




Effects of Soil and Water Conservation Practices on Runoff, Soil and Nutrient Losses in Alekt Wenz Watershed, Ethiopian Highland

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Abstract. Land degradation caused by soil erosion is a serious problem in northwestern Ethiopian highlands. To reduce the adverse impact of land degradation, soil and water conservation (SWC) measures were implemented. The presented study investigated the hydrological responses of SWC measures implemented in two nested watersheds situated in the northwestern Ethiopian highland. Rainfall, streamflow, sediment concentration, and sediment-associated and dissolved nutrient of N and P for 2015 and 2016 rainy periods were collected and analyzed. The watersheds received 665 mm in 2015 and 795 mm rainfall in 2016 from May to September. The median infiltration rates for treated and untreated watershed were 22 mm hr⁻¹, and 19 mm hr⁻¹ respectively. The direct runoff from treated watershed was 8.5 mm yr⁻¹ for 2015 and 9.6 mm yr⁻¹ for 2016. This is lower than the untreated watershed, which responded 17.3 mm yr⁻¹ for 2015 and 15.3 mm yr⁻¹ for 2016. The base flow from treated watershed was 180.7 mm yr⁻¹ for 2015 and 212 mm yr⁻¹ for 2016. It was higher than the untreated watershed, which responded 69.8 mm yr⁻¹ for 2015 and 195.4 mm yr⁻¹ for 2016. This figure shows that implemented SWC measures reduced the runoff responses by two-fold. Similarly, the SWC measures reduced sediment yield. The sediment yield from treated watershed was 2.4 ton ha⁻¹yr⁻¹ and 2.1 ton ha⁻¹yr⁻¹ in the year 2015 and 2016, respectively. This is lower than the untreated watershed that lost 6 ton ha⁻¹yr⁻¹ and 8.5 ton ha⁻¹yr⁻¹ in the year 2015 and 2016, respectively. The effectiveness of the SWC measures between the two watersheds was statistically significant with a significance level of 5%. However, it is important to investigate the long-term effects of SWC in reducing soil and nutrient losses.

Keywords: Erosion · Nutrient depletion · Runoff · Sediment yield · Soil and Water Conservation · Treated · Untreated

1 Introduction

The degradation of land, which declines the quality of land, will remain a global challenge for the 21st century. It results in a negative impact on agricultural productivity [1] and the quality of environmental aspects. It has adverse effects on food security and the quality of life [2]. According to [3] 3.6 billion hectares of land was lost annually due to adverse degradation on a global scale. Overall, the depletion of nutrients in the soil has been estimated at an average rate (kg/ha/year) 18.7 N, 5.1 P, and 38.8 K. This covers 59% N, 85% P and 90% K of harvested areas particularly parts of Africa, Asia, and Latin America [1]. According to [1] the total annual deficit of nutrients was 5.5 Mt (million tons) N, 2.3 Mt P, and 12.2 Mt K, associated with global crop production losses of 1136 Mt yr⁻¹. Land degradation happens all over the world but it is a particular problem in the highlands of sub-Saharan Africa [4].

Ethiopia is one of the hotspot area experiencing continuous natural resources degradation in a century [2]. The rate of land degradation exacerbated in the north-western Ethiopian highland where 85–90% of the population depends on agriculture and land resources [5]. Its consequences are affecting the food security of the population due to low productivity [6]. The decline of land productivity, which was induced by soil erosion is the major factor responsible for the recurrent malnutrition and famine in Ethiopia [7]. Half of the agricultural land is affected and accounts 1.5–2 billion tons in an annual soil losses rate [6, 8, 9]. This resulting 1.5 million tons of grain reduction for each production period [9]. Ethiopia losses 137 tons ha⁻¹ yr⁻¹ topsoil through soil erosion by water [10].

Since soil erosion is a natural hazard [11], it is difficult to stop and avoid. It is possible to control and reduce its adverse impact through the implementation of appropriate soil and water conservation (SWC) measures. In Ethiopia, after the declaration of wildlife conservation and development policy, the government initiated various studies and capacity building programs for massive SWC intervention [12]. Various SWC measures have been adopted and implemented by the food for work (FFW) program through government-led national campaign to control soil erosion by water [13].

