

Assessing the impacts of different land uses and soil and water conservation interventions on runoff and sediment yield at different scales in the central highlands of Ethiopia

Research Paper

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Abstract

To tackle the problem of soil erosion and moisture stress, the government of Ethiopia introduced a yearly mass campaign where communities get together and implement various soil and water conservation (SWC) and water harvesting (WH) practices. Although the interventions are believed to have reduced soil erosion/sediment yield and enhanced surface and ground water, quantitative information on the impacts of various options at different scales is scarce. The objective of this study was to assess the impacts of different land uses, SWC and WH interventions on water and suspended sediment yield (SSY) at plot and watershed scales in the central highlands of Ethiopia. Standard erosion plot experiments and hydrological stations were used to monitor the daily water and SSY during 2014 to 2017. The results show differences between treatments both at plot and watershed scales. Runoff and soil loss were reduced by an average 27 and 37%, respectively due to SWC practices at the plot level. Overall, SWC practices implemented at the watershed level reduced sediment yield by about 74% (in the year 2014), although the magnitude of sediment reduction due to the SWC interventions reduced over time. At both scales it was observed that as the number of years since SWC measures have been in place increased, their effectiveness declined due to the lack of maintenance. This study also revealed that extrapolating of plot data to watershed scale causes over or under estimation of net erosion.

Introduction

Land degradation in the form of soil erosion has significant on-site as well as off-site effects in Ethiopia. On site, it imposes an undesirable impact on agricultural production and undermines implementation and success of sustainable intensification (Adimassu *et al.*, 2012; Gebrehiwot *et al.*, 2013). Due to mismanagement, Ethiopia experiences the worst soil erosion problem in the world (Hengsdijk *et al.*, 2005). In the Blue Nile Basin, soil losses due to runoff vary from 1 to over 400 tons ha⁻¹ yr⁻¹ (Hurni, 1988; Mitiku *et al.*, 2006; Tebebu *et al.*, 2010). The empirical model also estimated that the average gross soil loss for the Blue Nile reached about 85 tons ha⁻¹ yr⁻¹ (Tamene and Le, 2015). Different studies also reported that high soil loss occurs from cultivated land, ranging from 50 to 179 ton ha⁻¹ yr⁻¹ (Shiferaw and Holden, 1999; Adimassu *et al.*, 2012). In addition, annual crop yield reduction of 1–2% is estimated due to soil erosion in Ethiopia (Hurni, 1993). Moreover, in Ethiopia approximately 17% of the potential agricultural gross domestic product in 1990 was lost because of soil degradation (EPA, 1997). The direct cost of soil loss due to mismanagement reaches at \$106 million a year (Bojo and Cassells, 1995). On the other hand, soil erosion also has tremendous off-site effects, specifically siltation of reservoirs, irrigation canals, flooding as well as deterioration of ecological services. It is estimated that the trans-boundary Rivers of Ethiopia alone carry about 1.3 billion tons of sediment each year (Birhane, 2003). Due to high soil erosion, it is also estimated that 95% of the Nile River sediment is coming from the Ethiopian highlands

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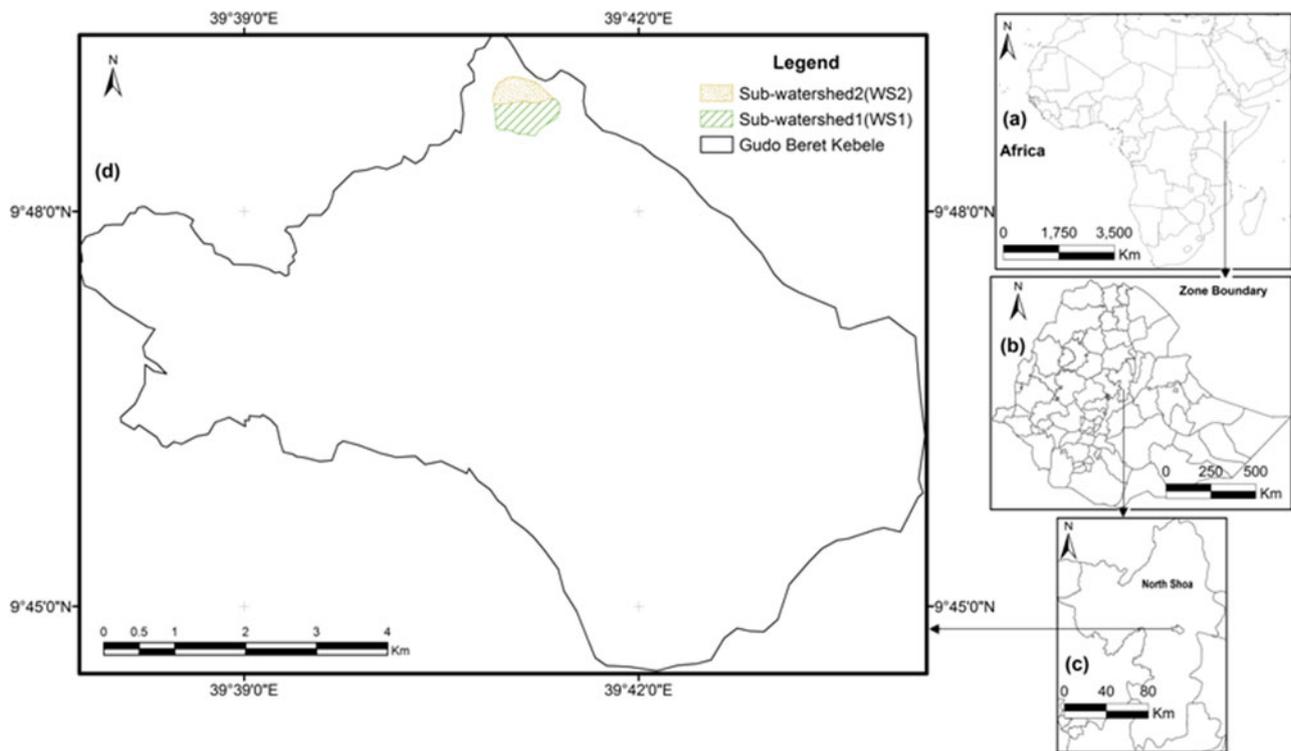


Fig. 1. Study location in the Gudo Beret Kebele, central Ethiopia; (a) location of Ethiopia in Africa; (b) Ethiopian zonal boundary; (c) North Shoa zone and (d) two study sub-watersheds in Gudo Beret Kebele.

(Ahmed and Ismail, 2008). The water harvesting (WH) schemes developed for supplemental irrigation in Ethiopia have been compromised due to rapid siltation (Tamene and Vlek, 2007). And so, the largest hydropower dam of Africa when completed (the Great Ethiopia Renaissance Dam) is expected to be suffering due to high siltation problem. The high soil erosion in the Ethiopian highlands also affects downstream hydraulic structures whereby siltation in Roseires Reservoir in the Blue Nile and Aswan High Dam in the main Nile has not only reduced a significant amount of reservoir capacity but also is a challenge requiring expensive irrigation canal maintenance (Ahmed and Ismail, 2008). On the other hand, land use land cover change has a considerable effect on stream flow (Bewket and Sterk, 2005; Rientjes *et al.*, 2011; Koch *et al.*, 2012; Tekleab *et al.*, 2013). Other studies have also reported that it has an impact on sediment yield (Girmay *et al.*, 2009; Setegn *et al.*, 2009; Gebremicael *et al.*, 2013; Maeda *et al.*, 2013; Spalevic *et al.*, 2017)

Considering the on- and off-site effects of soil erosion and the associated economic as well as environmental burdens, the government of Ethiopia designed a national program to tackle land degradation. Significant amount of soil and water conservation (SWC) work has been implemented as of 1975 (Shiferaw and Holden, 1999; Hurni, 2000c; Osman and Sauerborn, 2001; Taddese, 2001). After the 1984–85 drought, the massive re-afforestation and conservation campaign intensified until 1990 (Berry, 2003). Currently, there are government claims that billions of trees have been planted, and millions of hectares of land conserved through the construction of terraces, deep trenches, percolation ponds, etc. across the different parts of the country.

