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Groundwater Quality in an Upland Agricultural Watershed in the Sub-Humid Ethiopian Highlands

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Abstract

Agricultural intensification to meet the food needs of the rapidly growing population in developing countries is negatively affecting the water quality. In most of these countries such as Ethiopia, information on surface and especially groundwater quality is lacking. This limits the measure that can be taken to stop pollution. We, therefore, investigated the spatial and temporal variation of groundwater quality in the upland watershed. Tikur-Wuha watershed was selected because it is located in the Lake Tana watershed, which is seeing the first signs of eutrophication. Groundwater samples were collected from July 2014 to June 2015 from 19 shallow wells located throughout the watershed. Collected water samples were analyzed both *in situ* and in the laboratory to determine pH, electric conductivity (EC) and total dissolved solid (TDS), concentration of chemicals (nitrate, dissolved phosphorus, calcium, magnesium, aluminum and iron) and Escherichia coli (E. coli). We found that shallow groundwater had greater chemical concentrations and E. coli level in the monsoon rain phase than in the dry phase. Wells located down slope exhibited greater concentrations than mid- and upper-slope positions, with the exception of the nitrate concentration that was less down slope, due to denitrification in the shallow groundwater. Only E. coli level was above the WHO drinking water quality standards. Further studies on groundwater quality should be carried out to understand the extent of groundwater contamination.

Keywords

E. Coli, Lake Tana, Nitrate, Phosphorus, Pollution

1. Introduction

Groundwater is the most reliable source of drinking water in different parts of Africa [1]. It is available throughout the year and less contaminated than surface water because the rain is naturally filtered before it recharges the groundwater [2]. Despite this, studies in China [3], Turkey [4] and Portugal [5] have found that groundwater is contaminated with chemical and bacteriological contaminations due to anthropological factors such as dumping of industrial waste, improper waste management, application of fertilizers and pesticides [6] [7] [8].

Studies in Ethiopia have shown that groundwater is contaminated due to uncontrolled waste management, poor sanitation, poor management and use of fertilizers [9] [10] [11]. Samples collected from protected hand dug wells and developed springs located in the rural areas of Ethiopia showed that many wells have high level of E. coli [12] [13]. Similarly, a rapid assessment of drinking water quality in Ethiopia showed that the nitrate and fluoride concentration of more than 30% of water sources exceeded the WHO drinking water quality standards [14].

Cleanup of contaminated groundwater is cumbersome and costly [15]. Monitoring and detailed case studies of groundwater quality can provide an early warning system before cleanup is needed. Therefore, in this study, we investigated the spatial and temporal variation of shallow groundwater quality in the Tikur-Wuha watershed, Lake Tana basin where the first signs of eutrophication have been noted [16]. The Tikur-Wuha watershed was selected because it is typical for other watersheds in the highlands with intensive agriculture and the availability of shallow groundwater wells that provide water for household consumption.

2. Materials and Methods

2.1. Description of the Study Area

The study was conducted in the 1128 ha Tikur-Wuha watershed, situated in the upper Lake Tana basin of the Ethiopian highlands (**Figure 1**). Rainfall pattern of the watershed is mono-modal. More than 85% of the rainfall falls from May to September. The average annual rainfall from 2010 to 2015 was 1518 mm. Mean daily temperature was 15˚C. The parent material is Tarmaber basalt rock and major soil type is Chromic Luvisols [17]. The steady state infiltration rate of the soil ranged from 7 - 117 $\text{mm}\cdot\text{hr}^{-1}$, with a median of 31 $\text{mm}\cdot\text{hr}^{-1}$. Based on a 10-minute measured rainfall, only 6% of the rainfall intensity exceeded the median infiltration rate of the watershed. This indicates that most of the rain in the uplands infiltrated in to the soils and then either evaporated or flow as interflow and base flow from the top of the watershed to valley bottom and raising the water table close to surface during the rain phase of the monsoon. Rain on the saturated portions of the valley bottom became saturation excess runoff.

