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Research Article

Effects of Soil and Water Conservation Measures on Soil Quality Indicators: The Case of Geshy Subcatchment, Gojeb River Catchment, Ethiopia

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Land degradation is a global negative environmental process that causes the decline in the productivity of land resources' capacity to perform their functions. Though soil and water conservation (SWC) technologies have been adopted in Geshy subcatchment, their effects on soil quality were limitedly studied. The study was conducted to evaluate the effects SWC measures on soil quality indicators in Geshy subcatchment, Gojeb River Catchment, Ethiopia. A total of 54 soil samples (two treatments–farmlands with and without SWC measures $*$ three slope classes $*$ three terrace positions $*$ three replications) were collected at a depth of 20 cm. Statistical differences in soil quality indicators were analyzed using multivariate analysis of variance (ANOVA) following the general linear model procedure of SPSS Version 20.0 for Windows. Means that exhibited significant differences were compared using Tukey's honest significance difference at 5% probability level. The studied soils are characterized by low bulk density, slightly acidic with clay and clay loam texture. The results revealed that farmlands with SWC measures had significantly improved soil physical (silt and clay fractions, and volumetric soil water content (VSWC)) and chemical (pH, SOC, TN, C : N ratio, and Av. phosphorus) quality indicators as compared with farmlands without SWC measures. The significantly higher VSWC, clay, SOC, TN, C : N ratio, and Av. P at the bottom slope classes and terrace positions could be attributed to the erosion reduction and deposition effects of SWC measures. Generally, the status of the studied soils is low in SOC contents, TN, C : N ratio, and Av. P (deficient). Thus, integral use of both physical and biological SWC options and agronomic interventions would have paramount importance in improving soil quality for better agricultural production and productivity.

1. Introduction

Land degradation is a gradual, global negative environmental process and development issue that causes the temporary or permanent decline in the productivity of land resources' capacity to perform their functions [1]. Soil degradation, which involves physical, chemical, and biological degradation, is the key component of land degradation [2, 3, 4]. The most critical forms of soil degradation are depletion of soil quality and soil erosion by water [5]. Soil quality (SQ) is defined as "the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" [2]. Measurement of SQ requires identification of specific "indicators" that can be quantitatively measured over time and compared to reference conditions or judged against some common standards [6]. Thus, SQ indicators can be defined as those soil properties and processes that have greatest sensitivity to changes in soil function due to the change in land management practices on a short-term bases [7]. Hence, SQ assessments are the quantification of SQ indicators and are the measurable soil property that affects the capacity of a soil to perform a specified function [8].

The problems of soil degradation and low agricultural productivity are severe in the rural highlands of Ethiopia [9, 10]. SQ deteriorations in the country are mainly caused by water erosion due to rugged topography, mismanagement of land resources, and loss of vegetation cover [11]. Following the disastrous drought and famine of the 1984/85, mass settlement programs that had been carried out from northern to the southwest part of the country resulted in massive deforestation and soil degradation [12]. Research findings revealed that the rate of soil erosion on cultivated lands across the country was 42 $Mgha^{-1} year^{-1}$ [13]. Recent study [14] also estimated the rates of soil erosion as 20 $Mgha^{-1} year^{-1}$ on currently cultivated lands and 33 $Mgha^{-1} year^{-1}$ on formerly cultivated degraded lands in Ethiopia. Bewket and Teferi [15] and Gelagay and Minale [16] reported a soil erosion rate of 47 and 93 $Mgha^{-1} year^{-1}$ in Koga and Chemoga watershed, respectively. In Shomba subcatchment, Mekuria [12] also reported that the estimated mean annual rate of soil erosion in cultivated fields was 13.5 $Mgha^{-1} yr^{-1}$ that accelerates its rate beyond the tolerable level. The governmental and nongovernmental institutions have been investing huge financial and labor resources to tackle land degradation in Geshy subcatchment, Gojeb River Catchment of Ethiopia. Various soil and water conservation (SWC) technologies have been adopted and constructed in cultivated fields and the afforestation of hillsides by sustainable land management program (SLMP) under Ministry of Agriculture. Improved land management practices like SWC have been suggested as a key strategy to reduce land degradation and sustain soil quality [17, 18].

Though the prime aims of SWC interventions were to reduce soil erosion, restore soil quality, and enhance agricultural productivity, there are mixed and contradicting reports about its benefits implemented in Ethiopia. Several studies (e.g., [3, 5, 19, 20]) confirmed the significant positive effects of SWC technologies on soil quality and crop productivity. Other studies in various parts of Ethiopia [3, 17, 21, 22, 23] reported that SWC technologies have played a significant role in maintaining soil quality, enhancing agricultural production and mitigating land degradation. Contrarily, Wolka et al. [20] argued that croplands with level soil bund and stone bund and nonterraced did not show remarkable difference for some parameters and even less for some sites in Southern Ethiopia.

Thus, proper understanding and quantifying changes in soil quality resulting from SWC interventions is imperative, as it provides information on the effectiveness of diverse land management options. Effects of SWC interventions on soil quality are inherently site-specific, and no study has been conducted to evaluate its effects on soil quality in Geshy subcatchment. There is an urgent need to assess the effects of SWC measures on soil quality indicators. Therefore, the objective of this study was to assess the effects of SWC technologies on soil quality indicators in Geshy subcatchment of Gojeb River Catchment, Ethiopia.

2. Materials and Methods

2.1. Description of the Study Area. The study was conducted in Geshy subcatchment of Gojeb river catchment, Ethiopia, which covers a total area of 9628.5 hectares. Geographically, it lies between 07°22′-7°26′N latitude and 36°12′-36°24′E longitude with altitude ranges from 1600 to 1800 m.a.s.l. Thus, small tributaries along with the main stream, Geshy river, are from west, south-west, south, and south-east of Geshy river that flows to Gojeb river at its outlet (Figure 1).

Agroecologically, it falls in the wet/moist (Woina Dega) regime and is found in warm submoist lowlands, tepid submoist mid highlands, tepid humid to subhumid mid highlands, and warm subhumid lowlands [24]. Based on records in Gojeb meteorological station, the coolest months are June to August in the middle of the main rainy season, while the hottest months are from February to May. The rainfall is unimodal with low rainfall from November to February and the wettest months between May and September. The mean annual and monthly rainfall of 1762 mm and 136.3 mm and monthly mean maximum and minimum temperature of 25.3°C and 15°C (Figure 2), respectively, was recorded at Dirri meteorological station.

In the Geshy subcatchment, according to FAO soil classification, the soil mapping units are dominantly of Humic Nitisols (5971.78 ha, 62% of the total area) and Humic Alisols (3656.70 ha, 38%, Figure 3). The land use pattern is characterized by extensive cropland and mainly dominated by five LULC classes such as cropland, forest land, shrublands, woodland, and swamp area (Table 1). The total population is 14518 from which 7261 are men with total number of households 3060 [12].

2.2. Methods

2.2.1. Site Selection. A preliminary survey was conducted in one of the SLMP implementing sites, Geshy subcatchment to identify appropriate sites for sampling plots. Various SWC measures such as soil bunds and Fanya juu have been implemented through mass community mobilizations by SLM program. Hence, soil data were collected from farmlands with and without SWC measures and made comparison between these treatments at various slope classes and positions within the terraces. In the case of farm plots with SWC measures, the sampling plots refer to the area between the two successive terraces. In the case of farmlands without SWC measures, the sampling plots refer to the area under cultivation, which is found between successive farm boundaries. Then, the selected subcatchment was classified into different slope categories using a digital elevation model (DEM). The DEM output and the subcatchment soil map were used to classify the study area and to identify sampling plots. The study subcatchment were classified into flat to very gently sloping (<3%), gently sloping (3–5%), sloping (5–8%), strongly sloping (8–15%), moderately steep (15–30%), and steep to extremely steep