Despite non-systematic and scattered, results of some studies showed the impacts of the various interventions. For instance,

an impact assessment study in Anjeni watershed reported that land suitability of the watershed for crop production improved due to terracing (Alemu *et al.*, 2013). Moreover, the average financial internal rate of return was 301% in Anjeni watershed due to productivity enhancement caused by improved SWC practices (Adgo *et al.*, 2013). Integrated catchment management is also efficient and effective at combating land degradation in Northern Ethiopia (Nyssen *et al.*, 2009). Other studies (Descheemaeker *et al.*, 2006; Mekuria *et al.*, 2007; Yayneshet *et al.*, 2009; Angassa and Oba, 2010) also showed the success of interventions such as enclosures in some parts of the country. Most of the studies aimed to assess the impacts of interventions focused on single practice and/or have not assessed impacts at different scales. This study attempted to evaluate the impacts of land use/cover types and SWC practices on soil loss and runoff at different scales. It is also attempted to evaluate the reduction efficiency of the interventions over years. The information generated in the study will both provide evidence on the performances of the various SWC practices and helps raise awareness of the local communities and government bodies and facilitate planning and targeting.

Materials and methods

Location and brief description of the study area

This study was conducted in a watershed located in the most eastern part of the Jemma river sub-basin of the Blue Nile River Basin in Ethiopia (Fig. 1). Administratively, the site is located in the Gudo Beret Kebele (village) of the Basona Worena district. Considering temperature (six thermal zones) and moisture (seven classes of length of growing periods), Ethiopia is classified into 32 major agro-ecologies (MoARD, 2005). Based on this

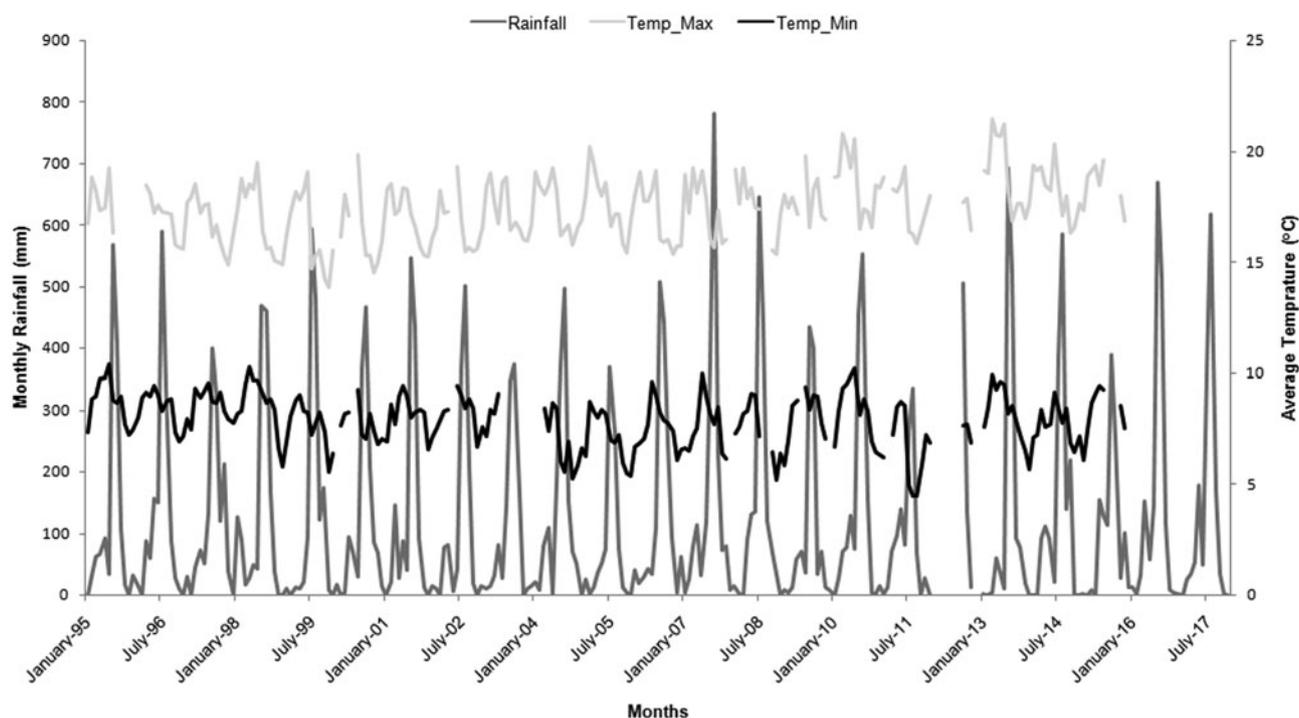


Fig. 2. Long term (1995–2017) monthly rainfall and average monthly temperature at Gudo Beret nearby metrological station in central Ethiopia.

classification, the study watersheds are classified as cool sub-moist highland, a zone covering more than 13,000 km² area (1.2%) of the country. For this class, temperature varies from 11 to 15°C with an elevation variation of 2400–3200 m above sea level.

Meteorological data from a nearby station show daily minimum temperature within a range of 0.5–19.5°C. The maximum daily temperature ranges from 9.5 to 28.5°C. Monthly rainfall distribution for each year is highly variable (coefficient of variation, CV > 30%) except in July and August (25%). Despite high monthly rainfall variability, annual total variability is quite low (CV = 16%) with an average rainfall amount of 1449 mm and standard deviation of 228 mm (Fig. 2). The nearby metrological station data also revealed that the study area received bimodal rainfall, *Kiremit* (June to September) being the long-rainy season and *Belg* (February to March) is short-rainy season. However, there is little occurrence of rains and/or absence during the short-rainy season (*Belg* rain). The same pattern is reported by other studies in the region (Engda, 2009).

The major farming system of the area is crop-livestock production. The major crops grown include barley, wheat, faba bean and potato. The area has generally moderate slope but descending to very complex, rugged and steep slope toward the Jemma River.

Selection and characterization of the sub-watersheds

Two proximate sub-watersheds with similar physiographic characteristics were identified to assess the impacts of SWC practices on runoff and soil loss. The two sub-watersheds are adjacent to each other with an altitude range between 3040 and 3160 m above sea level. Both sub-watersheds have oval shape where the dimension is wider at the middle part (Fig. 3).

Sub-watershed1 (WS1) where SWC practices were implemented as of 2013 is about 910 m long and 457 m wide at the middle part of the watershed. Sub-watershed2 (WS2) without SWC only

in 2014 is about 837 m long and 360 m wide at its middle part. SWC practices were introduced in sub-WS2 since 2015. About 87 and 85% of the area has slope greater than 8% for the WS1 and WS2, respectively (Table 1). Land use distribution of the two watersheds is similar whereby about 68 and 64% of the WS1 and WS2, respectively, are classified as cultivated land (Table 1).

Our field assessment and aerial photograph interpretation showed minor differences in overall topographic and geomorphological settings. The dominant landform elements in both sub-watersheds in ascending order are spur, ridge and slope (Table 1).

Data collection and analysis

Experimental set-up to assess soil erosion and runoff at the plot level

Runoff plots were setup within sub-WS1 to evaluate the effect of different land uses and SWC practices on runoff and soil loss during 2014 to 2017 rainy season (*Kiremit*) (Fig. 3). Four treatments (with different land use and management options) were assessed (Table 2). Treatment 1 was control (cultivation without soil bund) where rotation of faba bean with barley was practiced. Faba bean was planted in the first year of the experiment. Treatment 2 was similar land use to treatment 1 but it had SWC measures in place mainly level bund with trench. The spacing between consecutive conservation structures inside the plot was 12 m. Treatment 3 was established at woodlot (*Eucalyptus* trees) treated with well-established grassland underneath. Treatment 4 was grazing land (cut and carry practiced). The plot-level treatment at the grazing was within the treated watersheds, thus free roaming and grazing of livestock is restricted.

