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RESEARCH ARTICLE

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Impact of stone bunds on temporal and spatial variability of soil physical properties: A field study from northern Ethiopia

Andreas Klik[1] | **Christoph Schürz**[1] | **Stefan Strohmeier**[2] | **Nigus Demelash Melaku**[1,3] | **Feras Ziadat**[4] | **Andreas Schwen**[1] | **Claudio Zucca**[2]

[1] Department of Water, Atmosphere and Environment, Universitat fur Bodenkultur Wien, 1190, Vienna, Austria

[2] Integrated Water and Land Management and Ecosystems Program, International Center for Agricultural Research in the Dry Areas (ICARDA), Amman, Jordan

[3] Agricultural Research, Gondar Agricultural Research Center (GARC), 4835-537, Gondar, Ethiopia

[4] Food and Agriculture Organization of the United Nations, Land & Water (AGL), 00153, Rome, Italy

Correspondence
A. Klik, Department of Water, Atmosphere and Environment, Universitat fur Bodenkultur Wien, 1190, Vienna, Austria.
Email: andreas.klik@boku.ac.at

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Abstract

In the Ethiopian Highlands, stone bunds (SBs) are a common practice for soil and water conservation, influencing runoff and erosion processes from sloped agricultural areas. The objective of this study was to investigate how SBs affect spatiotemporal relationships of these processes to better understand their impacts on soil water development at the smallholder farmer's field level. Study area was the Gumara-Maksegnit Watershed in northern Ethiopia, where two representative transects were investigated: One transect crossed a 71 m-long field intersected by 2 SBs traced along the contour. The second transect crossed a similar hillslope without conservation structures at a length of 55 m representing baseline (untreated) conditions (no stone bund). During the rainy season of 2012, bulk density and volumetric water content were monitored, and tension disc infiltrometer experiments were performed to determine the saturated hydraulic conductivity and to derive soil water retention characteristics. Our observations show that SB decreased significantly soil bulk density in center and lower zones of SB transect compared with no stone bund. No temporal change was observed. Results targeting the surface soil moisture indicate that infiltration was higher with SB and happened earlier in the rainy season in the zones around the SBs. Saturated hydraulic conductivity was positively affected by SB and increased significantly. Improved soil hydrology by SB fields may increase crop yields by higher soil water contents but also by extending the growing season after the rainy season. Therefore, SBs are a successful measure to establish climate-resilient agriculture in the Ethiopian Highlands.

KEYWORDS

Ethiopia, soil degradation, soil properties, stone bunds, surface runoff

1 | INTRODUCTION

Soil erosion and degradation are a major problem in the northern highlands of Ethiopia. This part of the country is the most suitable land for agriculture and, therefore, essential for food production for human population and livestock. Competition for available resources such as forest and grazing land was forced by population growth and limited cropland. As crops are also produced on steeper terrain, surface runoff of rainwater and soil erosion are major threats to these areas because they deplete soils and decrease crop production (Nyssen, Poesen, Haile, Moeyersons, & Deckers, 2000). The agricultural production is additionally negatively affected by a strong climatic variability in the area and drought spells, which, for example, caused famine in 1973 and 1984 (Taddese, 2001). In cooperation with international agencies, Ethiopian government started then programs for soil conservation and afforestation.

Stone bunds (SBs) are widely used as soil and water conservation (SWC) structures in the Amhara region in northern Ethiopia. These bunds are 0.2 to 0.7 m high embankments built of large- and medium-sized rock fragments in shallow trenches along contour lines (Morgan, 2005; Nyssen et al., 2007). The stones are mostly collected from neighboring fields, and the height of the SBs varies between different regions. It needs less material movement to build them compared with bench terraces. Therefore, SBs are more adopted by small holder farmers. As the efficiency of those structures is decreasing with time because of accumulation of eroded sediment, a periodic maintenance is necessary.

Erosion and sedimentation processes along hillslopes are altered by SBs, and physical and chemical soil properties of the agricultural areas in the interspacing are also affected. SBs serve as a sink system when installed along the contour lines and trap runoff and sediment that leads to reduction of both runoff and soil loss (Taye et al., 2013). They increase bulk density (BD) in erosion zones and decrease it in depositional areas (Challa, Abdelkadir, & Mengistu, 2016). As BD is closely related to the saturated soil hydraulic conductivity K_{sat}, changes of this parameter also influence infiltration and runoff processes, soil water dynamics, and subsequently crop development (Alemayehu, Yohannes, & Dubale, 2006). A study by Alemayehu et al. (2009) in Eastern Tigray investigated the impact of integrated watershed management that included also SWC structures such as SBs, trenches, and runoff collection ponds on runoff and erosion. Tigray is located in the northern highlands of Ethiopia with a mean annual rainfall of 600–700 mm. They found that SWC structures decreased soil erosion and runoff whereas they increased soil moisture. Due to the retention of surface runoff at the SBs, the top soil on both sides of the SBs had a higher soil water content compared with areas apart. Vancampenhout et al. (2006) carried out a study in the same region to analyze the impact of SBs on crop yield and fertility. Their results show no negative effect of SBs on crop yield. Nyssen et al. (2007) demonstrated that the effect of SWC on soil water dynamics was even more important at greater soil depth (1.0–1.5 m). Beside the positive impact on crop development, higher infiltration into the soil increases water retention in the area and therefore decreases runoff peaks after heavy rainfall events. Better water retention of the soil is important to support crop growth especially during the short dry spells during the rainy season. Seleshi and Zanke (2004) analyzed long-term rainfall data (1965–2002) of 11 key stations in Ethiopia. They found no trend in the annual and seasonal rainfall total or rainy days for northern Ethiopia. However, they conclude that warm El Niño–southern oscillation episodes are associated with below-average rainfall during the rainy but also main growing season over the Ethiopian Highlands.

Wolka, Moges, and Yimer (2011) studied the effects of SBs on particle size distribution and chemical soil properties and its implications for crop production in southern Ethiopia. They concluded that the contribution of SBs alone with regard to improving soil conditions is not significant compared with cropland without these SWC measures. They performed their measurement only once and did not monitor if and how these soil parameters changed during a rainy season.