Similarly, a series SWC practices have been implemented in Northwestern part of Ethiopia by farmers through government led to a national campaign since 2012 [14, 15]. The practices include physical structures (terraces, stone-bund, check dam, and arc weir) and biological (native tree plantations, the establishment of pasturelands with a fence, sesbania (*sesbania grandiflora*), vetiver grass (*chrysopogon zizanioides*), and elephant grass (*pennisetum purpureum*)).

Soil and water conservation practices could have a role in reducing runoff generation in a rainy season [13]. This is increase base flow of a catchment by improving infiltration rate of the soil. Also, it increases dry season stream flow [16] and prevents rivers from drying up earlier. Generally, it is believed that the impact of conservation practices on hydrological responses mainly related to controlling surface runoff [13],

decreasing soil erosion and reservoir sedimentation [17, 18], improving soil fertility of farmland, and enhancing agricultural production [19, 20]. In the northwestern part of the Ethiopian highland, there have been hard enough scientific study to assess the extent of the effectiveness of implemented SWC activities on hydrological responses. In particular, the effectiveness of the implemented SWC practices for reducing soil loss, nutrient depletion and runoff generation have not been studied sufficiently. However, understanding the effects of conservation practices on the hydrological responses is crucial either to design measure that improves the benefits of SWC measures or sustaining existing conservation practices. This study was conducted in Alekt Wenz watershed to investigate the effectiveness of SWC practices on hydrological responses using two experimental nested watersheds under different degree of treatments.

2 Materials and Methods

2.1 Study Area Description

For this particular study, Alekt Wenz watershed was selected and it is found in Lake Tana sub-basin, the Blue Nile, Ethiopia and is located between 38°7'0"E to 38°8'0"E Longitude and 11°46'0"N to 11°48'0"N Latitude. The Alekt Wenz watershed has a total area of 321.6 ha with two adjacent nested watersheds. The adjacent watersheds were treated differently. The one with intensive SWC works and enclosure is called treated. The other watershed with sparse SWC activities and without enclosure is called untreated (Fig. 1). In terms of climatic condition, the study area has an average annual minimum, maximum and mean temperatures of 9.7, 22, 15.5 °C, respectively. The rainfall pattern is unimodal and occurs from May to September. The annual rainfall ranges between 856.8 and 1569.9 mm with a long-term average¹ of 1301 mm. The study area topography is characterized by extremely high relief and over 70% of the land extends from gentle to hill slope landscape. The elevation ranges from 2,779 m to 3000 m (a.s.l). Cultivated land, enclosed-pastureland, grazing land, and forest area are the dominant land use land cover types in the study watershed (Table 1). Cultivated and grazing land facilitated erosion, but forest and enclosed-pastureland reduce runoff generation and soil erosion.

Table 1. Land use/land cover of the two sub-watersheds.

Land use land cover	Treated area		Untreated	
	ha	%	ha	%
Cultivated	29.4	34	126.7	54
Grassland/Enclosure/	19.8	23	1.7	1
Forest	26.3	30	70.9	30
Grazing	11.4	13	35.4	15

¹ Debre-Tabor and Gassay meteorological station from 1951–2014.