After the locations and land uses were identified, hydrologically bounded runoff plots of 15 m length and 4 m width were

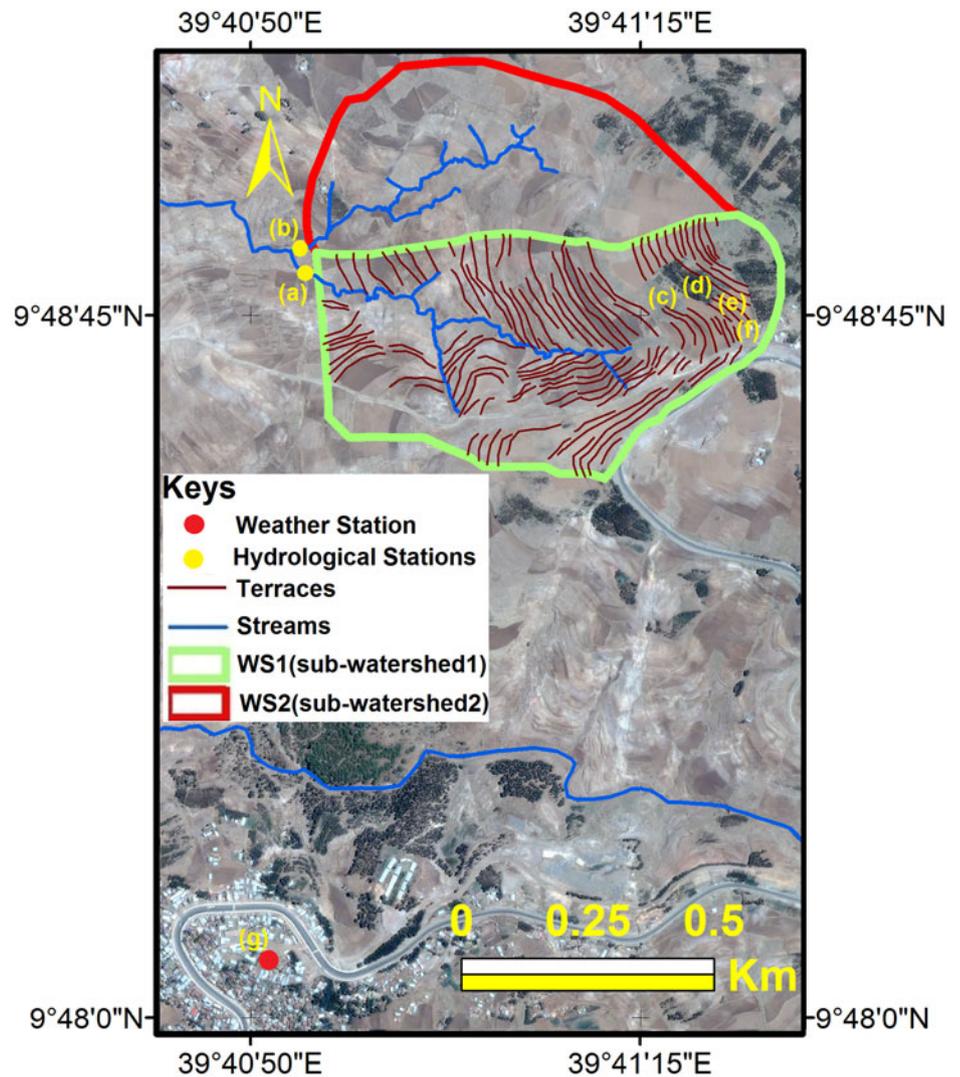


Fig. 3. Study sub-watersheds in the Gudo Beret village (Geda watershed), central Ethiopia; (a and b) locations of hydrological stations at the outlets of sub-watersheds WS1 and WS2, respectively; and runoff plots locations representing (c) grazing land; (d) woodlot; (e) crop with SWC; (f) crop without SWC and (g) weather station.

installed for each treatment (Fig. 4) within sub-WS1. Eight runoff plots (four treatments with two replications) were laid out on 10% land slope. Plot boarders were enclosed by iron sheets except for lower ends where collecting trough and slotting divisor were placed. The iron sheets were placed 18 cm above and 15 cm below the ground surface to prevent run-on entering into and runoff out of the plots. Water and sediment collection tanks (tank A and tank B) were placed in a cascading manner to receive runoff and eroded soil collected from each plot. Each tank was attached to the container through a device (slotting divisor) to receive fraction of runoff from each plot (Adimassu *et al.*, 2012). The two tanks were firmly fixed into the ground so that flood or subsurface flow will not overturn them. To complement the existing meteorological station (owned by national meteorological agency for precipitation and temperature), an automatic weather station (for precipitation, temperature, relative humidity, wind speed and soil moisture) was installed at Gudo Beret town, about 1 km away from the study plot location.

Runoff and soil loss estimation at the plot level

The depth of water collected in both tanks A and B was measured from each treatment using a graduated measuring stick every morning on a daily basis in order to determine the volume of runoff. After it was stirred thoroughly, half a litter of runoff sample

was taken for sediment concentration analysis using special evaporation method (Guy, 1977). In the laboratory, the water samples were put into the beakers and 10 ml of 10% HCl was used in each beaker as a flocculating agent to reduce the settling time of naturally dispersed clay and speed up the siltation process within 24 h. After carefully pouring out the clean water, the remaining turbid sample was taken and oven dried at 105°C for 24 h in order to determine the dry soil weight. In addition, the wet sediment on runoff collecting ditch (the place between the plot and the slot divisor) was weighed and known sample (100–250 g) taken for oven dried in order to determine the dry sediment weight. The suspended sediment concentration (SSC, g l^{-1}) of each sample was determined as the mass of suspended sediment divided by the sample volume. The SSC was then multiplied by the total daily volume of run-off in order to estimate the total suspended soil losses. The total daily soil loss was calculated as the sum of suspended soil loss and dry sediment from runoff collecting ditch.

Installing hydrological stations to estimate discharge and sediment yield at the watershed level

To facilitate comparing treatment effect, a pair of sub-watersheds with similar terrain, soil, and land use characteristics was identified within the study watershed. Two hydrological stations were

Table 1. Land use distribution, slope pattern and landform elements of the study sub-watersheds in Gudo Beret, North Shoa, Ethiopia

Land use and slope characteristics	WS1		WS2	
	Area (ha)	Area (%)	Area (ha)	Area (%)
Land use				
Crop	22.96	67.9	14.13	64.0
Grazing	7.59	22.4	6.35	28.8
Woodlot	2.24	6.6	1.33	6.0
Impervious	1.04	3.1	0.28	1.3
Slope class				
1 ≤ 8%	4.47	13.2	3.38	15.3
2 ≥ 8%	29.36	86.8	18.70	84.7
Landform elements: according to (Jasiewicz and Stepinski, 2013)				
Summit	1.98	5.8	0.95	4.3
Ridge	7.82	23.1	6.09	27.6
Spur	11.12	32.9	10.18	46.1
Slope	6.60	19.5	2.76	12.5
Hollow	5.65	16.7	1.71	7.8
Valley	0.66	1.9	0.38	1.7

then installed at the outlet of the two sub-watersheds to measure discharge and sediment yield (Fig. 3). The two sub-watersheds have an area of 33.83 and 22.08 ha. The former is treated with about 0.36 km ha⁻¹ length terrace integrated with trench and grass strips, while the second is without any significant SWC structures in place (only in 2014). SWC measures were implemented from 2015 onward (in sub-WS2) and our analysis considered temporal variation. Manual measurements of water flow and sediment sampling were made on two gaged streams at the outlets of the two sub-watersheds. Each measurement consisted of reading flow depth, determining runoff discharge (Q , m³ s⁻¹) using the velocity area method and sampling the suspended sediment. Gage readings were taken two times a day (morning and evening). If abrupt change in stream depth is observed especially during rainfall event, more than three measurements and sediment sampling were taken every day. To avoid bias on the estimation of the sediment export, data were collected as much as possible on a flow proportional basis since highest suspended sediments were observed during rainfall events. In order to determine discharge at different flow depth, velocity and cross-sectional area measurement were occasionally taken at the outlet of the watershed. Accordingly, measurements (at different depths in between 10 and 72 cm) were taken to determine discharge-depth relation. Rating (fitting) curves are determined for low (<15.5 cm), medium (15.5–30 cm) and high flow (>30 cm) in both WS1 and WS2 (Fig. 5). Refer to equations (Equations 1 and 2) in the section ‘Discharge, sediment concentration and sediment yield estimation’.

Discharge, sediment concentration and sediment yield estimation

Once flow depth data were collected, discharge (Q) was determined using the area velocity method (Bartram and Ballance,

1996; Vanmaercke *et al.*, 2010). To convert the flow depth to runoff discharge, depth–discharge relationships were developed between the manually measured instantaneous runoff discharges and their corresponding flow depth:

$$Q = rd^s \quad (1)$$

$$Q = ad^2 \pm bd \pm c \quad (2)$$

where Q is the discharge in m³ s⁻¹; d is the calibrated flow depth in cm and a , b , c , r and s are empirical constants. The power equation (Equation 1) is best fitted for low and medium flows in both watersheds. The polynomial equation (Equation 2) is best fitted for high flow in both watersheds. Refer to empirical constants of the fitting curves shown in Figure 5.

For sediment concentration analysis, around 500 ml river water sample was taken using integrated sediment sampling. The same procedure as in the section ‘Runoff and soil loss estimation at the plot level’ was used for sediment concentration analysis in the laboratory. Daily sediment export values were then calculated as (Asselman, 2000):

$$Q_{s,d} = \sum_i^n (Q_i \times SSC_i \times T_i) \quad (3)$$

where $Q_{s,d}$ is the daily sediment export (ton day⁻¹); n is the number of sediment sampling intervals per day; Q_i is the runoff discharge for each sediment sampling interval (m³ s⁻¹), derived from the continuous flow depth series with Equations (1) and (2); SSC_i is the corresponding estimated SSC (kg m⁻³) and T_i is the corresponding time interval (s). Total sediment export was then calculated as the sum of all $Q_{s,d}$ values. For statistical analysis purpose, the daily discharge data were summarized on weekly basis.

