60           | 9.90                     |
| Dr2        | down middle    | 24.5             | 0.71           | 17.46                    |
| Dr3        | down           | 18.75            | 0.33           | 6.23                     |

**Hydraulic conductivity (Ks)**

Generally, the soil had very low conductivity (less than 2.1 mm/hr) and varied spatially along the longitudinal slope. Values of Ks less than 2 mm/hr indicate slow conductivity class; hence, the soil was impermeable. Hydraulic conductivity was very low downslope compared to the upper slope gully. In this case, subsurface water could not transport easily and stored on the surface and discharged downslope as surface runoff. For soils with high Ks, water infiltrates into the soil at a higher rate and less is left to surface flow. The slow Ks is also attributed to the high clay content and low porosity of the soils. The Ks at the lower slope was six times greater than Ks at the upper slope of the same gully GU1, indicating that the transported material deposited at the lower slope had more permeability. Gully growth on these sites is more likely higher as the surface runoff moves faster downslope since less water infiltrates. This was supported by field observation that the gully bank had not to experience mass wasting and piping erosion as the banks were steep. Soils experience saturation had a common phenomenon of these activities.

**Atterberg limits**

The mean plastic limit (PL) and liquid limit (LL) values of these soil was 46.6% and 64.9%, respectively (Table 3). The mean plasticity index (PI) and liquidity index (LI) were 18.3% and 23.9%, respectively. According to Sower (1979), the PL and PI of all gully soils were under the category of highly plasticity since the values were greater than 30 and 17, respectively. As expected with the clayey nature of the soil the PI was greater, soils with a lower PI tend to be silt, and a
PI of 0 (non-plastic) has little or no silt or clay (Albracht and Benson, 2001). The Atterberg limits or clay plasticity are a function of particle size distribution, clay mineral types, and the surface area of clay minerals (Zhang and Frederick, 2017). The amount of water retained in soil mass depends upon available clay mineral in the soil. The activity of a soil (AS) is associated with clayey soils and assesses the water holding capacity of the soil. The change in soil volume from the swelling and shrinking characteristics of the soil is dependent on clay soil activity.

Table 3. Gully soil Atterberg limits in the study area.

| Gully soil | PL (%) | LL (%) | PI (%) | LI (%) | AS  |
|------------|--------|--------|--------|--------|-----|
| GU1        | 49.41  | 68.70  | 19.29  | 23.32  | 0.36|
| GU2        | 49.49  | 63.01  | 13.52  | 6.07   | 0.27|
| GU3        | 45.84  | 65.35  | 19.51  | 10.05  | 0.41|
| GU4        | 41.70  | 62.75  | 21.06  | 62.23  | 0.38|
| Mean       | 46.61  | 64.95  | 18.34  | 23.92  | 0.36|
| SD         | 3.69   | 2.76   | 3.31   | 27.26  | 0.06|

Remarks: PL = plastic limit, LL = liquid limit, PI = plasticity index, LI = liquidity index, AS = activity of a soil.

Table 1 shows all gully soils were grouped under the non-active as the AS was below 0.75, and all the values were from 0.27 to 0.41, indicating that the soils had the property of clay as kaolinite (Skempton, 1953). According to Mitchell and Soga (2005), the plastic and liquid limits measured at the kaolinite clays were about 30-110 and 25-40%, which is similar to our findings to the other types of clay minerals.

Discussion

Gully development and controlling practices

Gully development was surveyed based on its morphologic and sediment stored behind the check dams. The gully density and surface area were illustrated using the following Figure 4. It was important to understand the history of gully development in the area and it showed that gully density drastically increased over the past 7 years (Figure 4). Before 2013 there were no clearly defined dimensions of gullies observed. Since 2010 some ephemeral gullies at GU3 and GU4 observed. The total surface area covered by gullies in the study area was about 0.11 ha in 2013 and 1.08 ha in 2019. Gully density significantly increased from 0.13 km km<sup>-2</sup> in 2013 to 3.6 km km<sup>-2</sup> in 2019. This value of gully density indicated severity of gully erosion in the area (Hassen and Bantider, 2020). Due to the absence of gully treatment practices and poor management of livestock grazing, gully networks expanded further. Concerning the development of gullies, we tested the effectiveness of gully controlling measures using check dams (sandbag and rock). The change in gully morphology from the measured data in one rainy season indicated that all measured variables were in an increasing trend. The surface area (SA), cross-sectional area (CA), width depth ratio (WDR), and finally, the amount of soil lost from the gully was greater. The overall growth of gullies was determined by the increase in gully width, especially the top width (Figure 5). Sedimentation processes in the gully system were different from one to another reach in the upstream of the check dams and in the downstream reaches. In the upstream reaches sedimentations were taking place with decreasing the longitudinal gradient.