The amount and spatiotemporal distribution of soil water contents in the root zone determines crop development and crop yield. Data of near-surface water contents do not explicitly explain soil water storage or deep percolation, but studies by Wagner, Lemoine, and Rott (1999) and Brocca, Melone, Moramarco, Wagner, and Hasenauer (2010) indicate that these data can be usefully interpreted. Brocca et al. (2010) compared near-surface soil moisture data obtained from the Advanced SCATterometer onboard the Metop satellite with soil water contents measured with frequency domain reflectometry sensors and derived average root-mean-square error of 0.081, 0.104, and 0.118 $m^3 \cdot m^{-3}$ for 10, 20, and 40 cm soil depth, respectively.

According to the effectiveness of SBs as SWC, Nyssen et al. (2007) found a mean sediment deposition rate of 58 $t \cdot ha^{-1} \cdot yr^{-1}$ induced by SBs constructed in the Tigray highlands in North Ethiopia. Considering a measured mean annual soil loss by rill and interrill erosion of 57 $t \cdot ha^{-1} \cdot yr^{-1}$ and a mean tillage erosion rate of 19 $t \cdot ha^{-1} \cdot yr^{-1}$, 76% of total soil loss was trapped by the bunds. They observed also that SBs improved soil water content in deep soil horizons and increased mean crop yield from 0.58 to 0.65 $t \cdot ha^{-1} \cdot yr^{-1}$. On the other hand, studies from Hengsdijk, Meijerink, and Mosugu (2005) also performed in Tigray and Eritrea showed only limited effects on soil conservation and crop yield, respectively. Herweg and Ludi (1999) analyzed the performance of different SWC structures in northern Ethiopia and Eritrea and investigated regions with mean annual rainfall between 400 and 1,600 mm. At all sites, SWC structures reduced soil loss significantly whereas runoff was decreased only in semiarid sites. In areas with higher rainfall, nongraded structures may lead to waterlogging and consequently to breakage of SWC structure. Zougmoré, Guillobez, Kambou, and Son (2000) observed that the efficiency of the SBs depends on the distance between the structures. Soil water contents decreased with increasing distance from the stone line. Compared with a hillslope without SB, these SWC structures reduced surface runoff by 25% when SB spacing was 25 m whereas it reduced only by 5% with 50 m SB spacing. Nevertheless, farmers are not always convinced of the benefits of these structures (Tesfaye, Negatu, Brouwer, & van der Zaag, 2014). The efficiency of SB remains high only if the deposited sediment is removed in regular intervals. Plot studies by Taye et al. (2015) show that for rangeland, the storage capacity of SB declined by about 65% after 3 years. Many studies analyzed only the impact of SB on soil moisture and soil affecting soil physical properties such as BD. We wanted to investigate the effect of selected soil physical properties that are mainly responsible for infiltration/runoff processes and therefore also for soil water content. As these soil properties and state variables change over time due to soil management/tillage for seedbed preparation and planting but also because of soil consolidation, rainfall kinetic energy, and soil erosion and deposition, we were interested in investigating some of these changes throughout a rainy season.

Therefore, the objectives of this study were (a) to find relationships between the spatial distribution of soil BD, soil moisture, and saturated hydraulic conductivity and the location of SBs, (b) to monitor the temporal dynamics of these properties during a rainy season, (c) to better understand the impact of SBs on soil water movement and retention, and (d) to disseminate and discuss impacts of SBs on near-surface soil water dynamics.

2 | MATERIALS AND METHODS

2.1 | Study area

The field study was performed from June to October 2012 in the Gumara-Maksegnit watershed that is located in north-west Amhara in Ethiopia (Figure 1). This watershed is part of the greater Lake Tana basin and covers an area of approximately 54 km^2 with altitudes between 1,933 and 2,852 m a.s.l. This watershed was selected because it is representative for this region with respect to land use and

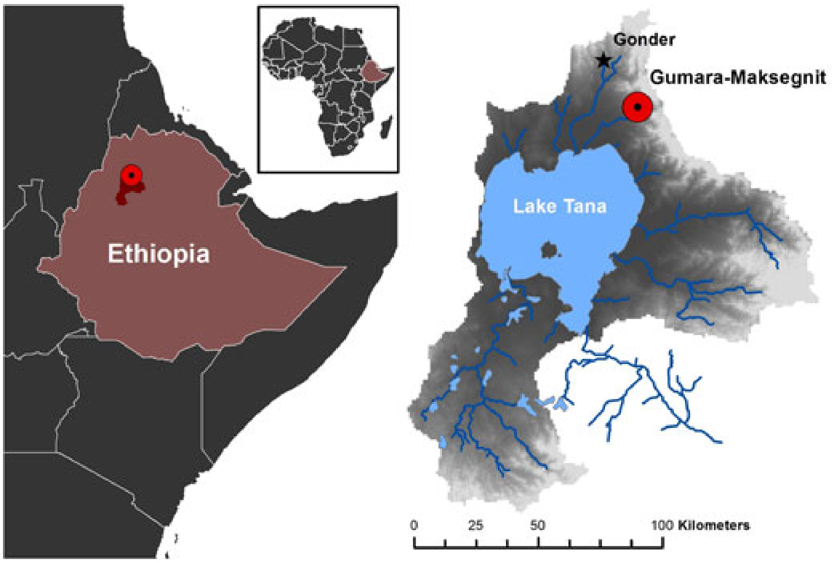

FIGURE 1 Location of the study area [Colour figure can be viewed at wileyonlinelibrary.com]

topography (Bayu et al., 2015). About 30% of the watershed has slopes <18%, and this area is used as cropland whereas the steeper parts are mainly forests (Addis, Klik, Oweis, & Strohmeier, 2016).

The mean annual rainfall (1997–2014) at the study site is 1,152 mm and varies between 641 and 1,678 mm (Melaku et al., 2017). More than 80% falls from June to September. The minimum and maximum temperatures are highest between March and May with maxima of 16.1 and 32.0 °C, respectively. The lowest minimum and maximum temperatures (10.6 and 25.3 °C) occur during the rainy season (GARC, 2010).