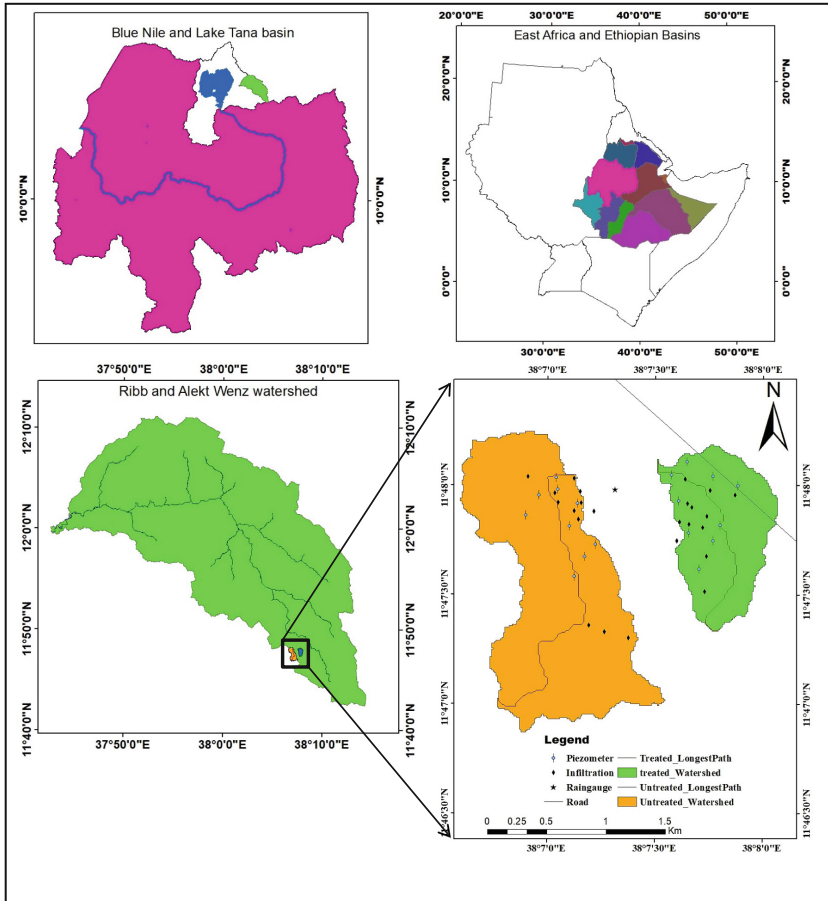


Fig. 1. Location map of the Alekt Wenz watersheds

2.2 Data Collection and Analysis

The land use/land cover map was prepared by supervised image classification. The satellite image was downloaded from earth explorer. To address the objectives of the study, rainfall, infiltration capacity, streamflow, suspended sediment concentration (SSC), dissolved and sediment-associated nutrient were directly measured during the rainy months of the monsoon (May to September) of 2015 and 2016. The remaining months of rainfall and sediment sampling were not measured as it was dry and sediment transport is so negligible. But the base flow was included as stream flow. The spatial information like locations of the outlets, rain gauge, piezometers, SWC structures, and infiltration measurement sites was conducted using GPS.

Digital elevation model (DEM) 12.5 m × 12.5 m resolution² was used to delineate the study watershed and calculate its slope, SWC implementation layout, area coverage by SWC activities. In the period 2015 and 2016, five minutes resolution rainfall data were collected with the automatic recording tipping bucket type rain gauge. It was installed on the common border of the two nested watersheds during the rainy season (early June to late November). In this study, infiltration rates were measured in early September 2015 at different land use/land cover and landscape positions on upper, middle, and the lower portion of the study watershed using the single ring (25 cm diameter) infiltrometer. The results of infiltration capacity were statistically analyzed with t-test to realize and compare the infiltration rate of the treated and untreated watersheds.

The perched groundwater levels were monitored using locally made piezometers from PVC tubes. The measurements were done an everyday morning at 9:00 o'clock. The readings were expected to indicate the position of the saturated soil water levels below the earth surface. Measurements of streamflow depth and surface velocity with a floating method were conducted on the two gauging stations. The gauging stations were instrumented by rectangular weir for treated and staff gauge for the untreated watershed. The discharges were computed by using area-velocity measurement method. The elapsed time required for the float to reach the outlets was recorded to compute the velocity.

Two pairs of data collectors had manually measured streamflow depth and velocity every 20 min following the commencement of rainfall-runoff events to the end of storm period. Storm period commonly understood as the time elapsed between the beginning and the ending of a single rainfall-runoff event [21]. The data recording continued until the runoff became sediment free. The stream discharge was computed by using the defined cross-sectional area (A) and measured stage (H). A power function of stage-discharge rating curves was developed to get continuous discharge data from treated and untreated watersheds (see Fig. 3a and b).