Land use, slope, terrace length and hydrological analysis

The land use of the study watershed was produced from high resolution (0.5) PLEIADES satellite image (2013) using ArcGIS 10.1. After defining training area and signature files, the maximum likelihood classification tool was used to produce land use map of the study area. Slope of the study watersheds was produced from the recently released SRTM 30 m DEM (Jarvis *et al.*, 2008). The length of the terrace of the study watershed was estimated from Goggle Earth (since the area has high resolution recent image) on screen digitizing using Google Earth tools (Fig. 3).

A web GIS-base Hydrological Analysis Tool was used to separate base flow using the recursive digital filter method (Lim *et al.*, 2005; Recha *et al.*, 2012). Total daily flow (91, 136, 94 and 91 days for the respective 2014, 2015, 2016 and 2017 year) were used for both watersheds in analysis. The base flow index (BFI) and the flashiness index (RB index) were used to characterize the impacts of land management in the sub-watersheds hydrology. The BFI (the ratio of base flow to total flow) indicates the dynamics of stream water in relation to the ground water aquifer (Moliere *et al.*, 2009; Berhanu *et al.*, 2015). The RB index indicates the frequency and rapidity of short term changes

Table 2. Treatments in terms of land use types and management practices for the study site

Treatment number	Treatment	Land use	Managements
Treatment 1	Control (cultivation without soil bund)	Crop land	Rotation of faba bean with barley was practiced in the farm. Faba bean (in 2014 and 2016) and barley (in 2015 and 2017) were planted during the time of the experiment
Treatment 2	Cultivation with soil bund and trench	Crop land	Recently constructed soil bund with trench. The dimension of the trench was 3.5 m length, 50 cm width and 30 cm depth. Spacing between conservation structures is 12 m. Similar cropping system and crop type to treatment 1 were used
Treatment 3	Eucalyptus trees	Woodlot	There is dense understory whereby the area between trees is covered by grass
Treatment 4	Grazing land	Grazing land	A controlled grazing system of cut and carry practice is used

**Fig. 4.** Setup of the experimental plot to assess runoff and soil erosion at the Gudo Beret village.

in stream flow (Baker *et al.*, 2004):

$$RB_{\text{index}} = \frac{\sum_{i=1}^n |q_{i-1} - q_i|}{\sum_{i=1}^n q_i} \quad (4)$$

where i is the time step ($i = 1, 2, \dots, n$) and q is the daily flow.

Data organization for scale comparison

In order to derive the watershed values, the plot soil loss and runoff values were used with the corresponding land use types and management practices. The weighted average plot values (based on proportional area of each land use) were used to compare with that of water and sediment yield measured at the watershed scale. Soil loss and runoff at the different scales were extracted per land use/cover types to understand major differences and possible drivers.

Data analysis (statistical)

The runoff and soil loss data were subjected to analysis of variance using the SAS statistical computer package version 8.2. The total variability for each trait was quantified using separate and pooled

analysis of variance over years using the following model (Gomez and Gomez, 1984):

$$P_{ijk} = \mu + Y_i + R_{j(i)} + T_k + TY_{(ik)} + e_{ijk} \quad (5)$$

where P_{ijk} is the total observation, μ is the grand mean, Y_i is the effect of the i^{th} year, $R_{j(i)}$ is the effect of the j^{th} replication (within the i^{th} year), T_k is the effect of the k^{th} treatment with i^{th} year, $TY_{(ik)}$ is the interaction of k^{th} treatment with i^{th} year and e_{ijk} is the random error. A least significant difference test at the 5% level of significance was used in order to establish the differences among the means.

Results

Runoff and soil loss at the plot level

Within 4 years, a total of 48 runoff events (15, 9, 9 and 15 events, in years 2014, 2015, 2016 and 2017, respectively) were observed. The highest mean runoff (434 mm) was observed on grazing land and was highly significantly ($P < 0.01$) different compared to that of the woodlot and managed crop land treatments

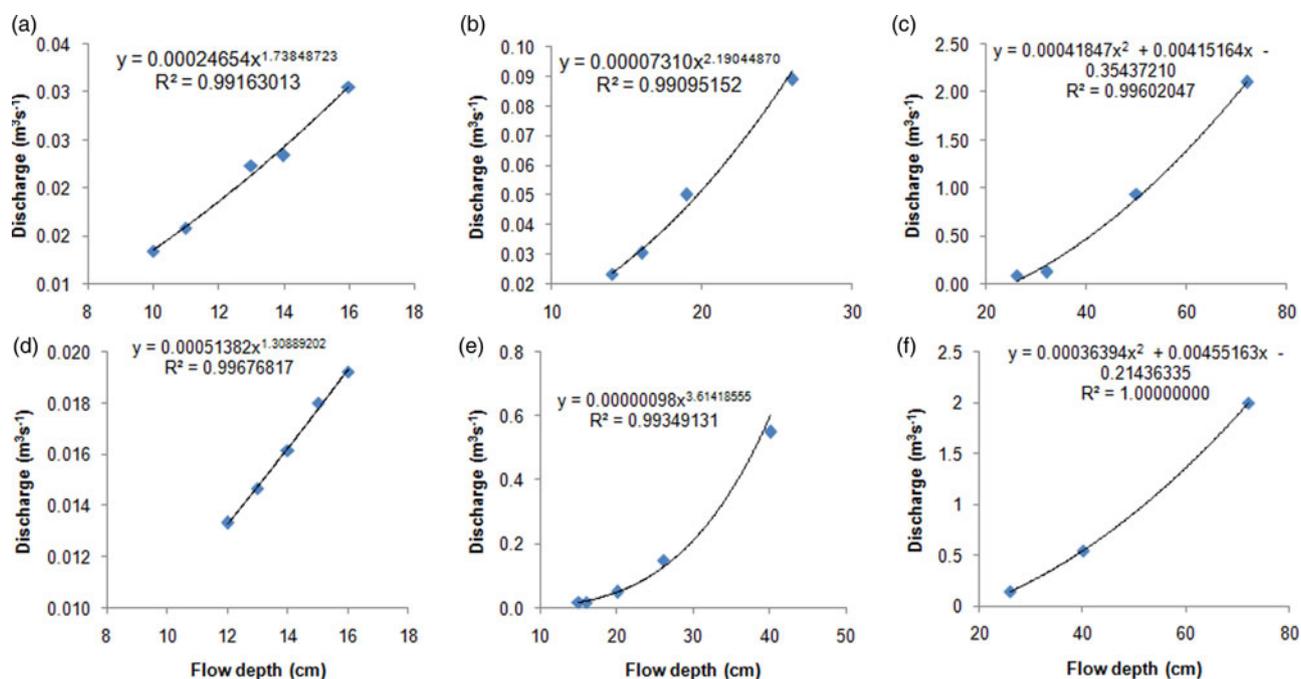


Fig. 5. Rating curves: (a), (b) and (c) are rating curves developed for the respective low, medium and high flow for WS1; and (d), (e) and (f) are rating curves developed for the respective low, medium and high flow for WS2.

(Fig. 6). In the period of our study, terraces together with trenches reduced runoff by 44, 31, 14 and 17% on crop land in comparison with unmanaged crop lands in the respective years of 2014, 2015, 2016 and 2017, with a mean reduction of 26%. Figure 6 shows that eucalyptus woodlots averagely reduced runoff by 20% over the study period in comparison with unmanaged crop lands.

In terms of soil loss, the highest mean rate (8.56 ton ha⁻¹) was recorded from unmanaged cropland and this is highly significantly ($P < 0.01$) compared to other land use types (Fig. 7).