The Ethiopian Highlands vary highly in altitude and topography. Above 1,500 m a.s.l. topographic factors such as slope aspect and general orientation of the valley are strongly correlated to precipitation (Goebel & Odenyo, 1984; Nyssen et al., 2005). According to the altitude related climatic zone classification of Hurni (1998), the zone between 2,300 and 3,200 m a.s.l. is cool and humid with barley as the predominant crop. The most important agricultural zone is between 1,500 and 2,400 m a.s.l. where all major rainfed crops, such as teff (*Eragrostis tef* Zucc.), sorghum (*Sorghum bicolor* L.), chickpea (*Cicer arientinium* L.), and maize (*Zea mays* L.) are cropped.

2.2 | Data collection and analyses

2.2.1 | Studied hillslopes

To study the impacts of SBs on hydrological processes along hillslopes, we chose an experimental site in the agricultural used lower part of the Gumara-Maksegnit watershed where several fields with and without SBs were adjacent with each other. The two investigated fields had a similar slope with an inclination of 8.4% (with SB) and 9.7% (without SB), respectively, which well-represented common Gumara-Maksegnit agricultural area conditions. In the beginning of June, the soil was ploughed with the help of an ox; sorghum (*Sorghum bicolor* L.) was planted in both fields in early June 2012 whereas chickpea (*Cicer arientinium* L.) was cropped as previous crop.

An approximately 100 m wide, representative hillslope was selected where fields with no stone bunds (NSB) and with SBs were both present. Two transects were drawn along the slope direction, about 40 m apart were defined (Figure 2). The soil texture of the study site was clay with 26% sand and 41% clay (Bayu et al., 2015; Klik et al., 2015). Particle size distribution was determined using the hydrometer method (Gee & Or, 2002). For these analyses, 30 disturbed soil samples were taken along the hillslopes (Figure 2).

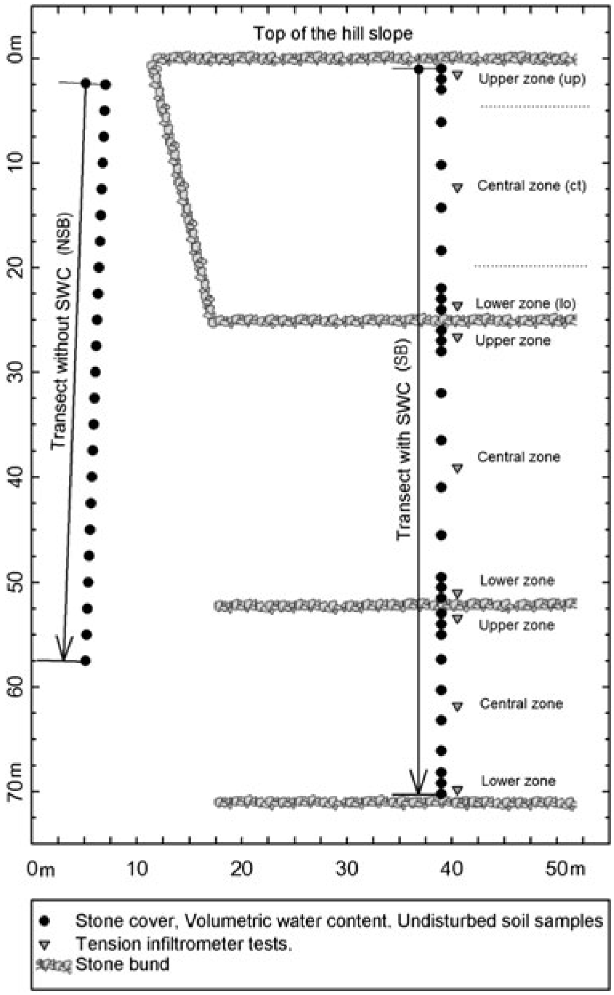

FIGURE 2 Layout of the studied transects. SWC = soil and water conservation; NSB = no stone bunds

The SB transect had a total length of 71 m and crossed two SBs approximately 25–30 m spaced and 40 cm high (Figures 2 and 3). The average distance of 25–30 m between SBs was then higher than the 15 m that is recommended by Lakew, Carucci, Wendem-Ageňehu, and Abebe (2005) for 10% slope. The SBs were built in 2011 when farmers collected stones from their own fields and piled them up to approximately 20–40 cm high SBs under supervision of the local government employees and extension people from the Amhara Regional Agricultural Research Institute. Since then, no maintenance of the bunds was done. For our investigations, the SB hillslope was divided into three parts: a zone just below the SB (upper zone—up), a central zone between two SBs (central zone—ct), and one just above the SBs (lower zone—lo) where runoff and sediment may be accumulated (Figures 2 and 3). The second transect had NSB and was 55 m long.

The following soil physical properties and state variables were determined along the hillslopes for 0–5 cm topsoil layer: near-surface soil water content, BD, and soil hydraulic conductivity. The measurements of soil moisture were carried out at nine times between end of June and end of August 2012, whereas the observations of BD and hydraulic conductivity took place on following dates: June 26, July 11, August 14, and August 20–30. The sampling and field measurements were performed in different spatial and temporal intervals based on the property to be analyzed and research staff availability.

Approximately 50 m east of the experimental site, a manual rain gauge had been installed in 2010 to obtain daily rainfall data. As the two transects are very close to each other, the rainfall was the same for both.

2.2.2 | Near-surface soil water content and BD

Undisturbed soil samples from 0 to 5 cm soil depth were taken with core cylinders (V = 200 cm^3). Aside from a distinct surface stone layer, the top soil below the surface layer allowed proper sampling by core cylinder to analyze soil BD and water content for sensor calibration. BD is an easily measurable parameter and determines the soil's pore space. The sampling strategy was designed in such way that we sampled denser around the SBs where higher changes of soil moisture and BD could be expected within shorter distances (Figure 2).