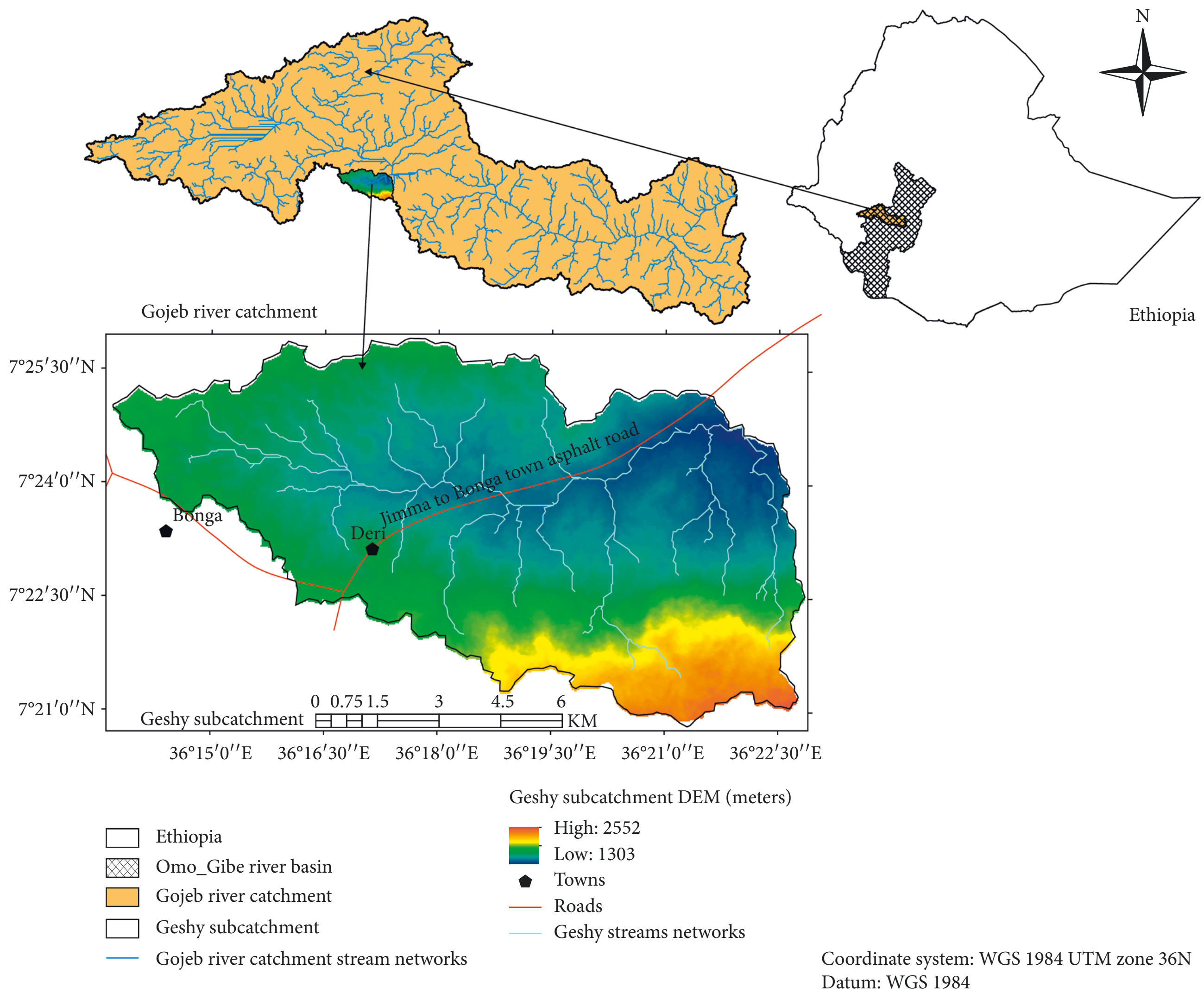

Figure 1: Study map of Geshy subcatchment, Gojeb River Catchment, Ethiopia.

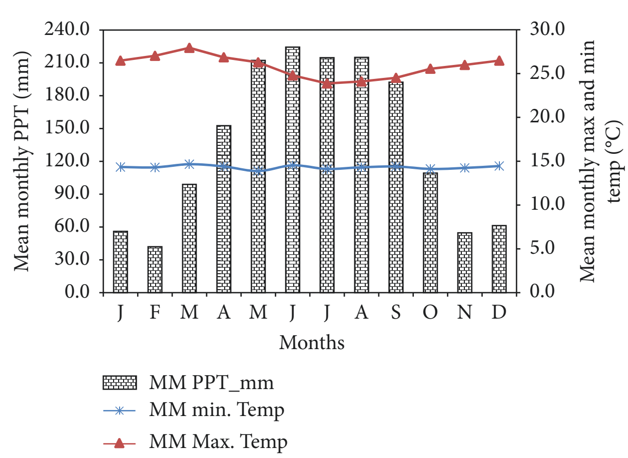

Figure 2: Mean monthly precipitation (mm) and mean monthly maximum and minimum temperature (°C) at Dirri meteorological station, Geshy subcatchment [25].

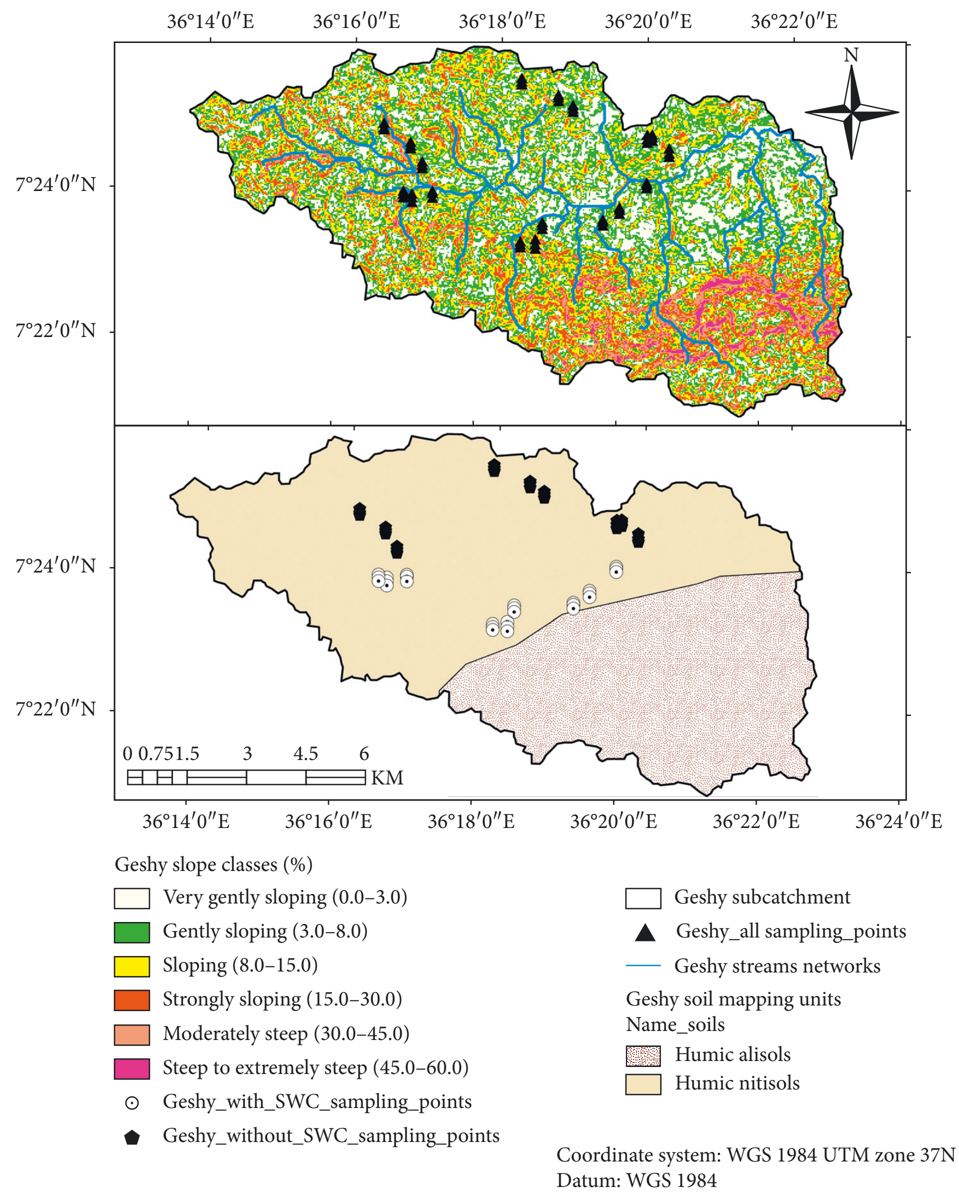

Figure 3: Maps showing slope classes, soil sampling points, and soil mapping units of Geshy subcatchment.

Table 1: Description of land use types identified in the Geshy Subcatchment, Ethiopia.

No.	LULC classes	Descriptions
1	Cultivation land	Arable and fallow land that grows annual, perennial crops and permanent fruit trees on the small or commercial level
2	Natural forest land	Natural vegetation area composed of undisturbed and disturbed, either or mixed of evergreen, deciduous, semideciduous with the area exceeds 0.5 ha, height ≥2 m, and Canopy cover ≥20%
3	Grazing land	Land with shrubs/bushes canopy cover ≥10% of bush, shrubs, and trees ≥10%. Grassland areas with/without scattered trees (<10 trees/ha), mainly short grasses used for grazing

(>30%, Figure 3) by adopting the FAO system [26]. Accordingly, representative sample plots from three slope categories, namely, lower (3–8%), middle (8–15%), and upper (15–30%), were identified by deliberately omitting the land with less than 3% slope with the assumptions of little erosion on this slope [27].