The total sediment yield from the watershed was computed through suspended sediment concentration (SSC) analysis. That means storm samples were fetched every 20 min until the flow rate dropped and the flowing water turned clear of sediment. Between three and seven samples of one-liter bottles collected during most of the storm event. The samples were filtered using standard Whatman filter papers with a pore opening of 2.5 μm. The filtered sediments were dried in an oven for 24 h at 105 °C. Suspended sediment was estimated by using the Gravimetric method and sediment yield was computed by using Eq. 1.

$$SY = SSC * V \quad (1)$$

Where SY is sediment yield, SSC has suspended sediment concentration (mg/l) and V is the volume of runoff (liter).

² Source of DEM (<https://www.asf.alaska.edu/>).

Time-integrated sampling technique was conducted for nutrient analysis. This was made by mixing equal volumes of sediment mixed water were collected with a regular time interval. The soluble nutrients within the streamflow at the outlets during the rainy season were measured in the water quality laboratory. The nutrient data particularly dissolved phosphorus (DP) and dissolved nitrogen (DN) were organized by making a composite of one storm’s samples and took 100 ml after preserved with 2 ml hydrochloric acid (HCl) to conserve from transport losses. The DP and DN were analyzed by palintest photometer model 7100. The lab analysis for sediment-associated nutrients was done in Amhara Design and Supervision Works Enterprise (ADSWE) soil laboratory. Composite sediment data for each month during the rainy period were taken and the associated nutrients (P by ppm for P and percent for N) were extracted. The particulate fraction of phosphorus was determined using the Olsen method while particulate nitrogen was determined using the Kjeldahl method (Fig. 2).

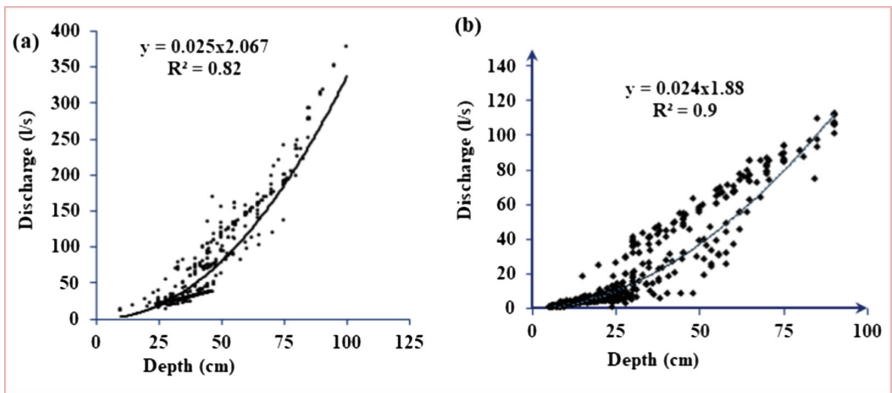


Fig. 2. Stage-discharge rating curve (a) for the untreated and (b) for the treated watershed.

$$N_{sd} = N_c * S_1 + N_d * V \tag{2}$$

Where N_{sd} is dissolved and sediment-associated nutrient loss (mg), N_c is nutrient concentration (mg/ton) and S_1 is the sediment load (ton), N_d is the dissolved nutrient concentration (mg/l) and V is the volume of direct runoff (litter).

The economic value that the farmers incurred to replace the nutrient losses due to runoff is computed based on the price of commercial fertilizers from the local distribution agency (see Tables 4 and 5). Mostly the farmers used UREA and DAP with the proportion of N and P for UREA, (46:0:0) and Diammonium Phosphate (DAP), (18:46:0) in fertilizer analysis system of (N: P: K) ratio, the ratio indicates that 46% of N in UREA and DAP contain 18% N, 46% P₂O₅ and 20% available P. The economic cost value per 1 kg of N and P were computed as follow:

$$\text{Cost of nitrogen} = \text{Price of 1kg Urea} / \text{N content in Urea} \tag{3}$$

$$\text{Cost of phosphorus} = [\text{price of 1kg DAP} - (\text{price of 1kg N} \times \text{N content})] / (\text{Available P in DAP}) \quad (4)$$

The average direct purchase price of 100 kg of UREA \$70 and DAP \$100 in the study period (2015). Also, the price of UREA and DAP including the credited cost were \$74.4 UREA and \$132.5 DAP per 100 kg. Depending on the value the estimated replacement cost for 1 kg N was \$1.6 and available P \$5.2.