In the central zones between the SBs as well as along the SB hillslopes where less abrupt changes were expected, we used lower samples density. Thirty undisturbed soil samples and soil water content measurements were taken along the hillslope with SB during each campaign resulting in a total of 90 cylinders for the whole study. Six cylinders were sampled in distances of 1 m below and above each SB (zones up and lo, Figure 2) to cover expected accumulation of sediments and their impact on investigated soil parameters based on visual marks investigated in the site. The additional measurements were taken along the central parts between the SB (zone ct) with intervals between 2.9 and 4.5 m to gain consistent number of samples for all observed zones, for example, SB distance slightly differ between the fields. This sampling layout facilitated analyzing the impacts of SB. Along the NSB hillslope, 23 samples were taken for each campaign in equally spaced distances of 2.5 m (Figure 2) to capture the local heterogeneity pattern of the agricultural fields.

FIGURE 3 Investigated stone bunds in the Gumara-Maksegnit watershed showing upper, central, and lower zone of stone bunds. Trampling path just below the stone bund can be seen [Colour figure can be viewed at wileyonlinelibrary.com]

At the same points along the hillslopes, stone cover of the soil was determined based on photo image classification. On June 25, photos were taken from 60 × 60 cm miniplots, located along the SB and NSB transects. All photos for this work were taken from the same height and perpendicular to the ground. The rock fragment cover was then evaluated using supervised classification tool in Arc GIS and also through manual analysis using AutoCAD (Schürz, 2014).

The shallow soil water content (0–5 cm) was measured using the Hydra Probe® Soil Sensor (Stevens® Water Monitoring System, Inc). The sensor determines indirectly soil moisture based on the different values of dielectric permittivity of air, soil, and water. It requires a soil-specific calibration considering its mineral and organic soil composition (Kammerer, Nolz, Rodny, & W. Loiskandl W., 2014; Seyfried, Grant, Du, & Humes, 2005). The calibration curve can be described as follows (Stevens Water, 2007):

$$\theta = A\cdot\sqrt{\varepsilon_r} + B,$$

where θ is the volumetric water content, ε_r is the real dielectric permittivity, and A and B are soil specific coefficients.

Throughout the whole period, 53 undisturbed soil samples were taken along the two transects (Figure 2) to cover a certain range for the volumetric water content for sensor calibration (Loiskandl, Buchan, Sokol, Novak, & Himmelbauer, 2010). We determined the dielectric permittivity value ε_r in at least four points around the sampling rings using the capacitive sensor in the field and calculated the mean electric permittivity for those measurements. Drying the soil samples in the laboratory resulted in the exact volumetric water content for each sample. From these data, following relationship was determined:

$$\theta = 0.0646\cdot\sqrt{\varepsilon_r} + 0.051.$$

2.2.3 | Hydraulic conductivity

For this study, three sets of tension disc infiltrometer measurements with three replications each were performed along the hillslope with SB only. The infiltration experiments were carried out at nine positions along the hillslope—three in up, ct, and lo zones (Figure 2). The first measurement campaign took place on July 11–13, the second one on August 14–17, and the third from August 29 to September 1, 2012. In such a way, we were able to investigate changes occurring throughout the rainy season.

For validation of the results, the calculated saturated water content θ_S was used. It was compared with the pore space determined from the BD of the undisturbed soil samples considering a particle density ρ_s of 2.65 g·cm^{-3}. On average, the pore space of the two investigated hillslopes was around 50–52%.

We used a tension disc infiltrometer with variable pressure supply and a disc diameter of 0.20 m (Soil Measurement Systems® Inc., Tucson, AZ). Three matric potentials of −8, −4, and 0 cm were maintained and quantified the quasi steady-state flow at each pressure. Along the SB transect, undisturbed soil samples were taken with three replications at the same positions as the tension infiltrometer measurements to determine initial and final volumetric water contents gravimetrically.

From the infiltration rates, the saturated hydraulic conductivity K_{sat} and the water retention characteristics were derived by means of the saturated water content (θ_s) and the parameters α and *n* of the van Genuchten soil water retention model (van Genuchten, 1980). We derived K_{sat} by the equation of Wooding (1968) on the basis of the steady state infiltration rates.

The van Genuchten parameter α is one of the two shape parameters to describe the water retention curve according to the van Genuchten model (van Genuchten, 1980). It is a scale parameter inversely related to the air-entry value and, therefore, is a scaling factor that determines the position of the maximum pore size maximum (Durner, 1994).

Soil water retention characteristics were determined inversely from the cumulative infiltration rates using the HYDRUS 2D/3D software package as proposed by Šimůnek and van Genuchten (1996, 1997) and Hopmans, Šimůnek, Romano, and Durner (2002). The software solves the Richards equation for radial symmetric Darcian flow (Šimůnek & van Genuchten, 2000; Warrick, 1992). K_{sat} was taken from Wooding's analytical solution. Based on the sand, silt, and clay content as well as on the soil's BD, the tortuosity parameter *l* was set to 0.5 (Mualem, 1976), and the residual water content θ_r was set to 0.090 m^3·m^{-3}. The remaining parameters θ_s, α, and *n* were estimated by minimizing the sum of squared errors between the observations of the tension infiltration experiments and the model predictions.

2.3 | Statistical analyses

All statistical analyses were performed using the statistical software R (R Core Team, 2013) at a significance level α of 0.05. We used the two-sample *t* test to compare the two treatments with (SB) and without stone bunds (NSB). For sample numbers larger than two, the pairwise *t* test and the Fisher's least significant differences test were used. Normality and homoscedasticity were tested using the Komolgorov–Smirnov test (R Core Team, 2013) and Levene's test. Additionally, all data were inspected visually using q-q plots.

3 | RESULTS AND DISCUSSION

3.1 | Soil water content in the 0-5 cm layer

In 2012, the annual precipitation reached 941 mm, which is about 20% lower than the long-term average of 1,152 mm. Of the daily rainfall events, 60% were less than 10 mm and 15% more than 20 mm. Therefore, the rainfall in the year 2012 can be considered as below average, less intense, but with more regular rainstorms.