2.2.2. Soil Sampling and Data Collection. In Geshy subcatchment, a reconnaissance survey was conducted to determine the representative SWC measures and soils sampling plots. Different soil sampling methods have their own advantages and a drawback. Landon [28] suggests judgment sampling for selection of typical sites is feasible to represent large areas. Furthermore, sample sites were characterized following the approaches used by Shiene [23], Winowiecki [29], Abegaz et al. [30], and Dagnachew et al. [25]. Accordingly, judgment sampling was used to take representative soil samples from farmlands with and without SWC measures. Following identification of sampling plots in different slope categories (3–8, 8–15, and 15–30%) and terrace positions (low-terrace, mid-terrace, and up-terrace), farmlands with SWC measures and composite soil samples were collected along the terraces at 50 cm distance from the respective auger to 20 cm depth through purposive sampling technique. For the farmlands without SWC measures, auger holes were opened on three slopes classes (3–8%, 8–15%, and 15–30%, Figure 3) and on three positions within the terraces on the considered piece of land under cultivation, i.e., one on the lower, middle, and upper ends of the plot. In the study subcatchment, all soil samples were taken from similar soil mapping units, Humic Nitisols, to see the effects of SWC measures on soil quality indicators. A portable global positioning system (GPS) was used to record the longitudes, latitudes, and altitudes of sampling points (Figure 3). The slope classes, the soil mapping units, and soil sampling points are shown in Figure 3 below.

Moreover, three sampling positions within the terraces of the fixed plots were selected, i.e., low-terrace (A), mid-terrace (B), and up-terrace (C) (Table 2). The location of the sampling points was as follows: (A) low-terrace position refers to the location 50 cm from the lower terrace riser in the upslope direction, (B) mid-terrace position is the midpoint between two successive terraces, and (C) up-terrace position refers to the location 50 cm from the lower wall of the upper terrace in the down slope direction. The 50 cm distance from both the lower and upper terrace wall is to reduce the effect of water accumulation and splash by the overtopping water, respectively [23]. The reason for selecting these three slope positions is that soils and their drainage conditions vary considerably over such areas. Furthermore, the Soil Conservation Research Programme (SCRP) did long-term series of productivity measurements using the same procedure, which can be used for comparing soil quality with agricultural production in these positions [25, 31]. Soil sampling was done from three slope categories and in three terrace positions with three replications (plots) (Figure 3, Table 2).

Thus, a total of 54 soil samples were collected for soil laboratory analysis from January to February 2016. After removing the top 5 cm soil to exclude litters and nematodes, the soil samples were thoroughly mixed, labeled, and bagged (2 kg samples) for laboratory analysis. Undisturbed soil samples were collected using a core ring sampler for the determination of dry bulk density and soil water content at the center of sampling plot. Thus, a total of 54 samples (27 samples from farm plots with SWC measures and 27 from farm plots without SWC measures) were collected for laboratory analysis.

Table 2: Soil sampling design in farmlands with SWC and without SWC measures.

Slope classes (%)	With SWC			Without SWC		
	R_1	R_2	R_3	R_1	R_2	R_3
	A	A	A	A	A	A
3–8	B	B	B	B	B	B
	C	C	C	C	C	C
	A	A	A	A	A	A
8–15	B	B	B	B	B	B
	C	C	C	C	C	C
	A	A	A	A	A	A
15–30	B	B	B	B	B	B
	C	C	C	C	C	C
Subtotal		27			27	
Overall			54			

Note: A = low-terrace, B = mid-terrace, and C = up-terrace positions. R_1, R_2, and R_3 represent replicate 1, 2, and 3, respectively.

2.2.3. Soil Laboratory. The soil samples were air-dried, crushed, and sieved through a 2 mm mesh sieve for analysis. The farmlands with and without SWC measures, slope, and terrace positions were used as independent variables (factors) and the soil quality indicators as the dependent variables. The selected soil quality indicators considered in this study were particle size distributions, dry bulk density, volumetric soil water contents, total porosity, pH, soil organic carbon (SOC), total nitrogen (TN), carbon-to-nitrogen ratio, and available phosphorus (AP). The dry bulk density (ρ) of the soil was measured from undisturbed soil samples collected using a core sampler after drying the core samples in an oven at 105°C [32] at soil laboratory of Jimma agricultural research center, Ethiopia, and calculated as the mass of oven-dried soil divided by 102.1 cm^3 volume of cores [25, 33] as follows:

$$\rho_s\left(\mathrm{gcm}^{-3}\right) = \frac{M_s}{V_b}, \tag{1}$$

where ρ_s = soil bulk density (gcm^{-3}), M_s = mass of soil after over dry (g), and V_b = bulk volume of the soil (cm^3).

Total porosity was estimated from bulk density and particle density (assuming particle density of 2.65 g/cm^3). Hence,

$$\text{total porosity (\%)} = \left(1 - \frac{\text{bulk density}}{\text{particle density}}\right) * (100). \tag{2}$$

The gravimetric soil water content (GSWC, %) was determined following the method described by [34]. Before the soil was oven-dried, the initial weights were measured followed by oven drying for 24 hours at 105°C and weighing the oven-dried soil. Gravimetric soil water content was determined using the following formula [25]:

$$\text{GSWC}\,(\%) = \frac{W_{\text{wet}} - W_{\text{wet}}}{W_{\text{dry}}}, \tag{3}$$

where GSMC = Gravimetric soil water content on mass basis (%), W_{wet} = the weight of the wet soil sample (g), and W_{dry} = the weight of the dried soil sample (g).

However, in relation to agricultural and engineering functions, volumetric is more relevant than gravimetric basis to express soil water content and was determined by multiplying the gravimetric soil water content with dry bulk density and divided it by 1 gcm^{-3} density of water [34].

Soil reaction (pH) and particle size distribution were determined using 1:2.5 (w/v) H_2O suspension glass electrode and hydrometer by Van Reeuwijk [35] and Haldar and Sakar [36] method, respectively. The SOC is determined by the Walkley and Black [37] method and TN by the Kjeldahl method as described in Black [32]. The available phosphorus (AP) was determined following the Olsen procedure [38]. The analysis was done at the National Soils Testing Laboratory following standard procedures, Addis Ababa, Ethiopia.

2.2.4. Statistical Data Analysis. Statistical differences in the selected soil quality indicators were analyzed among treatments (with and without SWC), slope classes, and terrace positions in the top 20 cm of soil depth and were tested using multivariate analysis of variance (MANOVA) following the general linear model (GLM) procedure of SPSS Version 20.0 for Windows. The soil spatial variability of each soil quality indicators were mapped using Geostatisical Analyst tools, Inverse Distance Weight (IDW) interpolation method, in ArcGIS 10.4.1 spatial analyst tools. All data on soil quality indicators were tested for normality prior to doing the analysis of variance. Means that exhibited significant differences were compared using post hoc test of Tukey's honest significance difference (HSD) at 5% probability level. Pearson's correlation coefficient was performed to examine all possible paired combinations between soil quality indicators to generate a correlation coefficient matrix.

3. Results and Discussion

3.1. Physical Soil Quality Indicators. Tables 3–7 show average, standard deviation values, the analysis of variance, and Pearson's correlation coefficient of soil physical and chemical quality indicators for each of the treatments (with SWC and without SWC measures), three slope classes, and terrace position in Geshy subcatchment. Moreover, the map of spatial variability of particle size distributions and bulk density was shown in Figure 4 below.

3.1.1. Particle Size Distribution (PSD). The soil particle size distribution in both with and without SWC treatment is shown in Table 3 and Figure 4. The analysis of variance (ANOVA) showed that, unlike sand fractions, silt and clay fractions were significantly varied ($P < 0.05$) with treatments (Table 6). Soils treated with SWC measures have significantly higher clay fractions compared with those without SWC measures. Conversely, silt fractions were significantly lower in farmlands with SWC than without SWC measures. Though not statistically significant, relatively higher sand fractions were recorded in soils treated with SWC than without SWC measures.

The dominant soil textural classes were found to be clay and clay loam fractions in with SWC and without SWC, respectively (Table 3). The ANOVA result showed that PSDs did not show any significant variation with slope classes and terrace positions and with their interaction effects (Table 6). However, in the farmlands with SWC, the overall average values of silt and clay fractions showed significant variation ($P < 0.05$), but sand did not show significant variation within the terrace position (Table 3). Accordingly, the overall average clay fractions in the lower (45.3%) were significantly higher than the upper terrace position (37.8%) in the farmlands with SWC measures. The overall average silt fractions in the lower (25.9%) were significantly lower than the upper terrace position (32.4%) in the farmlands with SWC measures. This could be attributed to its strong inverse correlation with clay fractions ($r = -0.943$, $P = 0.001$, Table 7). However, in the farmlands without SWC measures, the overall average sand, silt, and clay fractions did not show any significant variation within terrace positions (Table 3). This could be attributed to the effect of SWC measures on soil erosion and deposition processes. The PSD did not follow any distinct pattern across the slope positions both in the farmlands with and without SWC measures. Inline with this finding, Wolka et al. [20] found significant variations of silt and clay fractions ($P < 0.05$) in croplands underterraced than adjacent nonterraced croplands in Southern Ethiopia. Similarly, Mengistu et al. [3] and Demelash and Stahr [39] also reported significantly higher silt content in nonconserved than conserved lands in highlands of Ethiopia. Moreover, Hailu et al. [19], Shiene [23], and Mengistu et al. [3] also reported that soil texture differences between terraces at different slope could be related to erosion and deposition processes.