The morphological patterns in the upstream of the dam seems the cross-sectional area decreased after the implementation of check dams when the depth near the dam became shallower due to channel bed aggradation (Figure 3). Over a one-year measurement, the change in WDR increased showing a significant change in channel width erosion than gully bed aggradation (Table 1). The result indicated that the majority of sediments were derived from the gully bank erosion.

According to Castillo et al. (2003), there is a linear relationship between the probability of a dam being filled up with sediment with the contributing area and the size of cultivated land in the catchment. As indicated in the results section, this idea does not
support our findings as the uppermost boundary of the study area is fixed with asphalt road and no agriculture practiced (Basuki, 2017). However, the rainfall progression increases the runoff with the resultant failure of the dams; and the channel bed was highly eroded compared to aggradation. The gully channel capacity decreased and the increase in flow velocity in the downstream lead to lateral erosion. Both runoff and sediment overflowing near the flatter cultivated lands and the downstream end of gullies were discontinuous.

Figure 5. Change in average gully width over the monitoring period.

It was possible to capture a large amount of sediment in the gully system. More sediments were expected to be trapped in the sandbags with a larger surface area of the gully system. However, due to the difference in the dam height after filling up with sediment in the upstream and the downstream gully bed, the running water scoured the dam floor downstream and easily eroded. In addition, the dynamics of the local weather (rainfall and sun heat), the sandbags were unable to tolerate and cracked. Around five dams were failed in the second week of August, and at the end of August, the remaining dams had been completely damaged. In the rock dams, the structures’ failure was started from the dam side keys and water bypasses the structure. As observed from the field, all the rock dams had relatively well-accumulated sediments on one side of the bank, particularly the most downstream of the gully (Figure 3).

Gully erosion and soil properties

We analyzed the physical properties of soils to interpret the relationship with the development of individual gullies. A statistical relationship, the correlation between soil properties and gully erosion were done. As indicated in section gully development and controlling practices, most of the soil erosion in the gully system was related to the increase in average gully width. Therefore, the correlation was run between the change in gully width over the monitoring period for the selected soil properties. The analysis considered Atterberg limits, soil texture, bulk density, saturated hydraulic conductivity, and soil activity (Table 4).

Atterberg limits with higher values correspond to easily dispersive, low shear strength and increased soil erodibility (Mitchell and Soga, 2005; Wagner, 2013). Recently, Atterberg limits have been used as indicators for soil erosion processes resulted from natural and human-induced disturbances (Stanchi et al., 2015). As water content increases in the fine soil particles, it becomes softer and tends to shift from a solid state to a liquid state that weakens the soil structure, cohesive strength and instability. The coefficient of determination between PL and the CAW indicated the largest ($R^2 = 0.94$) and AS ($R^2 = 0.67$) as shown in Table 4. Both parameters were negatively and strongly correlated. CAW had a positive and weak correlation with PI and LI with $R^2$ of 0.27 and 0.66, respectively. The range indicated a reasonably good correlation though the PI or LI did not strongly affect the erodibility of the gully bank. This could be supported by the findings as explained in the results section; the value of LI was greater than zero, indicating that soils had weaker cohesion and are less resistant to water erosion. The activity of the soil showed the kaolinite soil as a non-swelling clay with a dispersive nature that facilitates soil erodibility. Water causes clay hydration and swelling and, therefore, decreases water infiltrability and then surface runoff. In this case, the concentration of surface runoff over a long time contributed to gully erosion. As observed from the field, the incision of all gullies may be from the dispersive nature of the soil. Some swelling nature of the clay also contributes gullying when water filled up the open cracks formed due to the swelling nature of the soil in the dry season. Once the gully channel formed, then the development of gully remains extensive.