Discharge and sediment yield at the watershed level

The comparisons of discharge and sediment yields at the watershed level are based on sub-WS1 with SWC and sub-WS2 without SWC practices for the year 2014, and with various ages of SWC practices in years 2015, 2016 and 2017 (Table 3). The results of the first year (2014) discharge and sediment yield assessment showed clear differences between the two sub-watersheds; with and without SWC practices. For statistical analysis purpose, the daily discharge data were summarized on weekly basis. Discharge showed significant variation ($P < 0.01$) between the two sub-watersheds in the first year. However, there were no significant differences in the second, third and fourth years (Table 4). Due to the lack of maintenance, the effectiveness of SWC is reducing over the years. This means that the SWC would not provide the intended service more than four years for this particular case. In the first year (2014) discharge was 298 and 535 mm from WS1 and WS2, respectively. A 44% reduction in discharge was observed due to the implementation of SWC measures at the sub-watershed scale. The intervention impact is also reflected on storm unit hydrograph (Fig. 8). The discharge of sub-WS1 is smaller due to the fact that some of the water is retained inside the trench for ground water recharge which can contribute to subsequent downstream base flow. The higher BFI (0.53) and the lower flashiness index (0.14) were also observed

in sub-WS1 in 2014. The daily result showed that a significant amount of discharge had occurred during rain events for sub-WS2. On the contrary, more or less uniform discharge with minimal fluctuation was observed for sub-WS1 (Fig. 9a). WS2 was more efficient in reducing surface runoff in 2016 and 2017, although, there was no significant difference between the two sub-watersheds (Table 4; Fig. 9c, d). An 8 and 2% reduction in discharge was observed in WS2 with younger SWC measures in comparison with WS1 with relatively older SWC measures, in 2016 and 2017, respectively. The WH efficiency reduction observed at the plot level is also reflected at the sub-watershed scale.

The suspended sediment yields (SSYs) of the sub-watersheds with (WS1) and without (WS2) SWC measures were significantly different ($P < 0.05$) at about 1.21 and 4.72 ton ha⁻¹, respectively in 2014 (Fig. 10a; Table 4). The SWC measures have trapped a considerable amount of sediment inside the trench in WS1.

WS2 was more efficient in reducing sediment in all the three years, although, the SSY was not significantly different in 2015, 2016 and 2017 (Table 4; Fig. 10b–d). In the fourth year (2017), the SSY was 3.70 and 3.03 tons per hectare of land from WS1 and WS2, respectively. A 18% reduction in SSY was observed due to the younger (3 years old) SWC measures in WS2 in comparison with the older SWC one (5 years old) in WS1. The volume of the trench is reducing over the years due to siltation and sedimentation. As a result the efficiency of the structure (SWC) reduces as the age increases. Although, the regular maintenance of the structure is important for sustainability, it is rarely happening in the area. The statistical analysis also showed that in terms of SSY, there were no significant differences between the one, two, three and four year old SWC measures in both sub-watersheds that were observed in the second and third years of study (Table 4; Fig. 10b, c).

Just like the plot level observation, as the number of years since SWC measures were in place increased, their effectiveness

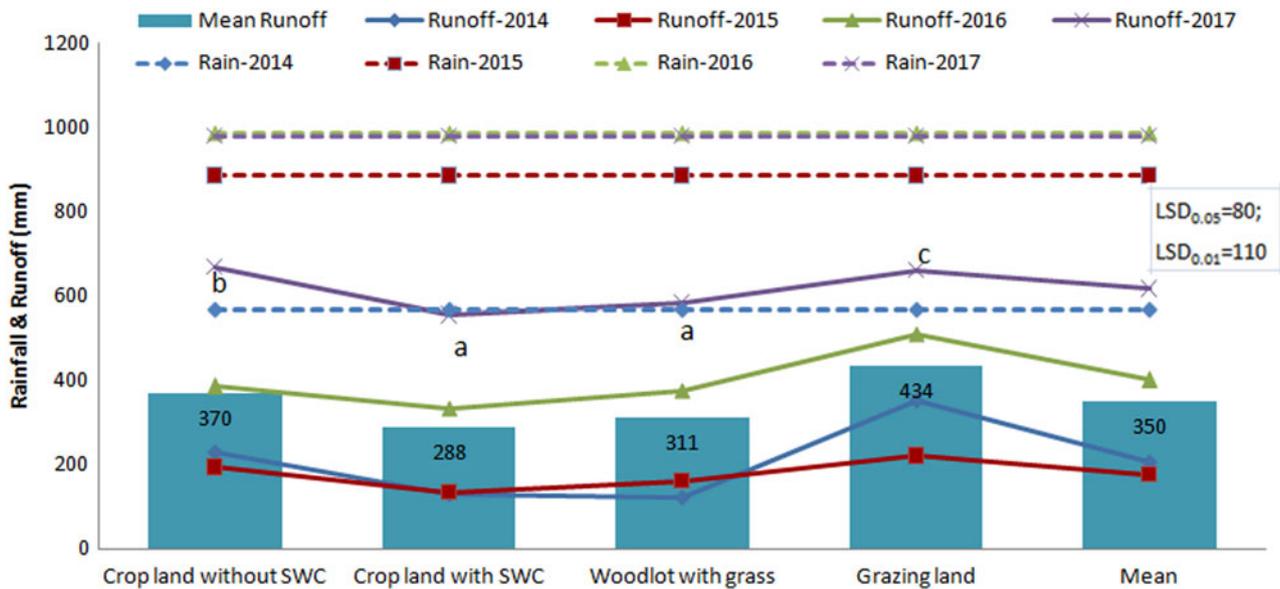


Fig. 6. The effect of land use and management on runoff at Gudo Beret village for runoff events recorded in years 2014, 2015, 2016 and 2017. Different letters denote statistically significant differences between the treatments at $P < 0.05$.

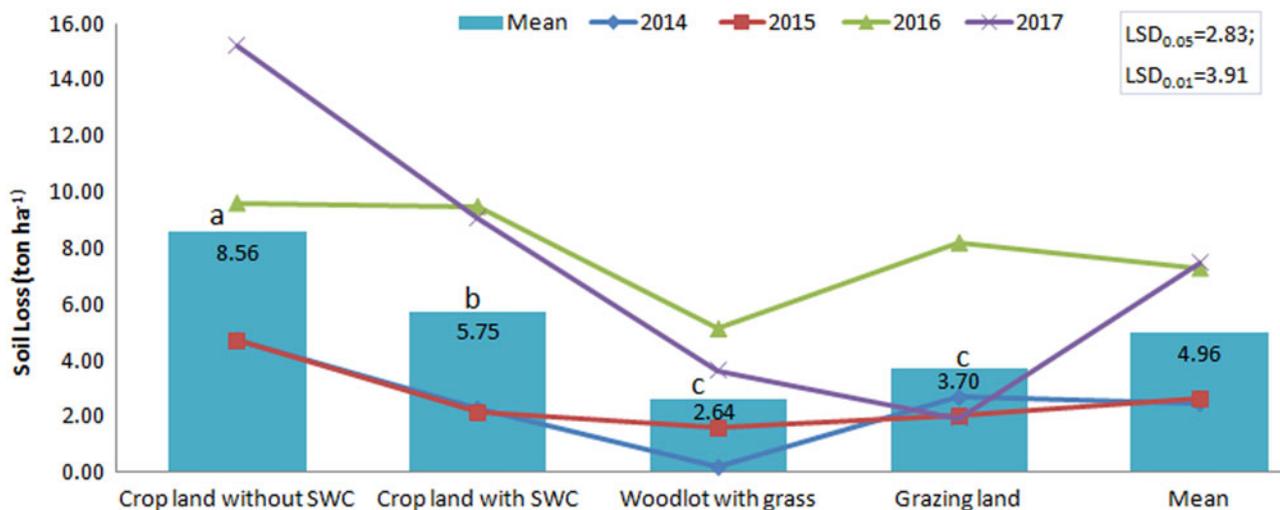


Fig. 7. Effects of land use and management on soil loss at Gudo Beret village for runoff events recorded in years 2014, 2015, 2016 and 2017. Different letters denote statistically significant differences between the treatments at $P < 0.01$.

Table 3. Number of years since the implementation of SWC in the study sub-watersheds

Year	Number of years since the implementation of the interventions	
	Sub-WS1	Sub-WS2
2014	2	0
2015	3	1
2016	4	2
2017	5	3

declined (Fig. 11). In the first year (2014), 80% more discharge retention and 291% more sediment yield reduction were realized due to SWC interventions at the sub-watershed level. In 2015, the

older structure in WS1 was only 8% more efficient than the newer structure. However, the older structure was 8 and 2% less efficient in discharge retention compared to the relatively newer structures in years 2016 and 2017, respectively. In terms of sediment reduction, SWC in sub-WS1 was 12, 17 and 18% less effective than the sub-WS2 in years 2015, 2016 and 2017, respectively. As the age of SWC increases the trap efficiency of the trench reduced due to the lack of regular yearly maintenance.