3.1.2. Bulk Density (ρ, gcm^{-3}). In Geshy subcatchment, the spatial distribution of bulk density was shown in Figure 4. The bulk density did not show any significant variations with treatments, slope classes, and positions within the terraces as well as their interactions effects (Table 6). The soil ρ_s are found within the critical level (1.00–1.40 gcm^{-3}) for both farmlands with and without SWC measures, which is an ideal condition for root growth for agricultural land use and rated as "low" for clay soils [34, 40]. The mean value of ρ_s in the farmlands with SWC was slightly lower than in without SWC measures (Table 3, Figure 4). Soil ρ was generally rated as "low" [28]. Similarly, Hailu et al. [19] and Mengistu et al. [3] reported that soil bulk density did not show significant variation between conserved and nonconserved farmlands. Conversely, they reported a significant variation of ρ_s with landscape positions. Shiene [23] also did not observe a significant difference in ρ_s across landscape positions in the Wello area. In contrast, Demelash and Stahr [39], and Abay et al. [41] reported a significant variation of ρ_s between the

Table 3: Mean values of dry bulk density (gcm^{-3}) and soil textures in 0.0- to 20.0 cm soil depth in the Geshy subcatchment.

Slope (%)	Terrace position	With SWC					Without SWC				
		ρ, gcm^{-3}	Texture (%)				ρ, gcm^{-3}	Texture (%)			
			Sand	Silt	Clay	Class		Sand	Silt	Clay	Class
3–8	Lower	1.35	28.7	24.3	47.0	C	1.43	29.7	32.3	38.3	CL
	Middle	1.23	29.3	30.3	40.7	C	1.30	29.7	35.0	35.3	CL
	Upper	1.20	29.0	31.7	39.3	CL	1.34	30.0	32.7	37.3	CL
	Average	1.26^{a}	29.0^{a}	28.8^{a}	42.3^{a}	C	1.36^{a}	29.8^{a}	33.3^{a}	37.0^{a}	CL
	SD	0.15	2.50	4.84	6.73		0.09	0.83	2.69	2.55	
8–15	Lower	1.43	29.3	27.7	43.3	C	1.31	28.3	34.3	37.7	CL
	Middle	1.34	29.3	28.7	42.3	C	1.35	29.7	34.3	36.3	CL
	Upper	1.35	29.3	31.7	39.3	CL	1.42	28.3	32.0	39.7	CL
	Average	1.37^{a}	29.3^{a}	29.3^{a}	41.7^{a}	C	1.36^{a}	28.8^{a}	33.6^{a}	37.9^{a}	CL
	SD	0.16	1.00	4.12	4.66		0.11	0.83	4.59	4.73	
15–30	Lower	1.42	29.0	25.7	45.7	C	1.30	28.3	33.3	37.3	CL
	Middle	1.32	30.7	29.3	40.0	C	1.27	29.7	32.7	38.3	CL
	Upper	1.39	32.3	34.0	34.7	CL	1.39	28.3	36.3	34.3	CL
	Average	1.38^{a}	30.7^{a}	29.7^{a}	40.1^{a}	C	1.32^{a}	28.8^{a}	34.1^{a}	36.7^{a}	CL
	SD	0.15	3.61	5.03	8.27		0.07	1.20	3.76	4.36	
Total	Lower	1.40^{a}	29.0^{a}	25.9^{a}	45.3^{a}	C	1.35^{a}	29.1^{a}	33.3^{a}	37.8^{a}	CL
	Middle	1.30^{a}	29.8^{a}	29.4^{ab}	41.0^{ab}	C	1.31^{a}	29.3^{a}	34.0^{a}	36.7^{a}	CL
	Upper	1.31^{a}	30.2^{a}	32.4^{b}	37.8^{b}	CL	1.38^{a}	29.2^{a}	33.7^{a}	37.1^{a}	CL
	Average	1.34^{a}	29.7^{a}	29.3^{a}	41.4^{a}	C	1.35^{a}	29.2^{a}	33.7^{b}	37.2^{b}	CL
	SD	0.16	2.60	4.51	6.52		0.09	1.34	3.63	3.87	

Note: overall means followed by the same letter (*s*) across columns and rows are not significantly different ($P = 0.05$) with respect to treatments, slope classes, and position within the terraces. ρ, bulk density; SD, standard deviation; C, clay; CL, clay loam.

Table 4: Mean values of volumetric soil water content (VSWC) and total porosity (TP) in 0 to 20 cm depth in the Geshy subcatchment.

Slope (%)	Terrace positions	With SWC		Without SWC	
		VSWC (%)	TP (%)	VSWC (%)	TP (%)
3–8	Lower	44.73	48.93	30.40	45.93
	Middle	34.30	53.70	26.00	50.90
	Upper	17.63	54.73	16.50	49.57
	Average	32.22^{a}	52.46^{a}	24.30^{a}	48.80^{a}
	SD	13.74	5.66	7.76	3.41
8–15	Lower	33.13	46.00	23.80	50.70
	Middle	29.47	49.43	26.03	49.33
	Upper	26.23	49.23	15.10	46.57
	Average	29.61^{a}	48.22^{a}	21.64^{a}	48.87^{a}
	SD	6.93	6.12	5.57	3.94
15–30	Lower	40.00	46.33	30.70	50.87
	Middle	32.77	50.20	21.63	51.87
	Upper	25.53	47.66	19.10	47.50
	Average	32.76^{a}	48.07^{a}	23.81^{a}	50.08^{a}
	SD	7.58	5.69	5.82	2.70
Total	Lower	39.29^{a}	47.09^{a}	28.30^{a}	39.17^{a}
	Middle	32.18^{b}	51.11^{a}	24.55^{ab}	40.70^{a}
	Upper	23.13^{c}	50.54^{a}	16.90^{c}	37.88^{a}
	Average	31.53^{a}	49.58^{a}	23.25^{b}	39.24^{a}
	SD	9.61	5.97	6.31	3.31

Note: overall means followed by the same letter (*s*) across columns and rows are not significantly different ($P = 0.05$) with respect to treatments, slope classes, and position within the terraces. SD, standard deviation.

conserved and nonconserved watersheds and among slope gradients. In contrast, Shiene [23] reported significant variation of ρ_s at the three terrace positions. Thus, the nonsignificant differences observed in soil physical quality indicators between farmlands with and without SWC measures may be related to the age of SWC structures.

3.1.3. Volumetric Soil Water Content (VSWC, %) and Total Porosity (%). In the Geshy subcatchment, the spatial distributions of VSWC TP and pH were shown in Figure 5. The overall VSWC was significantly varied with treatments and positions within the terraces ($P = 0.001$), but not significantly varied with slope classes ($P = 0.273$) and their

Table 5: Mean values of soil chemical qualities in 0 to 20 cm depth in the Geshy subcatchment.

Slope class (%)	Terrace position	With SWC					Without SWC				
		pH-H_2O	SOC (%)	TN (%)	C : N ratio	AP (ppm)	pH-H_2O	SOC (%)	TN (%)	C : N ratio	AP (ppm)
	Lower	6.27	3.43	0.28	12.12	3.26	6.43	3.50	0.29	12.21	1.74
	Middle	6.20	3.33	0.28	12.05	3.60	6.33	3.40	0.28	12.00	0.93
3–8 (%)	Upper	6.27	2.73	0.23	11.89	4.20	6.37	3.17	0.28	11.28	3.28
	Average	6.24^{a}	3.20^{a}	0.26^{a}	12.01^{a}	3.69^{a}	6.38^{a}	3.36^{a}	0.28^{a}	11.83^{a}	1.98^{a}
	SD	0.07	0.34	0.03	0.30	1.88	0.10	0.28	0.01	0.36	2.00
	Lower	6.23	3.47	0.28	15.16	1.08	6.33	3.10	0.26	12.09	3.31
	Middle	6.17	3.33	0.27	12.19	1.85	6.30	2.90	0.25	11.59	1.51
8–15 (%)	Upper	6.20	2.80	0.23	9.95	4.26	6.50	2.70	0.23	11.73	1.94
	Average	6.20^{a}	3.20^{a}	0.26^{a}	12.43^{a}	2.40^{ab}	6.38^{a}	2.90^{b}	0.25^{b}	11.80^{a}	2.25^{a}
	SD	0.12	0.43	0.04	2.49	1.84	0.17	0.32	0.02	0.41	1.55
	Lower	6.20	3.47	0.28	12.10	1.67	6.23	2.97	0.24	12.36	0.45
	Middle	6.20	3.33	0.27	13.06	0.79	6.30	2.87	0.24	11.95	1.71
15–30 (%)	Upper	6.07	2.83	0.23	12.87	2.55	6.40	2.70	0.22	12.09	1.48
	Average	6.16^{a}	3.21^{a}	0.26^{a}	12.68^{a}	1.67^{b}	6.31^{a}	2.84^{b}	0.23^{b}	12.13^{a}	1.21^{a}
	SD	0.19	0.51	0.04	0.98	1.00	0.14	0.16	0.01	0.29	1.15
	Lower	6.23^{a}	3.42^{a}	0.27^{a}	13.12^{a}	2.00^{a}	6.33^{a}	3.19^{a}	0.26^{a}	12.22^{a}	1.83^{a}
	Middle	6.19^{a}	3.39^{a}	0.26^{a}	12.4^{ab}	2.08^{a}	6.31^{a}	3.06^{ab}	0.26^{a}	11.8^{ab}	1.38^{a}
Total	Upper	6.18^{a}	2.82^{b}	0.25^{a}	11.57^{b}	3.67^{b}	6.42^{a}	2.86^{b}	0.24^{a}	11.70^{b}	2.23^{a}
	Av.	6.20^{a}	3.21^{a}	0.26^{a}	12.38^{a}	2.58^{a}	6.36^{b}	3.03^{b}	0.25^{a}	11.92^{b}	1.82^{a}
	SD	0.14	0.42	0.04	1.52	1.78	0.14	0.34	0.03	0.46	1.61