Seventy percent of the watershed, mainly on the mid slope and, to a lesser degree, on the upper slopes, is cropped with barley, wheat and potatoes during

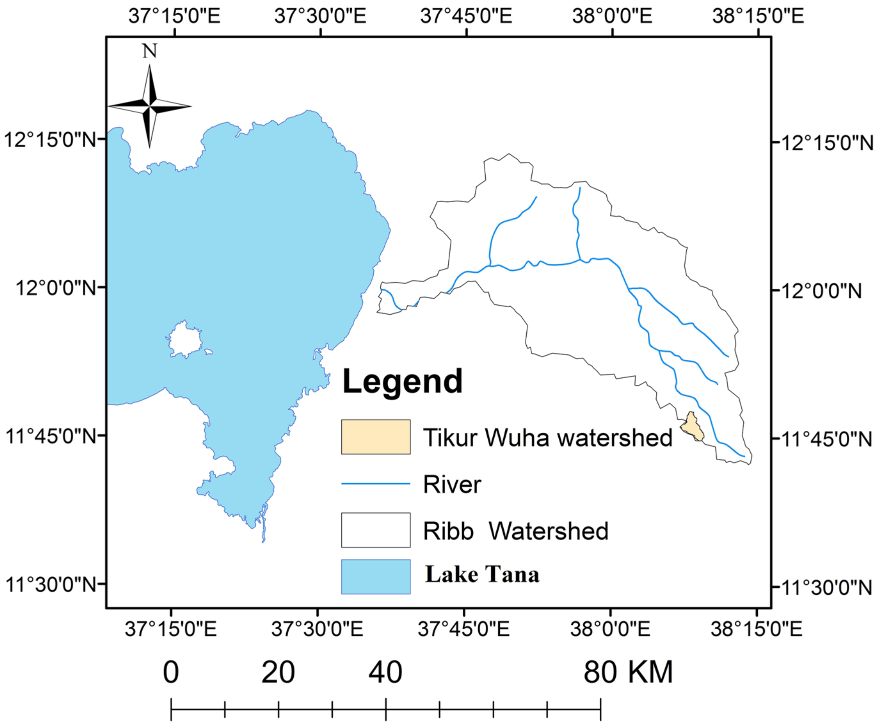

Figure 1. Location of Tikur-Wuha watershed in Ribb watershed that drains to Lake Tana.

rainy season. Bushes and shrubs that are located in the upslope, covers five percent of the watershed. Thirteen percent of the watershed is grassland on valley bottomland, with seasonally high groundwater and 12% consists of eucalyptus forest. The livelihood of the community largely depends on rain-fed agriculture. Commonly, the farmers use inorganic fertilizers like Urea composed of 45% - 46% nitrogen and diammonium-phosphate that contains 18% - 21% nitrogen and 46% - 53% P_2O_5. Households in the studied watershed obtain the drinking water from shallow groundwater.

2.2. Groundwater Sampling and Laboratory Analyses

Groundwater samples were collected from 19 wells located at three landscape positions (*i.e.* bottom, mid and up slope) (**Figure 2**, **Figure 3**). Well depths range from 5 - 13 m. The water levels of the wells were measured during rain phase (August) and dry phase (February) using deep stick and tape meter. Water levels at three landscape (top, mid and bottom slope) was averaged for different seasons (dry and rainy). The samples were taken after 5 - 8 minutes of pumping. Samples were collected using a 500 ml clear plastic jar with screw caps. Physical and chemical water quality characteristics were determined in samples taken monthly from July 2014 to June 2015. Bacteriological characteristics were analyzed in three-month intervals (*i.e.*, September, December, March, and June). The water table depth was measured in August 2014 and February 2015. The collected samples were put in an icebox and transported to the laboratory for analyses within 24 hours. Samples were analyzed for pH, EC, TDS, nitrate