As indicated in the results section, the texture of the soil in the study area is clay. The correlation found between clay content and erosion from the gully width indicated a positive slope ($+3.58$) and strong relationship ($r = 0.70$). The direction and strength of the correlation showed a linear relationship between
clay content and soil erosion. This could be due to soil dispersion which is the physical properties of the soil results from the reduction in the attraction forces between colloidal particles while wetting. This result was similar to studies conducted by Ezochi (2000), who reported that increased clay content in soils increase susceptibility to gully erosion. Soils containing large amounts of clay particles, indicated a higher degree of gully erosion and their frequency is more expected due to increased water saturation. In addition, Ramezanpour et al. (2010) demonstrated that if clay content is over 40.0%, small aggregates form and the soil eroded easily. However, according to Gollany et al. (1991), the decreases in the fraction of clay content increases soil erodibility. Whereas Pierson and Mulla (1990) reported no significant correlation between clay content and erosion. The discrepancy in soils with high clay content related to the type of colloids and cementing materials the soil composed. Clayed with calcium and magnesium saturated are more stabilized than clays saturated with sodium are easily dispersed and detached. The gully bank where the flow interacted with quickly eroded the side banks while the soil wetted. The regression between CAW and BD indicated a positive and strong relationship ($R^2 = 0.73$). As the BD of the soil increases, as expected, soil erodibility increases since the incoming water is unable to infiltrate and runs off.

The coefficient of determination indicated that a positive and strong correlation existed between BD with $R^2 = 0.73$. This could be expected that as the bulk density of the soil increases the erodibility of the gully bank increases. The reason was the increase in bulk density reduced the pore spaces of the soil and limits the infiltrability of water and the incoming rain lost as surface runoff with eroded materials. Whereas the $K_s$ had a weak and positive correlation ($R^2 = 0.26$). The result indicated that $K_s$ did not have much impact on gully widening in the area. Since we observe the level of erosion at the bank width, the erodibility of the soil on the exposed gully bank surface has a direct result from running water. It was expected if there was bank collapse (mass wasting) the $K_s$ has a direct impact. However, we did not observe mass wasting of gully bank on the field instead rills formed on the surface and contribute for erosion.

In general, BD, PL, LI and AS have a strong positive and negative correlation; whereas, clay content and LL has fairly good correlation and the other parameters had a weak correlation. Soil properties, except for texture, had a significant contribution for the development of gully erosion in the study area. In addition, anthropogenic activities played an important role in the development of gully erosion. The study area was a communal land where overgrazing predominantly practiced throughout the year. Livestock grazing contributed to hardpan formation and increased the bulk density and reduced the soil's ability to infiltrate water in its profile. These processes indirectly increased the surface runoff. In particular, the gully banks are non-vegetated and easily eroded while contact with livestock. It is concluded that both the soil's inherent properties and other man made factors contribute to the development of gullies.

Table 4. Regression analyses of change in average gully width with soil physical properties.

| Change in Average Gully Width (CAW) | Regression equation | $R^2$ |
|-------------------------------------|---------------------|-------|
| Sand                               | $y = -3.16x + 25.75$ | 0.14  |
| Silt                               | $y = -0.41x + 15.55$ | 0.02  |
| Clay                               | $y = 3.58x + 57.69$  | 0.49  |
| BD                                 | $y = 0.08x + 1.40$   | 0.73  |
| PL                                 | $y = -2.19x + 49.54$ | 0.94  |
| LL                                 | $y = -1.13x + 66.47$ | 0.45  |
| PI                                 | $y = 1.06x + 16.93$  | 0.27  |
| LI                                 | $y = 13.60x + 5.64$  | 0.66  |
| $K_s$                              | $y = 0.28x + 0.64$   | 0.26  |
| AS                                 | $y = -0.59x + 2.18$  | 0.67  |

Remarks: PL = plastic limit, LL = liquid limit, PI = plasticity index, LI = liquidity index, $K_s$ = hydraulic conductivity, AS = activity of a soil, BD = bulk density.