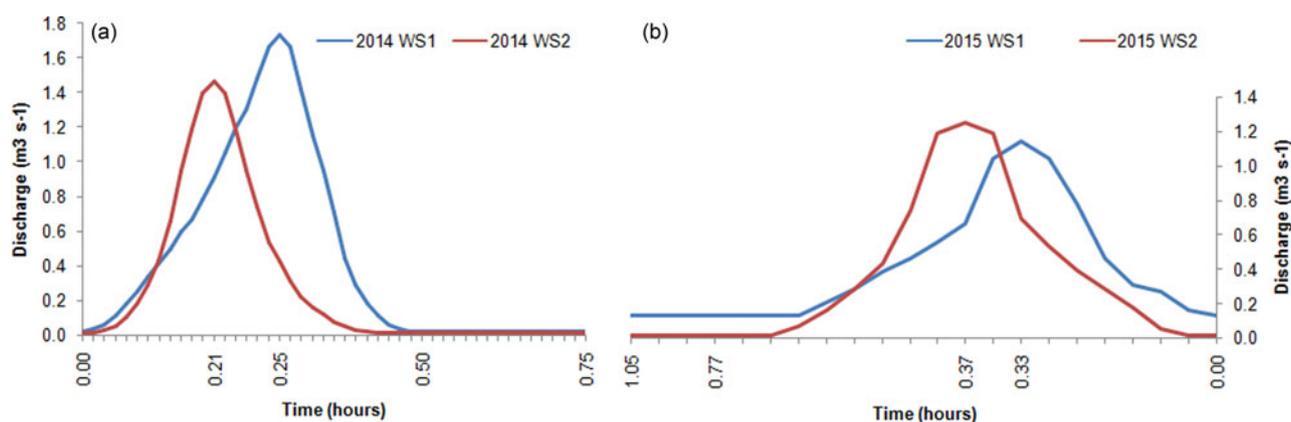
Soil loss estimates at different scales

Runoff and soil loss analyses were done at both plot and landscape scales. Table 5 shows the soil loss values at the plot level extrapolated proportionally to a watershed scale for WS1 and WS2 in 2014. Although, the experimental plots were located in WS1, the control (cropland without SWC) was used for

Table 4. Discharge and sediment yield during the study period (2014–2017) for the Gudo Beret village, central Ethiopia

Year	Sub-watershed	Discharge (mm)	Significance level	SSY (ton ha ⁻¹)	Significance level	BFI	Flashiness index
2014	WS1: 2 years SWC (33.83 ha)	298	**	1.21	*	0.53	0.14
	WS2: without SWC (22.08 ha)	535		4.72		0.34	0.41
2015	WS1: 3 years SWC (33.83 ha)	502	NS	4.96	NS	0.38	0.15
	WS2: 1 year SWC (22.08 ha)	540		4.38		0.38	0.26
2016	WS1: 4 years SWC (33.83 ha)	822	NS	9.34	NS	0.48	0.055
	WS2: 2 years SWC (22.08 ha)	755		7.76		0.55	0.060
2017	WS1: 5 years SWC (33.83 ha)	413	NS	3.70	NS	0.42	0.24
	WS2: 3 years SWC (22.08 ha)	405		3.03		0.36	0.31

**Highly significant ($P < 0.01$); *significant ($P < 0.05$) and NS: no significant difference.

**Fig. 8.** Unit hydrograph of storm events on: (a) August 24, 2014 and (b) August 28, 2015 for WS1 and WS2.

extrapolation in WS2. Sediment yield measured at the outlet of the sub-watersheds with SWC (WS1) is 1.21 ton ha⁻¹ while the calculated sub-watershed soil loss based on the plot values is 2.17 ton ha⁻¹, which is an over estimate by 79% in 2014. On the contrary, it is underestimated by 19% for sub-watershed without SWC (WS2) in 2014. In the period 2015–2017, the annual variation was significantly high ($P < 0.01$) and the calculated mean (based on plot data) was an underestimate for sub-watershed WS1 and overestimate for WS2 (Fig. 12).

The study shows that only 56% of the soil eroded at the plot level was lost from the conserved sub-watershed (WS1) due to the fact that most of the sediment had been trapped within the sub-watershed in 2014. The newly applied SWC practices in sub-watershed WS2 was on average 25% more efficient in reducing the soil loss than the old SWC in WS1 for the period 2015–2017 (Fig. 12). In this study, it was also observed that flashiness index negatively correlated with the SSY.

This study reinforced the fact that extrapolating plot data to the sub-watershed scale is problematic and does not give good estimation (Fig. 12 and Table 5).

Discussion

Runoff and soil loss at the plot level

The grazing land runoff amount was 24% higher than that of unmanaged cropland (control). This is possibly because the soil was compacted through livestock trampling, which can reduce

infiltration and increase surface runoff. This is in general agreement with another study which showed a lower infiltration rate on grazing land without manure application (Tadesse *et al.*, 2003). Crop land with SWC measures were averagely reduced runoff by 26% in comparison with unmanaged crop land. Other studies reported mean seasonal runoff reduction of 32% on level bunds, with spatial variability ranging from 27% in Andit Tid (North Shoa Zone, Ethiopia) to 39% in Maybar (Wello, Ethiopia) (Hurni, 2000a, 2000b). It is also observed that trench WH efficiency reduced over years due to the lack of maintenance. The well-established grass cover underneath the woodlot could have contributed to retarding surface flow and encouraging infiltration. Other studies also showed that younger (4 years old) eucalyptus can reduce runoff twice than that of older trees (Vertessy *et al.*, 1996).

The mean soil loss (3.7 ton ha⁻¹) of the grazing land is 51% lower in comparison with unmanaged crop land. This underlines the role of grasses in reducing soil erosion. This is contrary to observations by Tamene and Vlek (2007) where grazing areas showed a higher rate of soil erosion and gully formation. This could be due to differences in management between communal and private grazing lands where protection and management may not be at a more intense level in the former. It was also observed that terraces along with trenches reduced soil loss from cultivated plots by 37% in comparison with unmanaged crop land. A similar study in northern Ethiopia showed 68% annual reduction in soil loss from areas conserved with stone bunds coupled with trenches (Gebremichael *et al.*, 2005). It has