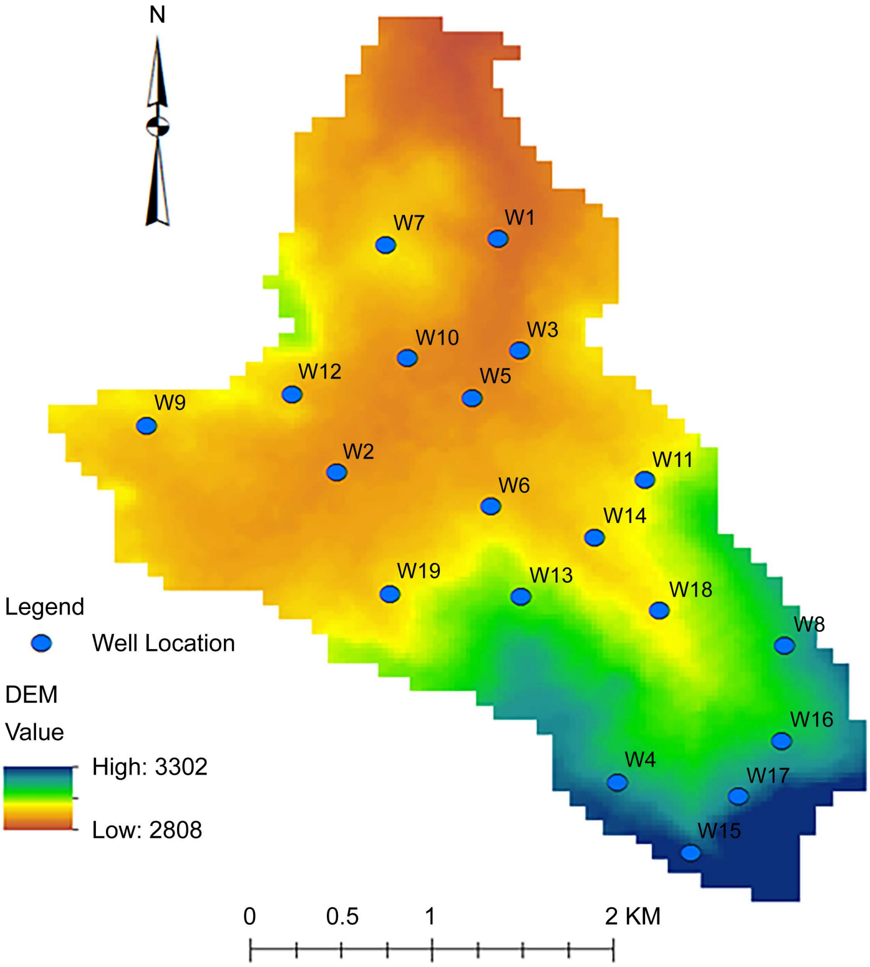

Figure 2. Location of wells for collecting water quality samples in the Tikur-Wuha watershed.

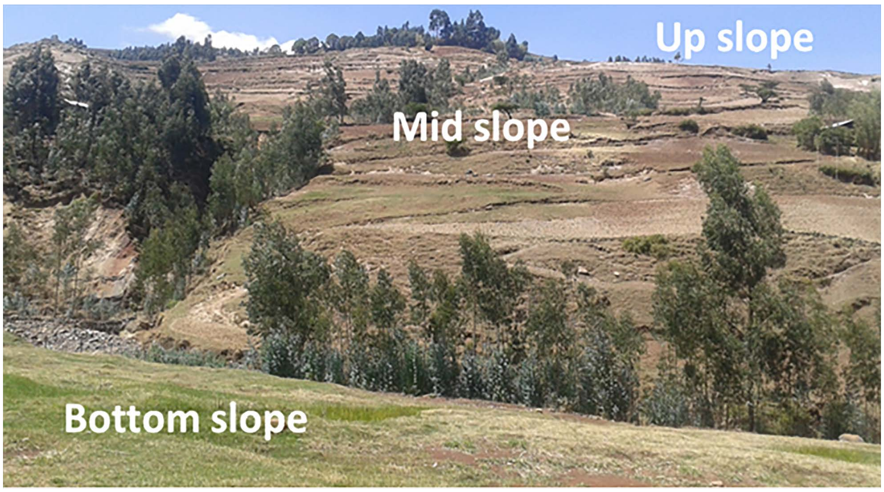

Figure 3. Photograph of Tikur-Wuha watershed depicting the three landscape positions: bottom slope or valley bottom; mid slope and up-slopes (Bottom slope of the watershed ranges from 2808 to 2996 m, mid slope from 2996 to 3101 and up slope from 3101 to 3302 m).