3 Results and Discussion

3.1 Rainfall Intensity and Infiltration

The study watershed received an annual rainfall of 665 mm for 2015 and 795 mm for 2016. The peak rainfall intensity was 93.6 mm hr⁻¹ for 2015 and 91.2 mm hr⁻¹ for 2016. To show the relationship between rainfall intensity and infiltration rate, the spatial average infiltration rate and exceedance probability of rainfall intensity were shown in Fig. 3.

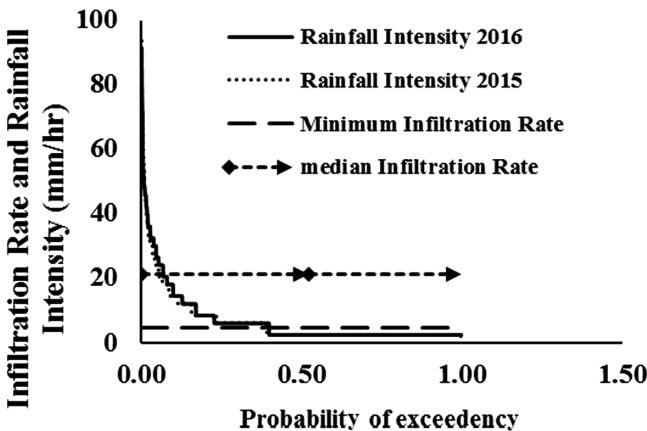


Fig. 3. The exceedance probability of average intensity and median infiltration rate for the Alekt Wenz watersheds in the year 2015 and 2016.

The steady-state infiltration rate for treated watershed ranged from 7 mm hr⁻¹ to 122 mm hr⁻¹ and for untreated watershed ranged from 5 mm hr⁻¹ to 90 mm hr⁻¹. The median infiltration rates from all 24 measurements were 22 mm hr⁻¹ for treated and 19 mm hr⁻¹ for untreated (Fig. 3). This value showed that the SWC activities enhance the infiltration rate in the treated watershed than the untreated one. To compare rainfall intensity with infiltration rate, median infiltration rate, and exceedance probability is meaningful parameters [21]. As shown in Fig. 3 the median infiltration is exceeded 6% in 2015 and 7% in 2016. Only 6% and 7% of the time infiltration rates were exceeded by rainfall intensity.

3.2 Perched Groundwater Level

Perched groundwater level rose up during August, and declined during September. The average water table level below the surface depth was 0.43 m, 0.83 m and 1.14 m for lower, middle and upper slope of treated watershed respectively (Fig. 4). For untreated watershed, the average water table level below the surface depth was 0.54 m, 0.70 m, and 0.77 m for lower, middle, and upper slope, respectively (Fig. 4). Perched groundwater levels fluctuate more on the untreated watershed because of the rainfall amount. The rainfall in the treated watershed has a chance to infiltrate and stabilize the fluctuation.