Conclusion

The study area is an active gully erosion dominating area because of the vulnerability of soil materials, sparse vegetation covers and anthropogenic factors. The morphological changes in the channels indicate an increase in WDR following sedimentation by check dams and aggradation at the gully bed and erosion at the gully bank. The check dams installed to reduce soil erosion and increase deposition within the gully system. Large amounts of sediment deposited during the rainy season and almost all dams have been completely filled up. The majority of the sediment emanated from the gully bank mobilizing high sediment load in the gully system. The sedimentation upstream of check dams causes a decrease in the longitudinal gradient and stored water temporarily. Thus, the channel showed stabilized in the upstream of the dams. However, at the end of monitoring the amount of sediment that was stored behind the check dams remained minor. The level of sedimentation was greater than the amount in the upstream. The sediments filled up the dams causing erosion downstream beside the side key erosion and failure of check dams due to lack of maintenance and reintroducing sediments transported into the channel. The leading cause for the dams' failure was that the water bypasses the structure on the side keys. The inherent soil properties and anthropogenic factors played an important role in the development of gully erosion. Though it is hard to manage the soil properties, the management of physical characteristics indirectly improves soil health. Finally, maintenance is the best option for reducing sediment production and a crucial part of planning effective management of gully erosion.
Acknowledgements

Debre Tabor University, Ethiopia, financially sponsored this research. We would like to thank the Fogera District Agriculture Office for supplying materials to manage the gully. Dr. Membere Teshome is sincerely praised by the author for remarking the paper and the reviewer for its crucial suggestions that helped to improve the manuscript.

References

Addisie, M.B., Ayele, G.K., Gessess, A.A., Tilahun, S.A., Zegeye, A.D., Moges, M.M., Schmitter, P., Langendoen, E.J. and Steenhuis, T.S. 2017. Gully head retreat in the sub-humid Ethiopian highlands: the Ene-Chilala catchment. Land Degradation & Development 28(5): 1579-1588.

Addisie, M.B., Ayele, G.K., Hailu, N., Langendoen, E.J., Tilahun, S.A., Schmitter, P., Parlange, J. Y. and Steenhuis T.S. 2020. Connecting hillslope and runoff generation processes in the Ethiopian Highlands: The Ene-Chilala watershed. Journal of Hydrology and Hydromechanics 68(4): 313 – 327, doi: 10.2478/johh-2020-0015.

Albrecht, B.A. and Benson, C.H. 2001. Effect of desiccation on compacted natural clays. Journal of Geotechnical and Geoenvironmental Engineering 127(1): 67-75.

Andriyanto, C., Sudarto, S. and Suprayogo, D. 2015. Estimation of soil erosion for a sustainable land use planning: RUSLE model validation by remote sensing data utilization in the Kalikonto watershed. Journal of Degraded and Mining Lands Management 5(1): 459-468, doi: 10.15243/jdmlm.2015.03.049.

Basuki, T.M. 2017. Sediment yield and alternatives soil conservation practices of teak catchments. Journal of Degraded and Mining Lands Management 5(1): 965-973, doi:10.15243/jdmlm.2017.051.965.

Berhanu, B., Melesse, A.M. and Seleshi, Y. 2013. GIS-based hydrological zones and soil geo-database of Ethiopia. Catena 104: 21-31.

Bewket, W. and Sterk, G. 2003. Farmers’ participation in soil and water conservation activities in the Chemoga watershed, Blue Nile basin, Ethiopia. Land Degradation & Development 13(3): 189-200.

Bulli, F. and Dramis, F. 2003. Geomorphological investigation on gully erosion in the Rift Valley and the northern highlands of Ethiopia. Catena 50(2-4): 353-368.

Bruce, C. 2011. Fact sheet on gully erosion, Department of Natural Resources and Water. Department of Environmental and Resources Management, 2011.

Castillo, V.M., Gomez-Plaza, A. and Martinez-Mena, M. 2003. The role of antecedent soil water content in the runoff response of semiarid catchments: a simulation approach. Journal of Hydrology 284(1-4): 114-130.

Castillo, V.M., Mosch, W.M., Garcia, C.C., Barberá, G.G., Cano, J.N. and López-Bermúdez, F. 2007. Effectiveness and geomorphological impacts of check dams for soil erosion control in a semiarid Mediterranean catchment: El Cárcavo (Murcia, Spain). Catena 70(3): 416-427.

Desta, L., Carucci, V., Wendem-Agenehu, A. and Abebe, Y. 2005. Community based participatory watershed development. A Guideline. Ministry of Agriculture and Rural Development, Addis Ababa, Ethiopia.