During the rainy season of 2012 (June to September), rainfall amount was 812 mm that accounts for 86% of the annual rainfall. Before the rainy season (January to May) and after the end of the rainy season (October to December) rainfall of 46 and 82 mm occurred, respectively, which represents 5% and 9% of annual precipitation.

Throughout the 67 days of investigation (June 22 to August 31), 67 rainfall events produced 698 mm rainfall. This results in a rainy day normal (i.e., the average rainfall depth on a rainy day; Vanmaercke et al., 2012) of 10.9 mm per day.

Rainy season started late in June, but most intensive rainstorms occurred in July and August. Therefore, in the end of June, the soil was rather dry and—due to shrinking—showed large cracks. For this date, Figure 4 shows a mean volumetric water content of approximately 30% for the SB transect. Besides a few soil moisture fluctuations in the close vicinity around the SBs (up and lo), no significant impact of SB is visible (Table 1). This indicates dominant infiltration processes due to large cracks and only a small amount of runoff that accumulated above the SBs.

In the following 3 weeks until July 11, 475 mm of rainfall increased the average soil water content in SB transect to 37% whereas it is only 33.5% for the NSB transect (Figure 4). Therefore, due to SB 10%, more water could infiltrate. Strong rainfall events occurred during this period. In the center positions (ct) of the SB transects, water contents similar to the NSB transect can be observed (Table 1). In the zones near

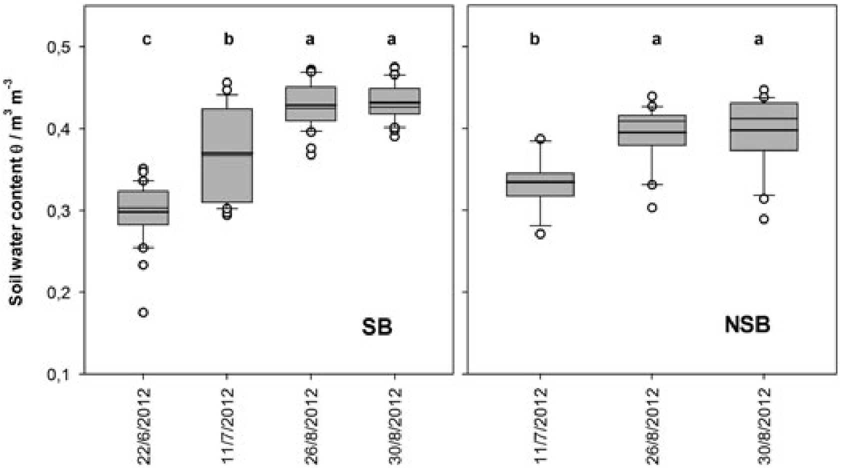

FIGURE 4 Development of mean and median soil water contents for transect with and without stone bunds (SB and NSB) for different dates. Same letters indicate no significant differences ($p < 0.05$) between box means (bold lines). SB = stone bund; NSB = no stone bunds

TABLE 1 Soil water contents at different dates along the hillslopes with stone bund and without stone bunds (no stone bunds)

	Precipitation	SB			
Date	between dates (mm)	Upper zone (up)	Central zone (ct)	Lower zone (lo)	NSB
June 22		30.6 ^{a}	28.4 ^{a}	30.9 ^{a}	n.m.
July 11	177	39.8 ^{a}	34.1 ^{b}	38.3 ^{a}	33.5 ^{b}
August 26	475	42.0 ^{a}	42.2 ^{a}	44.7 ^{a}	39.5 ^{b}
August 30	46	41.2 ^{b}	43.2 ^{ab}	45.2 ^{a}	39.8 ^{b}

Note. Values with same letter (a or b) along the row indicate no significant differences (p < .05) between means. n.m = no measurement; SB = stone bund; NSB = no stone bunds.

the SB (up and lo), soil moisture shows significantly higher values compared with the center positions (ct) and NSB. This indicates that runoff from the central parts accumulated above the SBs where infiltration was higher. Additionally, higher water contents in up zones lead to the assumption that some part of the runoff percolated through the SBs and infiltrated downstream to them.

At the end of August with ongoing intensive rainfalls, 78% of the pore space (SB: 54%, NSB: 50%) were water filled with soil water contents of 39.9% and 43.2% for NSB and SB, respectively (Figure 4). Along the SB transect, significant differences can be observed. Because of water retention of SB, water contents in lower zone are significantly higher than in upper zone just below the SB. The NSB transect shows similar soil moisture value as upper zone that indicates that less rainwater infiltrated into the soil (Table 1).

In Figure 5, the spatiotemporal development and distribution of soil water contents along both transects are displayed. In the zones above the SBs runoff accumulated, ponded, and partially flew laterally along the SBs. Due to water logging and eventual minor flow along the SB water infiltrated to a higher degree and led to an increase in soil moisture levels uphill but also to higher water contents in zones below the SB. With increasing time, the wetter areas especially above the SB got wetter and near to saturation level. Vancampenhout (2003), cited in Nyssen et al. (2007), found that because of SBs, the soil moisture storage was increased at both sides of the bund, especially on loamy and sandy soils. They also showed that in depth of 1–1.5 m, soil water content could be increased by 5–10% for at least 2 months after the rainy season. The assumption to relate near-surface water contents to those in deeper depth is supported by Brocca et al. (2010) who found a good correlation between Advanced SCATterometer determined near-surface soil moisture data and measured soil water contents down to 40 cm depth when considering the surface soil moisture behavior over time. Water in greater depth of the soil is less available for evapotranspiration (Nyssen et al., 2007) and may improve groundwater recharge (Prinz & Malik, 2002). Nevertheless, this relation depends on soil and profile characteristics.

The NSB hillslope does not show such a distinct pattern. Within the first 25 m, no significant change in water content over time can be observed. In the lower part of the 55-m-long hillslope, an increase in near-surface water content is visible. Overall, the values are much lower than in the SB transect.