Note: overall means followed by the same letter (*s*) across columns, and rows are not significantly different ($P = 0.05$) with respect to treatments, slope classes, and position within the terraces. SD, standard deviation.

Table 6: Results of the analysis of variance of soil quality indicators across the treatments, slope positions, and positions within the terraces in the Geshy subcatchment.

SQI	Treatment		Slope classes		Terrace position		Interaction							
							T ∗ S		T ∗ TePo		S ∗ TePo		T ∗ S ∗ TePo	
	MS	*P*	MS	*P*	MS	*P*	MS	*P*	MS	*P*	MS	*P*	MS	*P*
ρ	0.00	0.81	0.06	0.42	0.03	0.21	0.03	0.21	0.02	0.37	0.01	0.60	0.00	0.97
Sand	2.67	0.47	3.17	0.54	6.17	0.31	6.17	0.31	1.39	0.76	1.67	0.86	2.06	0.80
Silt	262	**0.00***	3.13	0.83	0.13	0.99	0.13	0.99	43.6	0.09	16.1	0.44	2.10	0.97
Clay	237	**0.01***	10.7	0.71	4.57	0.86	4.57	0.86	53.5	0.19	20.3	0.62	4.91	0.96
SWC	926	**0.00***	42.1	0.27	867	**0.00***	1.54	0.95	26.9	0.43	75.5	0.07	35.7	0.35
TP	1.50	0.81	21.1	0.44	39.4	0.22	39.4	0.22	25.3	0.37	16.5	0.62	3.32	0.97
pH	0.33	**0.00***	0.03	0.25	0.01	0.57	0.11	0.89	0.03	0.27	0.01	0.72	0.01	0.58
SOC	0.43	**0.04***	0.26	0.08	1.12	**0.00***	0.47	**0.01***	0.16	0.20	0.02	0.93	0.01	0.99
TN	0.00	0.33	0.00	**0.01***	0.00	0.07	0.00	**0.03***	0.00	0.70	0.00	0.24	0.00	**0.05***
C : N	2.77	**0.03***	1.05	0.14	4.84	**0.00***	0.25	0.62	1.28	0.10	3.86	**0.00***	4.26	**0.00***
AP	7.95	0.08	8.94	**0.03***	7.76	**0.05***	3.08	0.29	1.81	0.48	0.31	0.97	4.66	0.13

SQI, soil quality indicators; ρ, bulk density (gcm^{-3}); SWC, volumetric soil water content (%); TP, total porosity (%); SOC, soil organic carbon (%); TN, total nitrogen (%); C : N, carbon-to-nitrogen ratio; AP, available phosphorus (ppm); MS, mean square error; P, *P* value, *T*, treatments (i.e., with or without soil and water conservation measures); S, slope position; TePo, terrace positions. *significantly different at $P < 0.05$.

interaction effects of treatments, terrace positions, and slope classes ($P > 0.05$, Table 6). In farmlands with SWC measures, the overall average values of VSWC was, though not statistically significant, higher ($P > 0.05$, 32.22%) in the lower slope (3–8%) than the 8–15% slope (29.61%) but not with 15–30% slope classes ($P > 0.05$, 32.76%, Table 3). In farmlands without SWC measures, it did not show any significant variation with slope positions ($P > 0.05$, Table 3), which could be attributed to absence of SWC structures to trap sediment and store moisture. In respect to positions within the terrace, the VSWC showed significant variation ($P > 0.05$, Table 3) among lower, middle, and upper terrace positions. Accordingly, the significantly highest VSWC was observed in the lower terrace position (34.90%) than in the middle (27.57%) and upper (20.71%) terrace positions in the farmlands with SWC measures. However, it was significantly higher ($P < 0.05$) in the lower (39.29%) followed by the middle (32.18%), than the upper terrace position (23.13%, Table 3) in farmlands with SWC measures.

The overall average VSWC was found to be significantly higher in the lower terrace positions ($P < 0.05$, 28.30%) than the upper terrace positions ($P < 0.05$, 32.18%), but not with the middle of terrace positions ($P > 0.05$, 23.13%, Table 3). This could be attributed to the presence of significantly

Table 7: Pearson's correlation coefficient between soil quality indicators of SWC measures in Geshy subcatchment.

Soil quality indicators		ρ	Sand (%)	Silt (%)	Clay (%)	SWC, %	TP, %	pH-H_2O	SOC (%)	TN (%)	C : N ratio
Sand	r	0.02	1								
	P	0.88									
Silt	r	−0.18	**0.37****	1							
	P	0.20	**0.006**								
Clay	r	0.15	**−0.64****	**−0.94****	1						
	P	0.27	**0.000**	**0.000**							
SWC	r	−0.08	−0.15	−0.125	0.14	1					
	P	0.58	0.289	0.368	0.31						
TP	r	**−1.00****	−0.01	0.186	−0.16	0.07	1				
	P	**0.000**	0.92	0.179	0.24	0.60					
pH	r	−0.01	**−0.51****	0.067	0.12	0.03	0.00	1			
	P	0.95	**0.000**	0.632	0.44	0.82	0.98				
SOC	r	−0.04	0.124	**−0.40****	0.27	0.26	0.04	0.033	1		
	P	0.78	0.372	**0.003**	0.05	0.06	0.79	0.812			
TN	r	−0.15	0.084	−0.249	0.16	0.20	0.15	0.160	**0.74****	1	
	P	0.27	0.546	0.070	0.25	0.15	0.27	0.249	**0.000**		
C : N ratio	r	0.14	0.046	−0.236	0.17	0.05	−0.14	−0.192	**0.37****	**−0.34***	1
	P	0.33	0.741	0.086	0.21	0.71	0.33	0.165	**0.006**	**0.012**	
AP	r	−0.13	−0.071	−0.044	0.08	−0.17	0.13	−0.115	−0.249	0.012	**−0.35****
	P	0.37	0.610	0.750	0.58	0.224	0.37	0.406	0.070	0.930	**0.009**

ρ, soil bulk density; VSWC, volumetric soil water content; TP, total porosity; SOC, soil organic carbon; TN, total nitrogen; C : N ratio, carbon-to-nitrogen ratio; Av. P, available phosphorus. **Correlation is significant at the 0.01 level (2-tailed). *Correlation is significant at the 0.05 level (2-tailed). Values are Pearson correlation coefficient (r) $n = 54$.