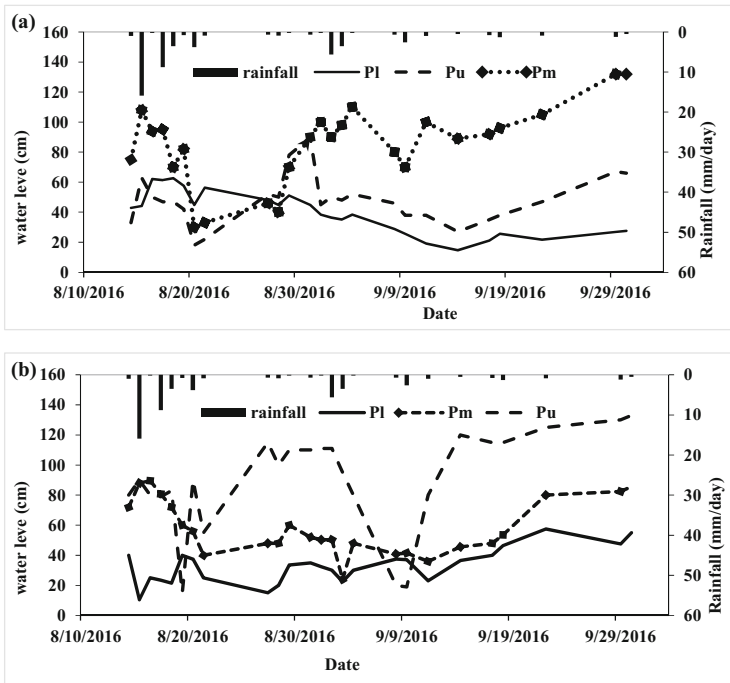


Fig. 4. Perched groundwater level (cm) from the soil surface: (a) from U1 (transect one) the untreated and (b) from treated watersheds (T1) (where PI = piezometer at the lower slope, Pm = at the middle slope and Pu = at the upper slope).

3.3 Streamflow Responses

The average runoff coefficients from treated watershed were 0.02 for 2015 and 0.04 for 2016 and from untreated watershed 0.1 in both of 2015 and 2016. Therefore, the untreated watershed was generating more direct runoff than the treated watershed in both data recording periods. Table 2 shows that the direct runoff reduced by 50.8% in 2015 and 42.2% in the treated during 2016. This results in 17% base flow increment were detected in the treated watershed.

Table 2. The annual direct runoff and base flow responses from *Alekt Wenz* watersheds.

	Treated		Untreated	
	2015	2016	2015	2016
Direct Runoff (mm)	8.5	9.8	17.3	15.3
Base flow (mm)	180.7	212	69.8	195.4

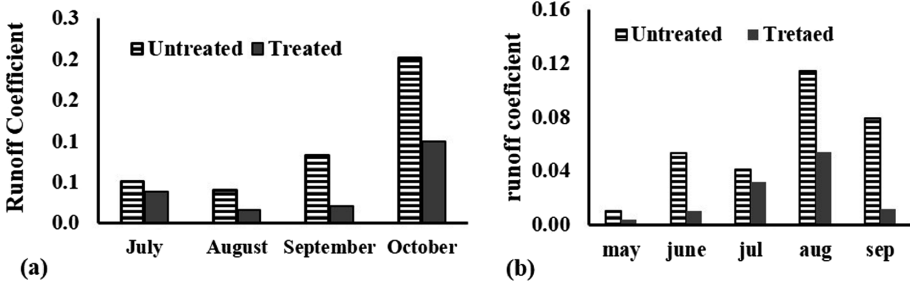


Fig. 5. Runoff coefficient monthly distribution of Alekt Wenz watershed (a) for 2015 and (b) for 2016.

During the late rainy season (August), the runoff was generated by low rainfall with saturated watershed and low infiltration capacity as shown in (Fig. 5).

Figure 6 shows that the streamflow depth was higher in the treated watershed during both data recording periods; this is due to the improvement of infiltration rate and base flow increment through the implemented conservation practices (Fig. 7).