The findings support that different processes develop along the SB hillslope indicating the significant impact of the SB structures on hillslope hydrology. The upper zone shows a highly variable behavior over time compared with the other zones. The increase in water content in the center zone indicates that in addition to rainfall infiltration, the wetting

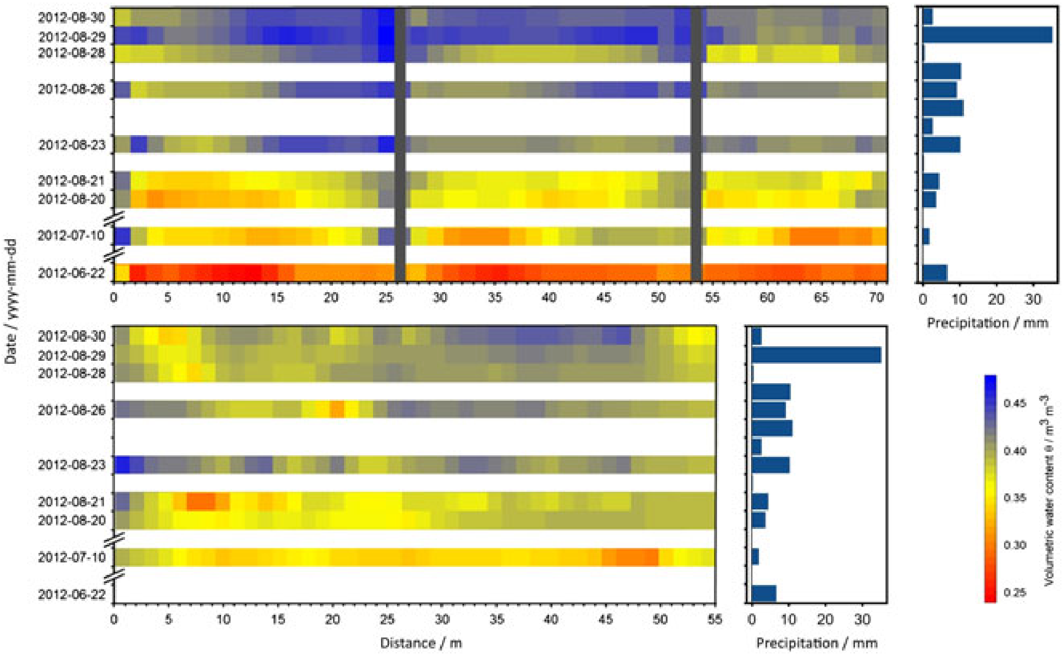

FIGURE 5 Spatiotemporal development of soil water content along stone bund and no stone bunds transect [Colour figure can be viewed at wileyonlinelibrary.com]

front due to throughflow of the SBs expands over time and also covers parts of this zone. At all times, the lower zone shows high water contents where runoff processes led to ponding and accumulation in this zone.

SB design varies in the different regions of Ethiopia. In Gumara Maksegnit, watershed SBs are low compared with other studies (e.g., Alemayehu et al., 2006). Especially in degraded or silted stage (after 2–3 years without maintenance), the local SBs, locally, turn to small terraces that may indicate marks of overspill at some spots.

The obtained results are supported by several other studies. Tenge, de Graaff, and Hella (2005) found out in Tanzania that SBs were effective in increasing soil moisture by 26–36% compared with land without protection measures. In addition, Zougmoré, Jaloh, and Tioro (2014) showed that SB reduced surface runoff and improved rain-water infiltration. Similar results obtained Challa et al. (2016) who found significantly higher soil moisture contents in fields with graded SBs.

Considering mean daily potential evapotranspiration rates of 3.9 and 4.6 mm for September and October calculated using CropWat 8.0 model (Food and Agriculture Organization [FAO], 2009) and assuming a rooting depth of 1 m, higher soil moisture in SB hillslopes extends availability of water for crop development for about 14 days after the end of the rainy season compared with NSB. This would be a very important positive impact of SB, although we have not data to validate it.

The evidence of throughflow of the SB indicates that the distances of 20–25 m produce too much runoff that cannot be conveyed by the SB. Therefore, the SB distance should be reduced as recommended by Lakew et al. (2005) for 10% slopes.

3.2 | Soil BD

Overall, the BD measured at the three dates ranged between 1.07 and 1.42 g·cm^{-3} for SB transect resulting in means between 1.20 and 1.23 g·cm^{-3} (Figure 6). The NSB transect had BD between 1.09 and 1.46 g·cm^{-3} with a mean of 1.32 g·cm^{-3}. For both hillslopes, the temporal changes between end of June and end of August are not significant (Figure 6), which indicates that BD did not change significantly during the rainy season.

When comparing spatial variability of BD, the values differ significantly between the zones near and between the SBs (Table 2). In the center zone as well as just above the SBs where sediment is deposited and forms an accumulation zone, we found similar bulk densities of 1.19 and 1.20 g·cm^{-3}, respectively. Below the SBs, significantly higher BD of 1.26 g·cm^{-3} was measured, which can be mainly attributed to the fact that it was used as footpath for the farmers (see Figure 3). However, similar BD pattern was also reported by Challa et al. (2016). The NSB treatment had the highest BD with 1.32 g·cm^{-3} ^{3} that was significantly higher than the values at ct and lo positions but not significantly different to the lo zone.

Higher BD relates with lower porosity and usually lower infiltration rate, which eventually leads to higher surface runoff and lower water contents in the root zone. Although no infiltration data are available for NSB, this conclusion can be derived from the SB observations (Table 2). Vice versa, significantly lower BD values in ct and lo zones relate with higher infiltration and higher soil water contents.

High BD may restrict root growth, movement of air, and water through the soil. This can result in shallow plant rooting and poor plant growth, which affects crop yield reduces vegetative cover available to protect soil from erosion. Compaction leads to increased runoff and erosion on sloping land and can create water logging on flatter areas (Arshad, Lowery, & Grossman, 1996).