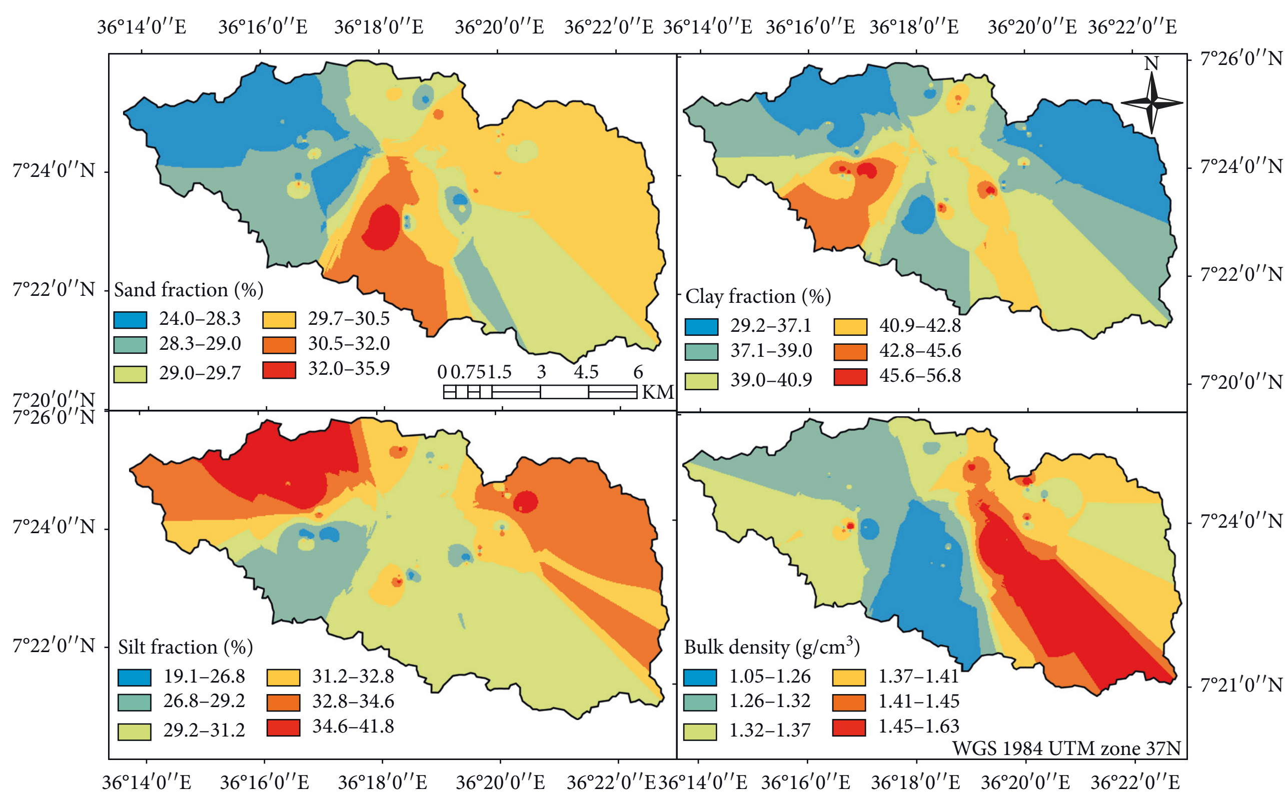

Figure 4: Spatial distribution of particle size distribution (%) and dry soil bulk density (gcm^{-3}) of Geshy subcatchment.

higher OM, clay soils, and the effect of SWC in reducing runoff velocity and enhanced infiltration than the faster runoff flow down the slope for farmlands without SWC measures. To put it in a nutshell, in the study subcatchment, the average VSWC in the farmlands with SWC measures have been found to be higher ($P < 0.05$, 49.58%) than

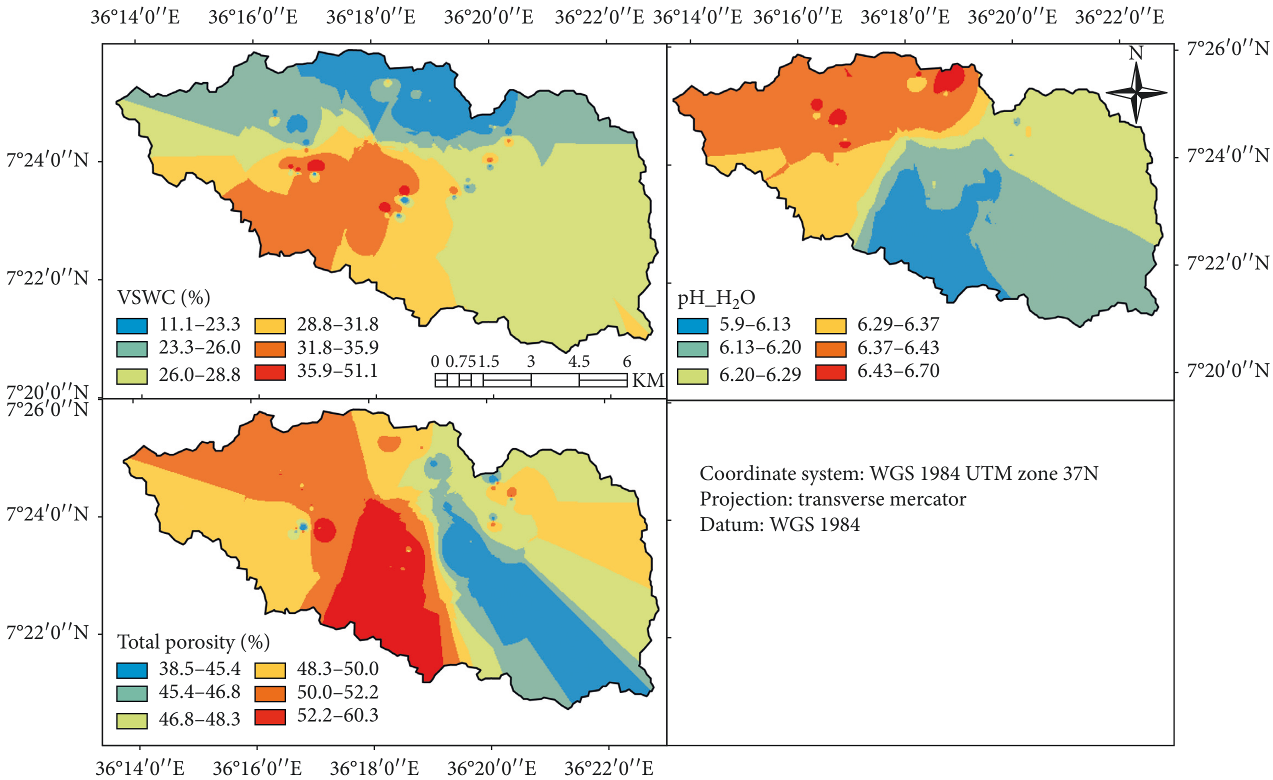

FIGURE 5: The map of spatial distribution of VSWC, TP, and soil pH in the Geshy subcatchment.

farmlands without SWC measures (49.58%), which could be attributed to the capacity of SWC technologies in enhancing soil quality improvement by trapping sediments and store moisture behind the structures. The TP (%) of the studied soils was not significantly varied with treatments, slope classes, and positions within the terraces as well as their interaction effects ($P > 0.05$, Table 6). Numerically, it is almost similar in both farmlands with and without SWC treatments, which might be attributed to the age of structures and insignificant variation of bulk density with treatments. In the studied soil, TP is strongly correlated with soil bulk density ($r = -1.00$, $P = 0.001$, Table 7).

Similarly, other studies [23, 41] revealed that terraces in the lower slope areas have gentler slopes and wider spacing, and as a result, the incoming runoff could remain for longer period and partly deposit suspended and dissolved materials.

3.2. Chemical Soil Quality Indicators. The map of spatial distribution of soil SOC, TN, C : N ratio, and AP was shown in Figure 6.

3.2.1. Soil pH_H$_2$O. Soil pH, which affects nutrient availability and toxicity, microbial activity, and root growth, is the first parameter to be considered in soil quality evaluation [42]. In the Geshy subcatchment, the spatial distribution of soil pH was shown in Figure 5. The ANOVA indicated that soil pH is significantly ($P = 0.001$) varied with treatments, but not with slope classes and positions within the terrace as well as their interaction effects ($P > 0.05$, Table 6). The overall average pH value in the farmlands with SWC is significantly lower than that of without SWC (Table 5). This may be attributed to the high annual rainfall in the subcatchment that leaches out the cations and leaves exchangeable complexes dominated by H^+ and Al^{3+} and the age of SWC structures. Variations in soil pH among slope classes were not statistically significant ($P > 0.05$), Table 6. In farmlands with SWC measures, soil pH value showed a decreasing trend with increasing slope classes (Table 5). In farmlands without SWC measures, soils in 3–8% have higher pH than the 15–30% of slope. Moreover, soil pH did not show any significant variations with terrace positions ($P > 0.05$, Table 5). However, its value was found to be higher in the lower (deposition zone) than the upper (loss zone) in farmlands with SWC measures (Table 5), which may be attributed to the positive effect of SWC practices to increase the pH of the soil and then reduces soil acidity.