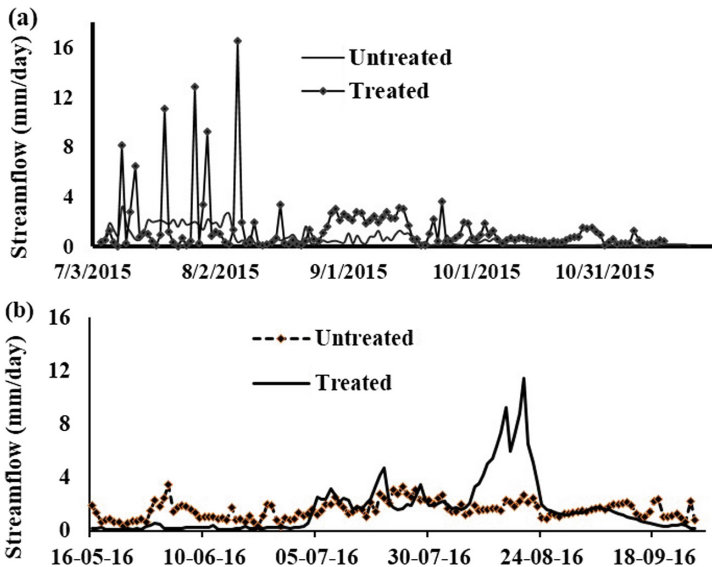


Fig. 6. Time series diagram showing discharge fluctuations obtained from the rating curves for a treated and untreated watershed (a) in 2015 and (b) in 2016.

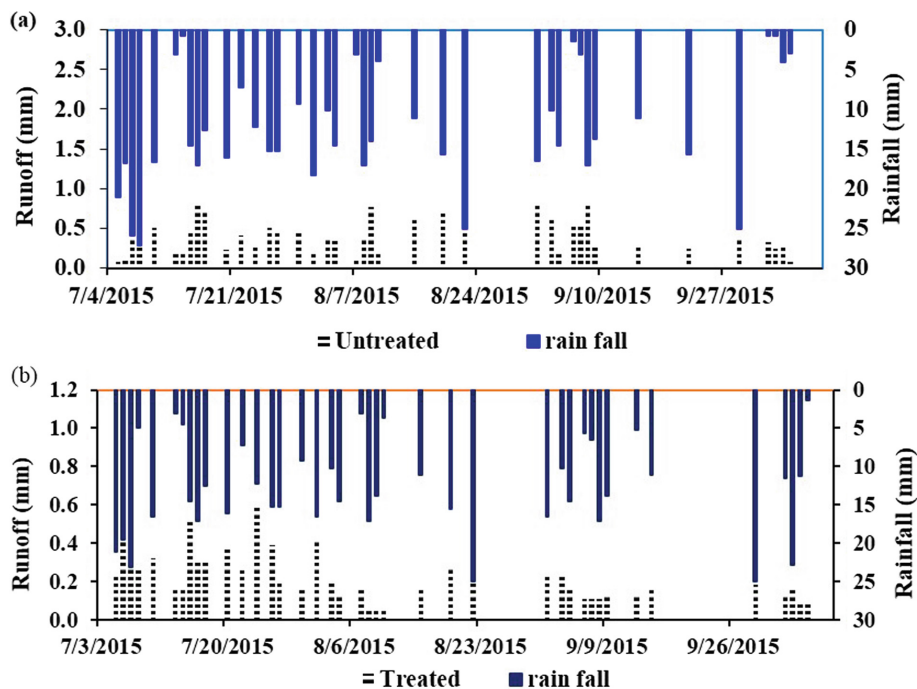


Fig. 7. The rainfall-runoff relationship in 2015 (a), for the untreated and (b), for the treated watershed of the rainy season.

3.4 Suspended Sediment Yield

The reduction of sediment concentration in the treated watershed was due to a decrease in runoff volume and trapped by stone/soil bunds and gabions. Sediment yield was higher during the beginning of the rainfall period because of formation of rills from plowing of the agricultural area. Table 3 shows that a loss from the untreated watershed is higher than the treated watershed. From a total of sediment yield delivery in Alekt Wenz watershed, the treated watershed shares 40.6% in 2015 and 19% in 2016. This is a lower contribution as compared to the untreated watershed sediment yield.

Table 3. Annual sediment yield losses from Alekt Wenz watershed in the year 2015–2016.