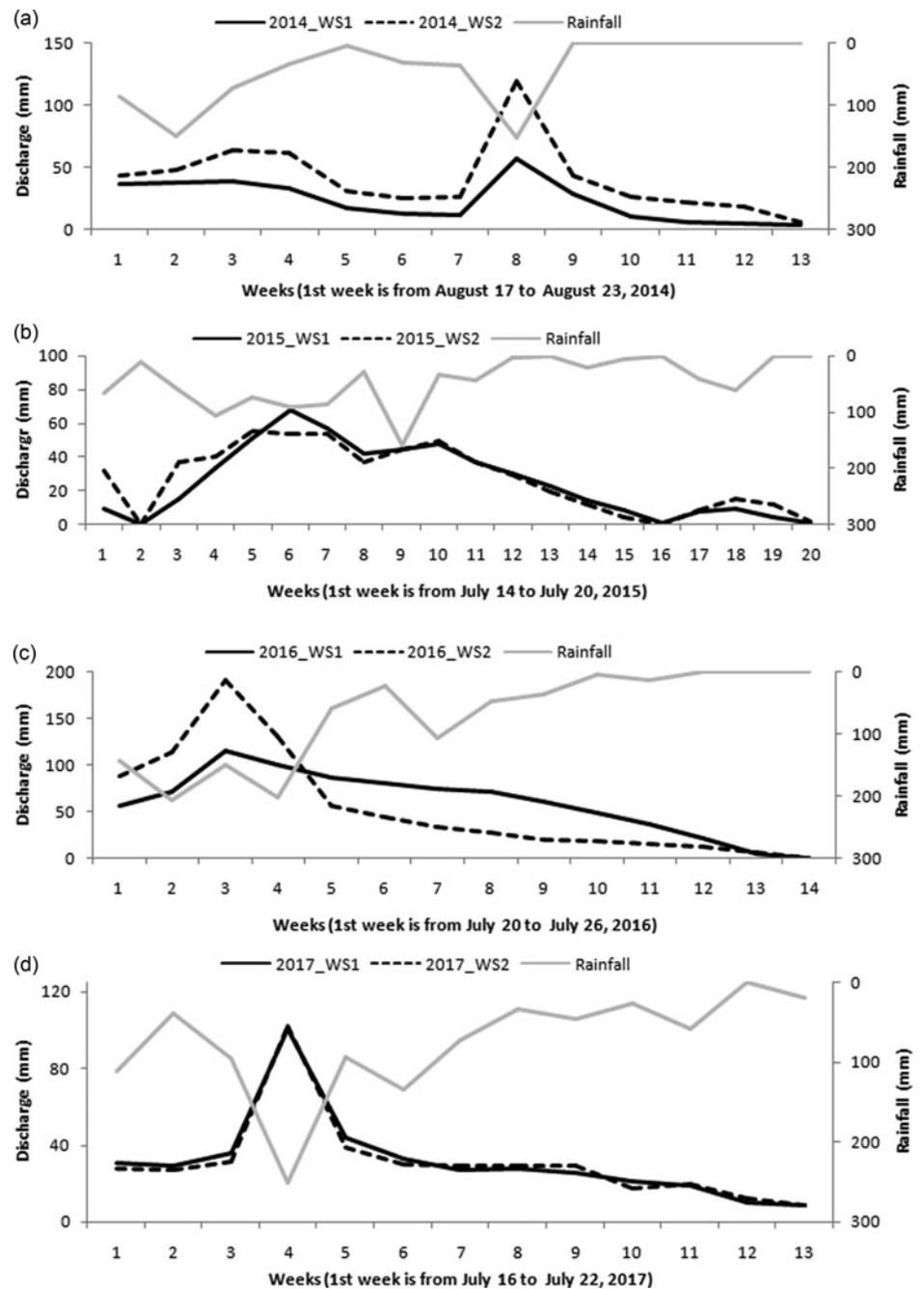


Fig. 9. Discharge at the outlet of two sub-watersheds at Gudo Beret site and rainfall (2014–2017); (a) WS1 with 2-year-old SWC and WS2 without SWC; (b) WS1 with 3-year-old and WS2 with 1-year-old SWC; (c) WS1 with 4-year-old and WS2 with 2-year-old SWC and (d) WS1 with 5-year-old and WS2 with 3-year-old SWC.

also been reported that terraces and bunds reduced soil loss by 61% at Myleba (Tigray), 63% at HendeLafto (Harerghie), 63% at Maybar (Wello), 78% at Andit Tid (Shewa), 59% at Anjeni (Gojam), 58% at Gununo (Gamogofa), 89% at Dizi (Illubabor), 47% at Galena (Shewa) with an average of 65% (Hurni, 2000a, 2000b; Haregeweyn *et al.*, 2012). Woodlots have shown very low soil loss (71% lower than that of unmanaged cropland) possibly because of the frictional resistance of dense grass cover underneath the trees (FAO, 2009).

Discharge and sediment yield at the watershed level

The study showed that the implementation of SWC measures at the sub-watershed level reduced discharge by 44%. Higher BFI and lower flashiness index were also observed. Other studies on

the effectiveness of integrated SWC measures at the sub-watershed scale also revealed a notable impact of SWC measures on runoff reduction; 18% at Enabered in Tigray region (Haregeweyn *et al.*, 2012), 88% at May Zeg-Zeg in Tigray region (Nyssen *et al.*, 2009) and 39% at Gununo in southern Ethiopia (Mitiku *et al.*, 2006).

The sub-watershed without SWC practices showed about threefold more sediment yield compared to that of with SWC measures. There might be a possibility of sediment re-deposition and thus sediment yield reduction (Trimble, 1983; Walling, 1983; Vente *et al.*, 2007). This demonstrates that SWC options can play a significant role in checking soil erosion and retaining sediment at the sub-watershed scale. A study by Nyssen *et al.* (2009) reported sediment yields reduction (78%) due to SWC intervention in northern Ethiopia (May Zeg-Zeg watershed). Another

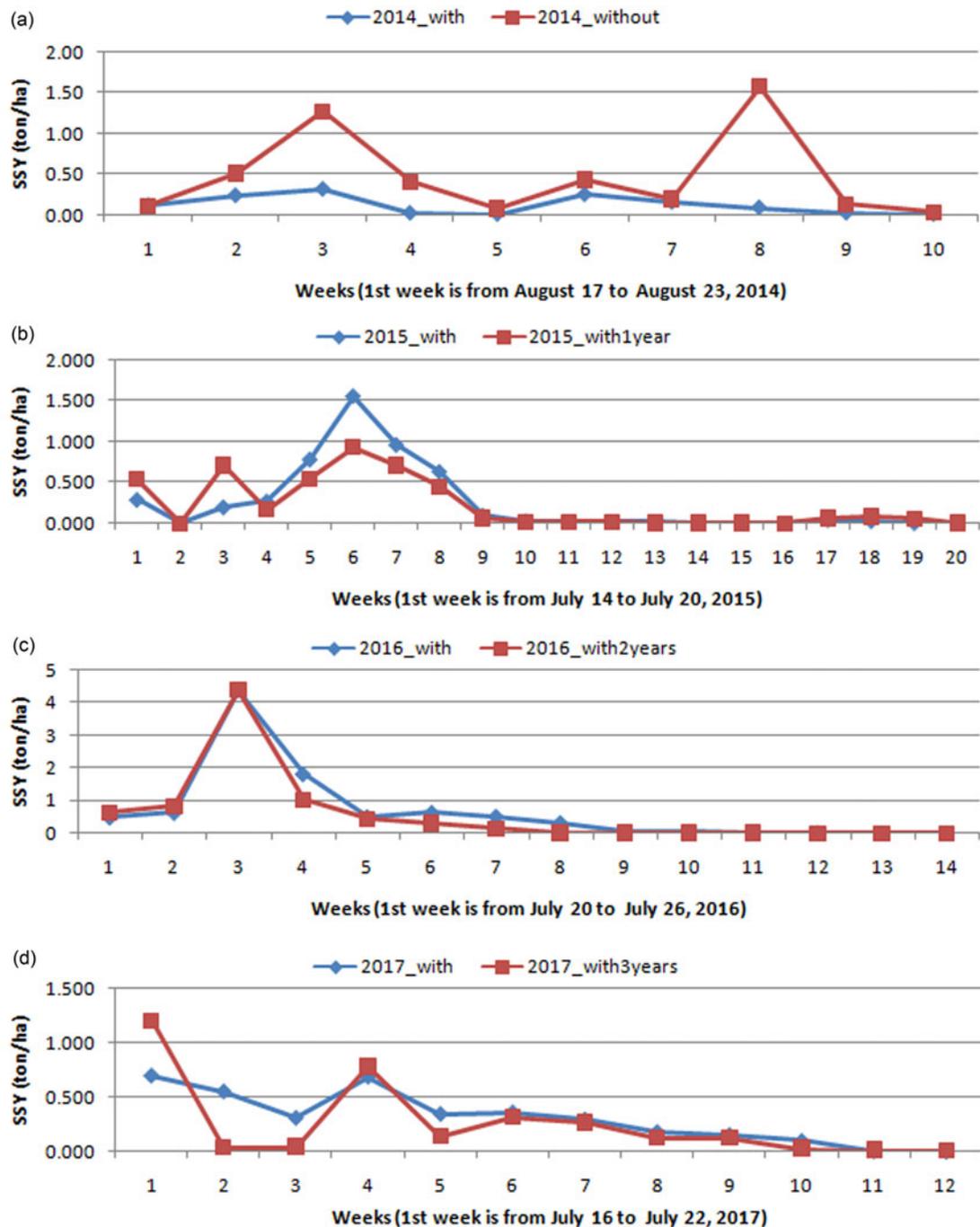


Fig. 10. SSY at the outlet of two sub-watersheds at Gudo Beret site (2014–2017); (a) WS1 with 2-year-old SWC and WS2 without SWC; (b) WS1 with 3-year-old and WS2 with 1-year-old SWC; (c) WS1 with 4-year-old and WS2 with 2-year-old SWC and (d) WS1 with 5-year-old and WS2 with 3-year-old SWC.

study also reported a 76% sediment yield reduction at Enabered (Tigray) (Haregeweyn *et al.*, 2012) due to SWC intervention at the watershed scale. There was also a notable impact of SWC measures on sediment yield reduction (86%) at Gununo catchment in southern Ethiopia (Mitiku *et al.*, 2006).