Ezochi J.I. 2000. The influence of runoff, lithology, and water table on the dimensions and rate of gullying processes in eastern Nigeria. In International Symposium of Gully Erosion Under Global Change. Gath University of Leuven, Belgium (pp. 16-19).

Frankl, A., Deckers, J., Moulaut, L., Van Damme, A., Haile, M., Poese, J. and Nyssen, J. 2016. Integrated solutions for combating gully erosion in areas prone to soil piping: innovations from the drylands of Northern Ethiopia. Land Degradation & Development 27(8): 1797-1804.

Frankl, A., Poese, J., Haile, M., Deckers, J. and Nyssen, J. 2013. Quantifying long-term changes in gully networks and volumes in dryland environments: the case of northern Ethiopia. Geomorphology 201:254–263. doi: 10.1016/j.geomorph.2013.06.025.

Gollany, H.T., Schumacher, T.E., Evenson, P.D., Lindstrom, M.J. and Lemme, G.D. 1991. Aggregate stability of an eroded and desurfaced Typic Argiustoll. Soil Science Society of America Journal 55(3): 811-816.

Hassen, G. and Banlader, A. 2020. Assessment of drivers and dynamics of gully erosion in case of Tabota Koromo and KoromoDanshe watersheds, South Central Ethiopia. Geoenvironmental Disasters 7(1): 1-13.

Langendoen, E. J., Zegeye, A., Steenhuis, T., Ayele, G., Tilahun, S. and Ayana, E. 2014. Using computer models to design gully erosion control structures for humid northern Ethiopia. In ICHE 2014. Proceedings of the 11th International Conference on Hydroscience & Engineering (pp. 1137-1146).

Lestaringhs, I.D., Widianto, W., Agustina, C., Sudarto, S. and Kurniawan, S. 2018. Relationship between land degradation, biophysical and social factors in Leksos Watershed, East Java, Indonesia. Journal of Degraded and Mining Lands Management 5(3): 1283-1291, doi: 10.15243/jdmlm.2018.053.1283.

Liao, Y.S., Yuan, Z.J., Zheng, M.G., Li, D.Q., Nie, X.D., Wu, X.L., Huang, B., Xie, Z. and Tang, C.Y. 2019. The spatial distribution of Benggang and the factors that influence it. Land Degradation & Development 30: 2323–2335.

Mitchell, J.K. and Soga, K. 2005. Fundamentals of Soil Behavior (Vol. 3). New York: John Wiley & Sons.

Molla, T., Tesfaye, K., Mekibib, F., Tana, T. and Tadesse T. 2020. Rainfall Variability and its Impact on Rice Productivity in Fogera Plain, Northwest Ethiopia. Ethiopian Journal of Agricultural Science 30(2): 67-79.

Mukhopadhyay, S., Masto, R.E., Tripathi, R.C. and Srivastava, N.K. 2019. Application of soil quality indicators for the phytorestoration of mine spoil dumps. In Phytomanagement of Polluted Sites, Elsevier: 361-388.

Nyssen, J., Poese, J., Gebremichael, D., Vancampenhout, K., Daez, M., Yildego, G., Govers, G., Leirs, H., Moeyersons, J., Naudts, J. and Haregeweyn, N. 2007. Interdisciplinary on-site evaluation of soil conservation tools to control soil erosion on cropland in Northern Ethiopia. Soil and Tillage Research 94(1): 151-163.

Nyssen, J., Poese, J., Moeyersons, J., Deckers, J., Haile, M. and Lang, A. 2004. Human impact on the environment in the Ethiopian and Eritrean highlands—a state of the art. Earth-Science Reviews 64(3-4): 273-320.

Nyssen, J., Poese, J., Moeyersons, J., Haile, M. and Deckers, J. 2008. Dynamics of soil erosion rates and controlling factors in the Northern Ethiopian Highlands—towards a sediment budget. Earth Surface Processes and Landforms 33(5): 695-711.

Nyssen, J., Poese, J., Veyret-Picot, M., Moeyersons, J., Haile, M., Deckers, J., Dewit, J., Naudts, J., Tekla, K. and Govers, G. 2006. Assessment of gully erosion rates...
through interviews and measurements: a case study from northern Ethiopia. Earth Surface Processes and Landforms 31(2): 167-185.