Similarly, Hailu et al. [19] and Ademe et al. [21] found maximum pH value of 6.27 and 5.65 on bottom and upper landscape positions in farmlands with SWC measures, respectively. Amare et al. [22] and Mengistu et al. [3] also observed a higher pH on soils of the toe and crest slopes than for those in other landscape positions. This could be due to the fact that the high rainfall coupled with steeper slopes might have increased leaching, soil erosion, and a reduction in soluble base cations leading to higher H^+ activity and registered as decreased pH [26]. Wolka et al. [20] and Ademe et al. [21] reported significant variations

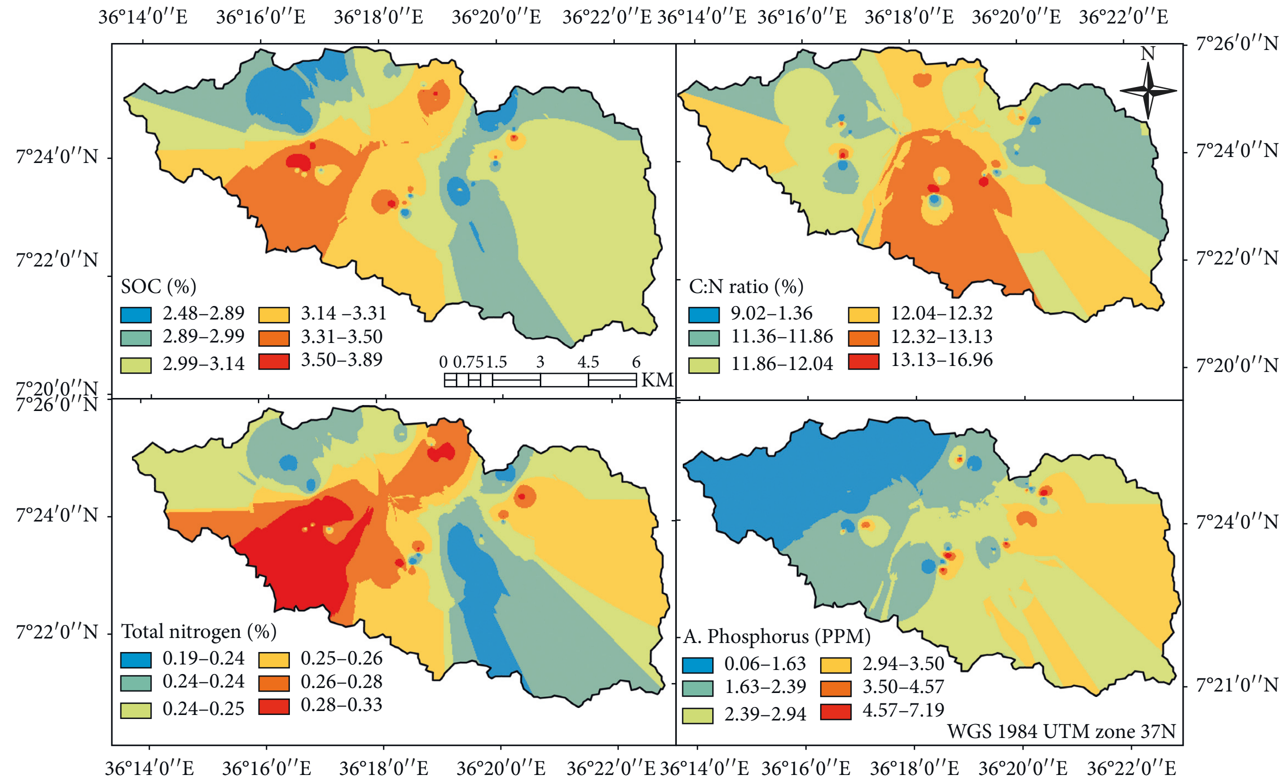

Figure 6: Map of the spatial distribution of SOC, TN, C : N ratio, and AP in the Geshy subcatchment.

of pH value for SWC practices and found higher pH value in areas with SWC practices than areas without SWC practice in Southern Ethiopia. Studies elsewhere [3, 22, 39] and [41] revealed no significant differences in pH of soils between conserved and nonconserved lands. On the contrary, Hailu et al. [19] reported lower pH value in control farmland and higher in Fanya juu 10 years aged. Amare et al. [22] also reported relatively lower pH mean value for the loss zone, while the highest in the accumulation zone. This could be attributed to the presence of higher exchangeable cations due to reduced erosion [3, 21, 23]. According to Landon [28] soil pH rating, the pH of the studied soils is categorized as medium and is rated as slightly acidic.

3.2.2. Soil Organic Carbon (SOC, %). In Geshy subcatchment, the results of ANOVA indicated that SOC was significantly varied with treatments ($P = 0.04$), positions within the terraces ($P = 0.00$), and the interactions among treatments and slope classes ($P = 0.01$) (Table 6). The overall average value of SOC in farmlands with SWC measures (3.21%) was relatively higher than under farmlands without SWC (3.03%) measures (Table 5). This might be attributed to accumulated and retained OM due to SWC measures undertaken in the subcatchment, whereas the lowest OC may be attributed to the loss in the form of decaying leaves, stems, and roots from surface soil due to lack of physical barriers.

In the farmland without SWC, SOC content was found to be significantly higher in the 3–8% (3.36%) than 8–15% (2.90%) and 15–30% (2.84%) slope classes ($P < 0.05$, Table 6) in which it showed increasing trend with decreasing of slope classes. The lowest SOC in the upper slope classes may be attributed to the severity of soil erosion and transportation of organic matter to the lower slope through runoff and erosion. The results indicate that SOC is inversely related with slope gradient. In farmland with SWC measures, SOC did not show any significant variations with slope classes (Table 6), which could probably be due to the establishment of SWC structures to enhance in situ conservation and reduce further erosion processes.

With respect to positions within the terrace, SOC content exhibited significant variations both in the farmlands with and without SWC measures ($P < 0.05$, Table 6). In the farmland with SWC, the overall mean value of SOC contents in the lower (3.42%) and mid-terrace (3.39%) positions were significantly higher than that of upper one (2.82%, Table 5). Similarly, in farmlands without SWC, its contents in the lower positions (3.19%) were significantly higher than that of upper (2.86%) terrace positions ($P > 0.05$, Table 6). This variation in SOC could be attributed due to the erosion reduction effects of SWC measures implemented and biomass accumulation [41, 43]. Amare et al. [22] also observed significant variations of SOM contents between accumulation and loss zones within the farmland terraces. Terracing reduced soil erosion and improved deposition and trapped material such as plant litter [23]. Soils from the conserved area can actively eroded the soil loss zone and deposited to the soil accumulation zone, creating spatial variability in terms of moisture and nutrient availability within the interconserved space [41]. The accumulation of SOC is one of the initial soil forming processes and is determined by physical, chemical, biological, and anthropogenic factors with complex interactions [44].

Similarly, Mulugeta and Karl [45], Hailu et al. [19], Abay et al. [41], and Hishe et al. [46] observed significant variation of SOC with respect to SWC measures. They reported significantly lower SOC content under the farmland without SWC than cultivated land under 5 and 10 years of aged Fanya juu structures. Hailu et al. [19] reported significant variations in SOC contents with slope gradient and observed higher mean SOC in the lower slope than in the higher slope gradient. In the study subcatchment, the higher OC content at the bottom of slope position could be due to lower erosion rate and higher biomass production [21, 22]. Moreover, studies by Bot and Benites [47] revealed that SOM accumulation is often favored at the bottom of hills due to higher moisture content than at mid or upper slope classes and transportation of SOC to the lowest point in the subcatchment through runoff and erosion processes. Hishe et al. [46] also reported a direct relationship of SOC with the vegetation cover and conservation measure applications. According to Landon [28] rating for tropical soils, the overall mean value of SOC contents both in the farmlands with and without SWC is rated as low (2–4%). This could be an indication to further implementing integrated SWC technologies to enhance SOC and improve soil quality for better agricultural production and productivity.

3.2.3. Total Nitrogen (%) and C : N Ratio. In Geshy subcatchment, the results of ANOVA indicated that TN was not significantly varied with treatments (P = 0.33) and terrace positions (P = 0.07), but statistically significant with slope (P = 0.01) and the interactions effects of treatments with slope classes (P = 0.03, Table 6). The analysis of variance results revealed that TN was significantly varied (P = 0.01, Tables 5 and 6) with slope classes. Accordingly, it was significantly higher in the 3–8% slope (0.28%) than in the 8–15% (0.25%) and 15–30% slope (0.23%) ranges in the farmlands without SWC measures, but not in farmlands with SWC measures. In Geshy subcatchment, the Pearson correlation coefficient showed that TN content of the studied soils is strongly and positively associated with soil OC contents (r = 0.975, P = 0.001, Table 7).

Therefore, the removal and burning of the potential sources of SOC like crop residues, manure, and any other household wastes along with soil erosion will automatically leads to soil TN depletion, which may probably be the cause for loss of grain production [41]. Similarly, Wolka et al. [20] also reported a nonsignificant difference in TN concentration of soils between conserved and nonconserved watersheds. Conversely, several researchers [19, 21, 39, 41, 45] reported significantly higher TN in farmlands with SWC measures as compared to the nonconserved land. Abay et al. [41] and Hailu et al. [19] reported significant variation in TN with slope gradient in which TN was higher in the lower slope than in the higher slope gradients. This might be due to the removal of OM from the steep slopes as a result of soil erosion and leaching to the down slope. Moreover, Shiene [23] and Mengistu et al. [3] reported a nonsignificant difference in TN concentration of soils across landscape positions in Ethiopian watersheds. According to Landon [28] ratings, the TN of the studied soils both in farmlands with and without SWC is rated as medium (0.2–0.5%). These may be attributed to the relatively less physical protection against water erosion, continuous cultivation and use of crop residues, and stocks for fuel and animal feed rather than leaving in the farmlands to decompose and enrich the soil OM content. Carbon-to-nitrogen (C : N) ratio is an index of nutrient mineralization and immobilization whereby low C : N ratio indicates higher rate of mineralization [42].