Soil loss estimates at different scales

Extrapolating plot level results to watershed was overestimated by 79% for managed (WS1) and underestimated by 19% for unmanaged (WS2) sub-watersheds in 2014. Other studies reported

similar overestimation of erosion results due to extrapolation (Loughran, 1989; Evans, 1995). It is also reported that extrapolating plot level results to the watershed level and beyond can bring misleading results (Pimentel *et al.*, 1995; Trimble, 1999; Cammeraat, 2002; Leys *et al.*, 2010). Even, extrapolating small watershed results to a large region have proved controversial (Pimentel *et al.*, 1995; Trimble, 1999). Soil loss data obtained at the plot scale are difficult to extrapolate at the catchment level, because the heterogeneity of a catchment is always higher than that of a plot (Stroosnijder, 2005). Moreover, the delivery, transport and storage of sediment are highly scale dependent and

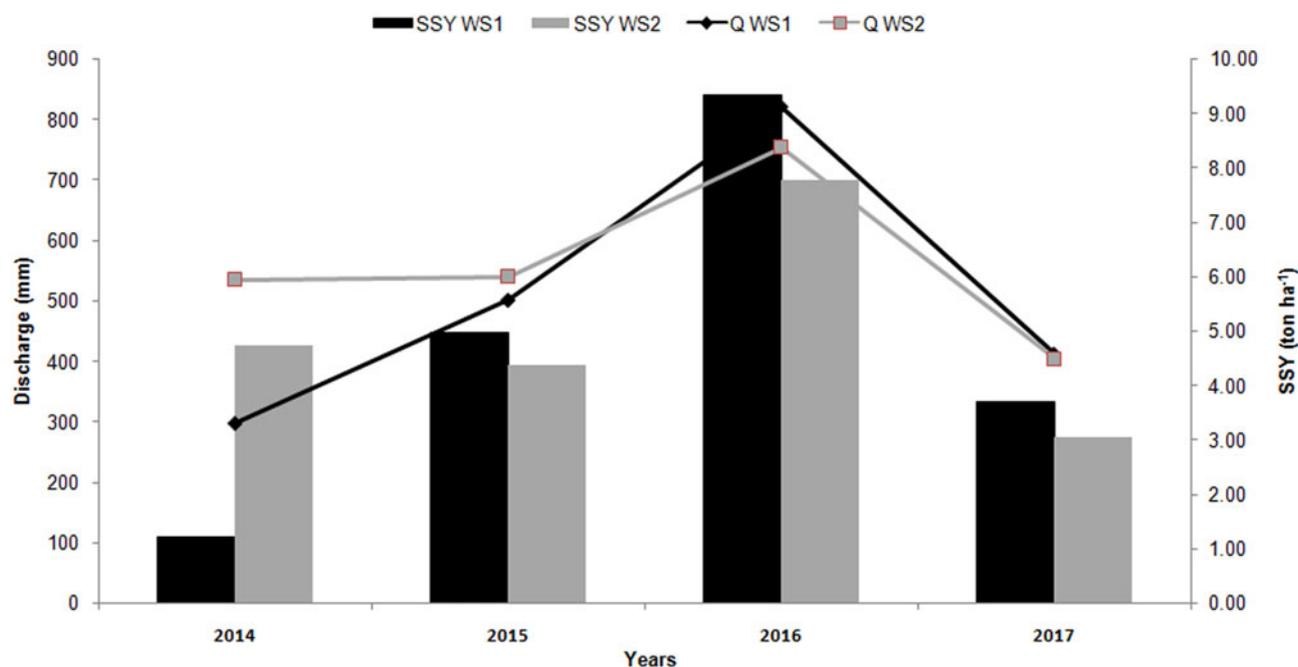


Fig. 11. Discharge (Q) and SSY at the outlet of two sub-watersheds at Gudo Beret site (2014–2017); (2014) WS1 with 2-year-old SWC and WS2 without SWC; (2015) WS1 with 3-year-old and WS2 with 1-year-old SWC; (2016) WS1 with 4-year-old and WS2 with 2-year-old SWC and (2017) WS1 with 5-year-old and WS2 with 3-year-old SWC.

Table 5. Sub-watershed soil loss per land use/cover class extrapolated/calculated from plot values in the Gudo Beret Kebele, central highlands of Ethiopia (2014)

Land use	Sub-watershed with SWC (WS1)			Sub-watershed without SWC (WS2)		
	Area (ha)	Plot soil loss (ton ha ⁻¹)	Watershed soil loss (ton)	Area (ha)	Plot soil loss (ton ha ⁻¹)	Watershed soil loss (ton)
Crop	23.00	2.28	52.30	14.10	4.72	66.70
Grazing land	7.44	2.68	19.90	6.31	2.68	16.90
Woodlots	2.24	0.21	0.47	1.33	0.21	0.28
Badland	0.15	4.72	0.71	0.04	4.72	0.19
Impervious	1.04			0.28		
Total per watershed	33.83		73.50	22.08		84.10
Total per hectare			2.17			3.81

controlled by hydrological and geomorphologic processes (Walling, 1983; Cammeraat, 2002; de Vente and Poesen, 2005).

However, soil erosion should be assessed and described at different scales for better understanding (Stroosnijder, 2005). A study on soil loss at different scales provides different benefits for different stakeholders. A plot level study (on-site impact) gives an idea of what is happening within the farm and gives the fertility dynamics of the farm and fertilizer use efficiency. Plot level studies are useful to farmers and practitioners. On the other hand, a sub-watershed level study (off-site impact) gives the overall interaction of the erosion process and gives the net runoff and sediment yield. At the sub-watershed level, the regional managers and policy makers are much more interested.

This study reinforced the fact that extrapolating plot data to the sub-watershed scale is problematic and does not give good estimation. The plot data did not reflect the overall interaction of the erosion process with in the sub-watershed. Therefore,

care should be taken while extrapolating plot data because it could be either by far greater, or smaller than the net soil erosion.

Conclusion and recommendations

The study showed significant differences at both plot and sub-watershed levels in runoff and soil loss between ‘treated’ and ‘non-treated’ areas. Although the efficiency reduced over years, in areas where there were terraces coupled with trenches, there was reduction of runoff and soil loss. The runoff retained within the trenches is useful because it can contribute to increased soil moisture in the landscape. There is also more water retained within the watershed during rainy season as the SWC practices significantly improved water retention capacity of the sub-watershed. Regular trench maintenance and cascading WH practices can also be implemented across the landscape to further improve and sustain the water retention capacity as well as reduce downslope erosion.

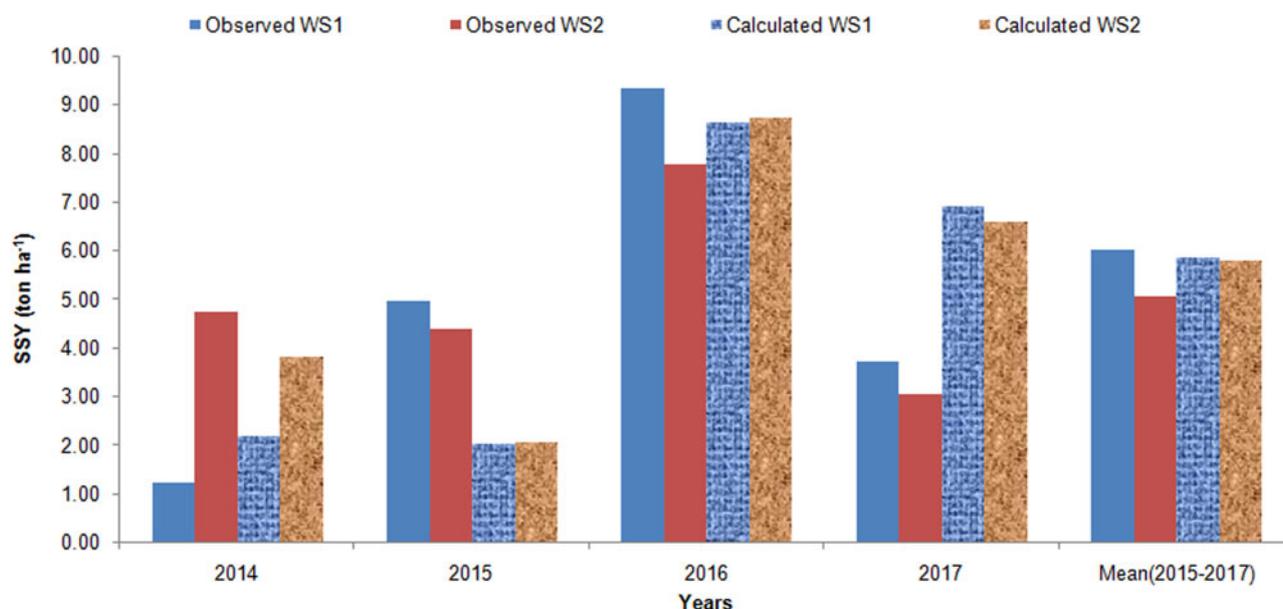


Fig. 12. Observed SSY at the outlets of sub-watersheds and calculated soil loss based on plots data for WS1 and WS2.

To sustain the productivity of the sub-watersheds, there should be integrated SWC with purposeful regular maintenance of structures. Further studies on the costs and benefits of the SWC interventions are needed to establish their adoption and scalability.

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