Sediment yield ($\text{t ha}^{-1}\text{yr}^{-1}$)	Treated	Untreated
2015	2.4	6
2016	2.1	8.5

The sediment losses from treated part of Alekt Wenz watershed was very much lower than Debre Mawi watershed which had losses of $13 \text{ ton ha}^{-1}\text{yr}^{-1}$ [22]. This value was higher as we compared to the untreated part of Alekt Wenz watershed. The reason

for this difference is higher runoff volume with a different number of active gully heads in Debre Mawi watershed [22] than Alekt Wenz watershed. Besides to this, there is less gully treatment measure in Debre Mawi watershed [23]. However, sediment yield from the untreated watershed of Alekt Wenz was higher than Andit Tid $5.4 \text{ ton ha}^{-1}\text{yr}^{-1}$ and Maybar ($8.8 \text{ ton ha}^{-1} \text{ yr}^{-1}$) [24].

The treated part of Alekt Wenz generated lower sediment yield than Andit Tid and Maybar. Also, Anjeni watersheds lost higher sediment with the value of $22.5 \text{ ton ha}^{-1} \text{ yr}^{-1}$ than Alekt Wenz [24]. This indicated that the SWC practices in Alekt Wenz watershed were more effective than other watersheds. The results of the t-test at 0.05 significance level indicated that the sediment yield from the two watersheds varies significantly. This indicates the implemented SWC practices were effective in reducing sediment losses.

3.5 Nutrient Losses

This study indicated that lower soil nutrient loss from treated watershed than the untreated watershed in both 2015 and 2016. Losses of dissolved nitrogen were higher than losses of dissolved phosphorus, which is lost as sediment-embedded due to the higher affinity of suspended sediment to absorb phosphorus nutrients [25].

As shown in Table 4, the implemented SWC practices have the capacity to diminish nutrient losses from treated watershed by 99% of P and 67.7% of N as compared to untreated watershed during 2015.

Table 4. Nutrient losses and corresponding replacement cost for *Alekt Wenz* watershed in the year 2015.

Watershed Status	Nutrient type	Nutrient losses	Replacement Cost (\$)
		(kg ha^{-1})	$\text{ha}^{-1}\text{yr}^{-1}$
Treated	Psd*	0.02	0.1
	Nsd**	8.2	13.2
Untreated	Psd	0.2	1.2
	Nsd	25.4	41.1

*P_{sd} (Dissolved and sediment-associated Phosphorus),

**N_{sd} (Dissolved and sediment-associated Nitrogen)

Table 5. Nutrient losses and corresponding replacement cost for *Alekt Wenz* watershed in 2016.

Watershed Status	Nutrient type	Nutrient losses (kg ha^{-1})	Replacement Cost (\$) $\text{ha}^{-1}\text{yr}^{-1}$
Treated	Psd*	0.16	0.8
	Nsd**	11.92	19.3
Untreated	Psd	0.8	4.1
	Nsd	61.01	98.6

*P_{sd} (Dissolved and sediment-associated Phosphorus), **N_{sd} (Dissolved and sediment-associated Nitrogen).

During 2016, 75% of P and 64.8% of N, dissolved nutrient losses were conserved by SWC activities from treated watershed when we compared with the untreated watershed (Table 6). The farmers who live in the untreated watershed incurred a higher cost (\$42.3) than the treated one (\$13.3) to replace the lost N-P nutrient in 2015. Also, the untreated watershed incurred \$102.8, which is higher than the treated one (\$20.1) to replace the nutrient of N and P.

4 Conclusions

This study showed that SWC practices were effective in reducing runoff, losses of sediment and soil nutrients as well as in increasing infiltration rate. The farmers incurred nearly 80.4% cost for fertilizer application in the untreated watershed than the treated watershed. Generally, the conservation practices enhance infiltration rate and contribute water to the groundwater, and base flow in the treated watershed had been improved.

Therefore, implementation of SWC practices according to hydrological characteristics of the watershed is crucially mandatory to reduce sediment losses. To realize the effectiveness of various SWC measure continuous hydrological data recording and evaluation of the data are very important. It is important to investigate the long-term effect of SWC measures in reducing soil and nutrient losses. In addition, it is important in evaluating the linking between watershed characteristics and hydrological responses.

In this study, different SWC measures are proposed for the untreated watershed, such as the treatment of gullies, gabions, land development, biological measures, and exclosures to control soil and nutrient losses.

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