Ideal values for plant growth are <1.10 g·cm^{-3} (Arshad et al., 1996). For clay soils, BD of 1.4 may be critical for plant growth at which root penetration is likely to be severely restricted (Hazelton & Murphy,

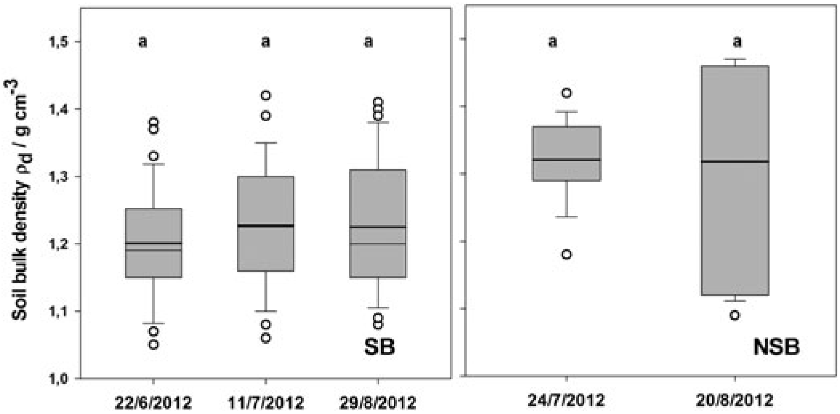

FIGURE 6 Mean and median soil bulk density of hillslopes with (SB) and without stone bunds (NSB) throughout the investigation period. Values with same letter indicate no significant differences ($p < .05$) between means. SB = stone bund; NSB = no stone bunds

TABLE 2 Stone cover, bulk density, saturated hydraulic conductivity and van Genuchten α along the hillslope with stone bund and without stone bunds (no stone bunds)

		SB			
Parameter	Unit	Upper zone (up)	Central zone (ct)	Lower zone (lo)	NSB
Stone cover	m^2·m^{-2}	0.15 ^{b}	0.16 ^{b}	0.05 ^{a}	0.22 ^{c}
Bulk density	g·cm^{-3}	1.264 ^{a}	1.194 ^{b}	1.202 ^{b}	1.320 ^{a}
Saturated hydraulic conductivity K_{sat}	cm·s^{-1}	0.0065 ^{b}	0.010 ^{a}	0.0102 ^{a}	n.m.
van Genuchten α	cm^{-1}	0.162 ^{ab}	0.188 ^{a}	0.140 ^{b}	n.m.

Note. Values with same letter (a, b or c) along the row indicate no significant differences ($p < .05$) between means. n.m. = no measurements; SB = stone bund; NSB = no stone bunds.

2010; Jones, 1983). Of all SB measurements, 11% but only 4% of NSB data were <1.10 g·cm^{-3}. Contrary, only 3% of all measured SB points had BD > 1.4 g·cm^{-3} but 33% of NSB data exceeded this value. However, without proper crop yield data, we are not able to further investigate the effects on crop development and yield.

In the central highlands of Ethiopia, Challa et al. (2016) investigated the effects of SB on selected soil properties. They found significant lower bulk densities in graded SB compared with non-conserved fields. Their conclusions agree with our results although their BD range between 1.12 and 1.17 g·cm^{-3} for terraced and for non-conserved farm plots at 15–20% slope and, therefore, are lower than our results.

3.3 | Saturated hydraulic conductivity

The water content at saturation should be equal or less than the pore space. We did not estimate the residual water content θ_r, but set it to a constant value of 9.0% to improve the numerical stability of the simulation by decreasing the number of estimated parameters. The van Genuchten parameter *n* was predicted by the simulation although it is rather uncertain. Therefore, these two parameters were also omitted in the statistical analyses. For further temporal and spatial analyses, we used only the saturated hydraulic conductivity K_{sat} and the van Genuchten parameter α.

From July to end of August, the mean K_{sat} of all three hillslope positions along the SB transect shows a significant reduction as well as a decrease in variability (Figure 7) although values can be considered as very high. The reduction of K_{sat} can be explained by the consolidation of the top soil and partly by the surface sealing due to the rainfall kinetic energy impact and to the natural swelling of the clay minerals.

When comparing different zones along the hillslope, the upper zone shows significantly lower mean K_{sat} values with smaller variance than the other two zones (Table 1). These higher K_{sat} values of up zone can be attributed to the BD of 1.26 g·cm^{-3} of this zone, which is significantly higher than in the ct and lo zones (Table 2). Between the ct and lo zones, such significant differences in K_{sat} were not found (Table 2).

From July 11 to August 20, we measured a decrease of K_{sat} over time in the ct and lo positions of the SB transect (Figure 8). The highest reduction was found for the lo zone with a decrease of 60% for from 0.0137 to 0.0056 cm·s^{-1} from July 11 to August 20. A similar behavior showed the ct zone with a much lesser reduction of K_{sat}. The up zone delivered relatively low values throughout the investigation period without much change.

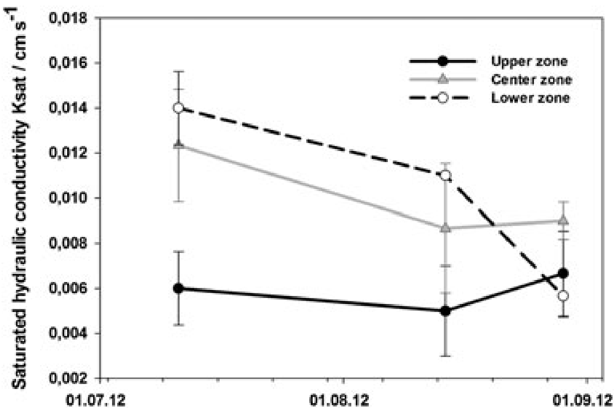

FIGURE 8 Temporal distribution of mean saturated hydraulic conductivity for the upper, center, and lower zone of the transect with stone bunds

Pachepsky, Timlin, and Rawls (2001), for example, found a relatively strong relationship of the soil water retention characteristics with soil texture, especially sand and silt content. Usually, higher content of sand is found in positions where water erosion takes place. Subsequently, silt and clay content are then higher in the sedimentation zones (Ziadat, Taimeh, & Hattar, 2010). This accumulation of fine particles as well as the sealing of the soil surface due to ponding water can be responsible for the decrease of K_{sat} in the lo zone. As no significant differences in soil fractions were detected along the SB transect, the found differences in the K_{sat} cannot be