Pierson, F.B. and Mulla, D.J. 1990. Aggregate stability in the Palouse region of Washington: effect of landscape position. Soil Science Society of America Journal 54(5): 1407-1412.

Poesen, J., Vandekerckhove, L., Nachtergaele, J., Oostwoud Wijdenes, D., Verstraeten, G. and van Wesemael, B. 2002. Gully erosion in dryland environments. In: Bull, L.J. and Kirkby, M.J. (eds.), Dryland Rivers: Hydrology and Geomorphology of Semi-Arid Channels. Wiley, Chichester, UK, 229-262.

Ramezanpour, H., Esmaeilnejad, L. and Akbarzadeh, A. 2010. Influence of soil physical and mineralogical properties on erosion variations in Marlylands of Southern Guilan Province, Iran. International Journal of physical sciences 5(4): 365-378.

Saxton, K.E. and Rawls, W.J. 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Science Society of America Journal 70(5): 1569-1578.

Saxton, K.E., Rawls, W., Romberger, J.S. and Papendick, R.I. 1986. Estimating generalized soil-water characteristics from texture. Soil Science Society of America Journal 50(4): 1031-1036.

Skempton, A.W. 1953. The colloidal activity of clays. Selected Papers on Soil Mechanics 106-118.

Stanchi, S., Falsone, G. and Bonifacio, E. 2015. Soil aggregation, erodibility, and erosion rates in mountain soils (NW Alps, Italy). Solid Earth 6(2): 403.

Steinbu, T.S., Collick, A.S., Easton, Z.M., Leggesse, E.S., Bayabil, H.K., White, E.D., Awulachew, S.B., Adgo, E. and Ahmed, A.A. 2009. Predicting discharge and sediment for the Abay (Blue Nile) with a simple model. Hydrological Processes: An International Journal 23(26): 3728-3737.

Tebetu, T.Y., Abiy, A.Z., Zegeye, A.D., Dahlke, H.E., Easton, Z.M., Tilahun, S.A., Collick, A.S., Moges, S., Dadgari, F. and 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. Hydrology and Earth System Sciences 14(11): 2207.

Valentin, C., Poesen, J. and Li, Y. 2005. Gully erosion: impacts, factors and control. Catena 63(2-3): 132-153.

Wagner, J.F. 2013. Mechanical properties of clays and clay minerals. Developments in Clay Science 5:347-381.

Wakindiki, I.C. and Ben-Hur, M. 2002. Soil mineralogy and texture effects on crust micromorphology, infiltration, and erosion. Soil Science Society of America Journal 66: 897-905.

Wang, J.G., Feng, S.Y., Ni, S.M., Wen, H., Cai, C.F. and Guo, Z.L. 2019. Soil detachment by overland flow on hillslopes with permanent gullies in the Granite area of southeast China. Catena 183: 104235

Wischmeier, W.H. and Smith, D.D. 1978. Predicting rainfall erosion losses: a guide to conservation planning (No. 537). Department of Agriculture, Science and Education Administration.

Yitbarek, T.W., Belliethathan, S. and Stringer, L.C. 2012. The onsite cost of gully erosion and cost-benefit of gully rehabilitation: A case study in Ethiopia. Land Degradation & Development 23: 157-166.

Zegeye, A.D., Langendoen, E.J., Guzman, C.D., Dagnew, D.C., Amare, S.D., Tilahun, S.A. and Steenhuis, T.S. 2018. Gullies, a critical link in landscape soil loss: A case study in the subhumid highlands of Ethiopia. Land Degradation & Development 29: 1222-1232.

Zegeye, A.D., Langendoen, E.J., Stoof, C.R., Tilahun, S.A., Dagnew, D.C., Zimale, F.A., Guzman, C.D., Yitaferu, B. and Steenhuis, T.S. 2016. Morphological dynamics of gully systems in the subhumid Ethiopian Highlands: the Debre Mawi watershed. Soil 2(3): 443-458.

Zhang, K. and Frederick, C.N. 2017. Experimental investigation on compaction and Atterberg limit characteristics of soils: Aspects of clay content using artificial mixtures. KSCE Journal of Civil Engineering 21: 546-553.