In the Geshy subcatchment, C : N ratio showed significant variation across treatments (P = 0.03), terrace positions (P = 0.00), and the interaction effects among treatments, slope, and terrace positions (P = 0.00, Table 5). However, variation was not significant with slope classes (P = 0.14) both in farmlands with and without SWC measures. Accordingly, in the farmland with SWC, C : N ratio was significantly higher (12.38) than farmlands without SWC (11.92). Across the treatments, C : N ratio in the lower terrace is significantly higher than the upper terrace positions (Table 4). According to Hazelton and Murphy [34] ratings, the overall mean value of C : N ratio in both farmlands with and without SWC treatments is rated as low. It is more or less considered as normal for an arable soil, and decomposition may proceed at the maximum rate possible under environmental conditions [34]. In contrast, Hailu et al. [19] reported that the C : N ratio did not show any significant variation across treatments, but with slope gradients.

3.2.4. Available Phosphorus (AP, ppm). The map of spatial distribution of AP was shown in Figure 6. The ANOVA results revealed that AP was significantly varied with slope classes (P = 0.03) and positions within the terrace (P = 0.05), but not with treatments and their interactions ($P > 0.05$, Table 5, Figure 6). Though not statistically significant, soils under SWC practice (2.58 ppm) had higher available P than soils without SWC measures (1.82 ppm, Table 4). The lower P from areas without SWC was possibly due to the difference in the past land degradation resulting from continuous cultivation, extractive plant harvest, and soil erosion.

The concentration of AP was significantly varied among the slope classes and positions within the terrace (Table 5). In the farmlands with SWC measures, AP is significantly higher in the slope classes of 3–8% (3.69 ppm) than in 15–30% (1.67 ppm), while in the farmlands without SWC, it did not show any significant variation (Table 4). In line with these findings, Hailu et al. [19], Mengistu et al. [3], and Hishe et al. [46] reported insignificant differences in AP among conserved and nonconserved fields in Ethiopia watersheds. In contrast, Mulugeta and Stahr [45], Wolka et al. [20], and Ademe et al. [21] reported a significantly higher AP in soils of the conserved than nonconserved lands. Similarly, Mengistu et al. [3] observed significant difference in AP concentration among soils of upper and middle, and upper and lower subwatershed locations. Ademe et al. [21] and Amare et al. [22] reported higher AP in the bottom slope position and the lower value at upper one. In contrast, Hailu et al. [19] and Shiene [23] reported insignificant variation in the available P among the landscape positions.

With respect to positions within the terrace, the overall mean value of available P in the farmland with SWC was significantly higher in the upper terrace position than in the lower one (Table 5). However, in the farmland without SWC, its value was not significantly varied within terrace positions. In contrast, though not significant, Amare et al. [22] reported relatively higher available P in the deposition than loss zone. According to Landon [28] ratings, the critical level classification for AP is low and deficient (Table 5) in both farmlands with and without SWC measures. The lower plant AP could be attributed to inherent soil properties such as P fixation by iron and aluminum, while the differences between farmlands with and without SWC could be related to OM input differences [21, 23]. This indicates that there is high deficiency of AP in Geshy subcatchment, which may retard plant growth as AP is one of the essential elements in the soil nutrient. The presence of organic P content depends upon a number of factors such as climate, vegetation, soil texture, land use, and fertilizer applications. Moreover, the availability of phosphorus in the soil is higher in the pH range 6.0-7.0 [46, 48]. In general, it can be concluded that Geshy subcatchment was characterized by low AP, and this could be due to the existence of slightly acidic soil and the presence of low SOC. This result is supported by Hishe et al. [46] who found AP decreased with higher acidic soil pH. This is true that nutrients are recycled by decomposition through the SOM and provides more than 90% nitrogen and about 50–60% P and sulfur [48]. Therefore, liming acidic soils and addition of phosphorus-contained fertilizers can improve its availability.

3.3. Correlation Matrix of Physical and Chemical Soil Quality Indicators. A partial correlation was carried out to investigate the relationship between each single soil quality indicator and the other 8 parameters considered in the analysis of this study. The SOC was very strong positive significant correlation with total nitrogen ($r = 0.74$, $P = 0.001$) and carbon-to-nitrogen ratio ($r = 0.37$, $P = 0.006$, Table 7) and negative significant correlation with silt fractions ($r = 0.40$, $P = 0.003$, Table 7). This result is directly similar with the findings of Hishe et al. [46] and Abay et al. [41] who studied on the Middle Silluh valley of Northern Ethiopia and central highlands of Ethiopia, respectively. Sand fraction has shown positive significant correlation with silt fraction ($r = 0.37$, $P = 0.006$) and negative significant correlation with clay fraction ($r = -0.614$, $P = 0.001$) and soil pH ($r = -0.51$, $P = 0.001$). Likewise, clay fraction was very strong negative significant correlation with silt fraction ($r = -0.94$, $P = 0.001$, Table 7). Soil ρ was very strong negative significant correlation with total porosity ($r = -1.00$, $P = 0.001$). Moreover, carbon-to-nitrogen ratio has negative significant correlation with total nitrogen ($r = -0.34$, $P = 0.012$) and AP ($r = -0.35$, $P = 0.009$, Table 7).

4. Conclusions

The problems of soil degradation, primarily of soil quality deteriorations and low agricultural productivity, are severe in Ethiopia mainly caused by water erosion due to rugged topography, mismanagement of land resources, and loss of vegetation cover. This study was intended to assess the effects of SWC on soil quality indicators in Geshy subcatchment of Gojeb River Catchment, Omo-Gibe Basin, Ethiopia. The results revealed that soils from the farmlands with SWC measures had significantly improved soil physical (silt and clay fractions, VSWC) and chemical (pH, SOC, TN, C : N ratio, and AP) quality indicators compared with those from the farmlands without SWC measures. Improvements due to SWC measures were also observed in terms of particle size distributions, VSWC, pH, SOC contents, TN, C : N ratio, and AP; however, the differences in some of the tested indicators were not statistically significant with respect to SWC measures, slope classes, and positions within the terraces.

Soils treated with SWC measures have significantly higher clay fractions compared with those without SWC measures. Conversely, silt fractions were significantly lower in farmlands with SWC than without SWC measures that might be attributed to its strong inverse correlation with clay fractions. Moreover, the significantly higher clay fractions in lower terrace positions (deposition zone) of farmlands with SWC measures indicated the effect of SWC measures on soil erosion and deposition processes. The dominant soil textural classes were found to be clay and clay loam in farmlands with and without SWC measures, respectively. In the study subcatchment, the implementation of SWC measures, slope classes, and terrace position did not significantly influence bulk density and total porosity, which might be related to the young age of the structures. Though soil bulk density is low for clay soils, the studied soils can be considered as an ideal condition for root growth for agricultural land use. Moreover, unlike farmlands without SWC, VSWC was significantly improved with decreasing slope classes in farmlands with SWC measures. The significantly highest VSWC in the lower terrace (deposition zone) than upper terrace positions in both farmlands with and without SWC measures could be attributed to the presence of significantly higher SOC contents, clay soils, wider, and gentler nature of depositions zones of terraces.

Geshy subcatchment is characterized by slightly acidic soils. The SOC content and C : N ratio were significantly influenced by SWC measures and varied with positions within the terraces. As a result, higher improvement of SOC and C : N ratio in farmlands with SWC was exhibited than under farmlands without SWC measures, which might be attributed to the accumulation and retention of OM. Moreover, SOC content and C : N ratio showed increasing trend with decreasing of slope classes and terrace positions due to transportation of SOC to the lowest point through runoff and erosion processes. The higher SOC content and C : N ratio at the bottom slope classes and terrace positions was due to lower erosion rate and higher biomass production, which could be due to the erosion reduction and deposition effects of SWC measures implemented and biomass accumulation. Generally, in the Geshy subcatchment, SOC contents and C : N ratio were found to be low, which could in turn be an indication to further implementing integrated SWC technologies to enhance SOC and improve soil quality for better agricultural production and productivity.

On the other hand, SWC measures did not bring significant improvement in TN and AP but statistically varied with slope classes that showed increment with decreasing slope gradient. This might be due to the removal of OM from the steep slopes as a result of soil erosion and leaching to the down slope. The status of TN and AP of the studied soils is medium and low (deficient), respectively, which might be attributed to the continuous cultivation, extractive plant harvest and soil erosion, and use of crop residues and stocks for fuel and animal feed rather than leaving in the farmlands to decompose and enrich the soil OM content. Therefore, the removal and burning of the potential sources of SOC like crop residues, manure, and any other household wastes along with soil erosion would lead to soil TN depletion and loss of grain production. Though the concentration AP is one of the essential elements in the soil nutrient, it was found to be low and deficient, which could be attributed to inherent soil properties such as P fixation, low SOC contents, and slightly acidic nature of the studied soils. The observed soil quality improvement was, however, generally low from what could possibly be achieved by sustainable land management using various SWC technologies. Hence, integral use of both physical and biological SWC options and agronomic interventions would have paramount importance in improving soil quality.

Data Availability

All the data related to this manuscript submission will be available upon the request.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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