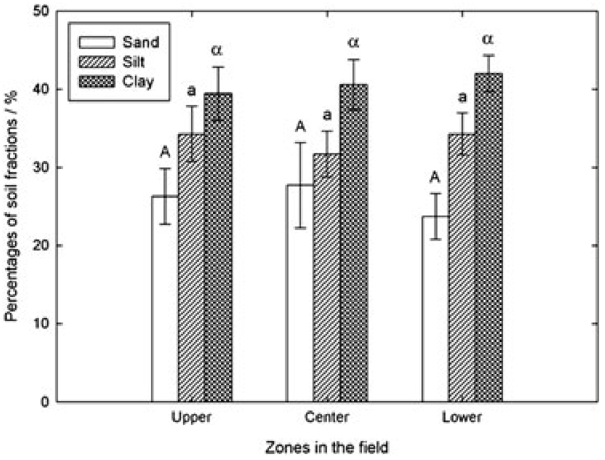

FIGURE 9 Distribution of sand, silt, and clay contents at different positions along the stone bund transect

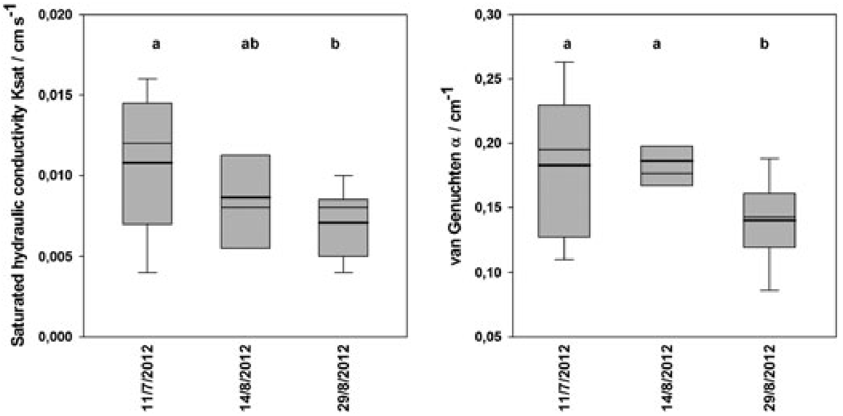

FIGURE 7 Mean and median saturated hydraulic conductivity and van Genuchten α for investigated hillslopes with stone bund and without stone bunds (no stone bunds) throughout the investigation period. Values with same letter indicate no significant differences ($p < .05$) between means

FIGURE 10 Soil structure of the upper and center zone (left) and of the lower zone right of the transect with stone bunds (right) [Colour figure can be viewed at wileyonlinelibrary.com]

explained by differences in soil texture (Figure 9). Visual inspection of the transect in the field, however, suggest strong differences in soil structure (Figure 10). Although mainly platy structure was found in the upper and center positions of the SB transect, fine grained aggregates were present in the accumulation zones above the SB.

An influence of stone cover on saturated hydraulic conductivity also cannot be derived. In the up and ct zones, stone cover ranged between 15% and 16% (Table 2). These values are similar to those determined by Nyssen et al. (2007). As the SBs were built with stones from the surrounding area, the lo zone shows a significantly lower cover of only 5%, but K_{sat} does not significantly differ between ct and lo zones.

3.4 | Van Genuchten parameter α

Although the measurement data are highly variable, we determined smaller α values in the up and lo zones just above and below the SBs whereas highest values were obtained in the ct zone (Table 2). A decrease of α values indicates a decreasing influence of big cracks (because of swelling) and a rising effect of mesopores. As up zone was also used as trampling path, it has also the highest BD and lowest K_{sat}. A negative impact of sedimentation on K_{sat} along the SB was therefore not detected. Initially, big cracks between the platy aggregates were dominant for saturated water flow in the ct zone. During the rainy season, these cracks closed due to swelling processes. This resulted in a decrease of K_{sat} when mesopores of the soil were dominating. The lo zone with fine to medium grained structure was less affected by the changes of cracks during the rainy season. No other data of this parameter was found in the literature.

4 | SUMMARY AND CONCLUSIONS

From this study, we can conclude that the successful implementation of SBs has many benefits regarding soil moisture. SBs increase soil water contents along the hillslope by interrupting hillslope hydrology and therefore increasing time for infiltration, especially near the SBs. Rain water is partially ponding and infiltrating and excess water is running off along the contour SB.

Increase of near-surface soil water content over the rainy season was found in both transects with and without SB. However, the increase was higher and also happened earlier in the rainy season in the zones around the SB compared with the center zone of the field and to the transect without SB. The time–space plot of soil moisture shows that, especially in the midphase of the rainy season, zones above and below SB show an increase by 15% compared with the center zones and by almost 20% compared with NSB. As areas close to SBs were used by the farmers as pathways, soil BD and saturated hydraulic conductivity were significantly affected. BD of NSB was about 7–10% higher than those of SB. SBs decreased BD significantly in center and lower zones between the structures. No significant change of this soil property throughout the rainy season could be observed for both investigated transects. The saturated hydraulic conductivity was significantly affected by SB. Overall, K_{sat} decreased significantly from June to September. The highest values were obtained in the accumulation zone along the SB. As no significant differences in soil fractions were detected along transect, the found in the K_{sat} cannot be explained by differences in soil texture. Visual inspection of the transect in the field, however, suggests strong differences in soil structure. Although mainly platy structure was found in the upper and center positions of the SB transect, fine-grained aggregates were present in the accumulation zones above the SB.

Based on our results, future studies should focus on how the improved soil hydrology performs after the end of the rainy season and how this affects the amount and spatial distribution of crop yield in SB field.

Although a periodic maintenance of these soil conservation structures is absolutely necessary to keep their efficiency, SBs are proven and successful measure to improve soil moisture and water retention to establish climate-smart agriculture in the Ethiopian Highlands.

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ORCID

Andreas Klik http://orcid.org/0000-0002-3299-1721

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