(NO_3^-), calcium (Ca), iron (Fe), magnesium (Mg), aluminum (Al), phosphorus (P), and Escherichia coli (E. coli). TDS and EC were determined *in situ* using dissolved solid tester, while a portable pH meter was used to determine pH. The dissolved ions species (NO_3^-, P, Ca, Mg, Al and Fe) were determined in the laboratory based on American Public Health Association's standard method [18] using a Plain test 7100 spectrophotometer with a detection limit of 0.001 mg/L [16].

The compartment bag test was used to determine the most probable number (MPN) of E. coli. The plastic bag contained internal compartments of different volumes, analogous to using a series of bottles or tubes of culture bacteria. The concentration of bacteria in the samples estimated from the combination of positive/negative compartments gave the most probable number of E. coli per 100 mL.

2.3. Statistical Analysis

Following [18], data were analyzed using the IBM SPSS Statistics 20 software. Two-way multivariate analyses of ANOVA were used to determine the effect of season (wet and dry), and slope position on shallow groundwater quality. The data were checked for normality using the Shapiro-Francia test and homogeneity of variances using Leven's test. All tested parameters were normally distributed.

3. Results and Discussion

3.1. Results

Groundwater was shallower in the valley bottom than uphill (**Figure 4**, **Table 1**). In August, during the rainy phase, the average groundwater depth was 2.4 m for the wells located in the valley bottom, while 7.7 m for mid and 9.7 m for upper slope positions. In February, in the dry phase, the average water table depth was 5.4 m for the valley bottom whereas 9 m and 10 m deep for the mid and upslope

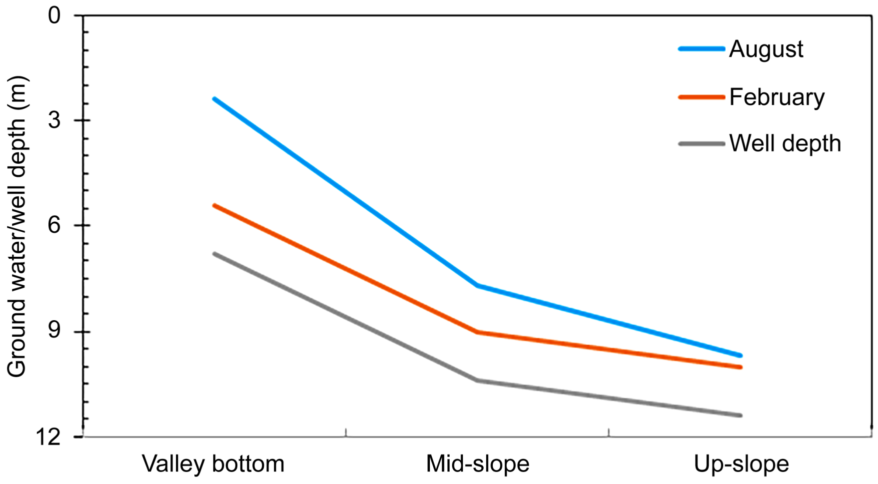

Figure 4. Average groundwater depth up slope, mid slope and in the valley boom in the Tikur-Wuha watershed at the end of the rain phase in August and near the end of the dry phase in February.

position respectively. The temporal variation in groundwater depth was less in the upper slope position than downslope positions (**Figure 4**). The water levels in the wells in the valley bottoms rise to close to the surface during rainy phase and then decreased during the dry phase. Upslope the water levels were always deep and varied little throughout the year. The spatial and temporal variations of the shallow groundwater level was similar with other sub humid watersheds in the Ethiopian highlands [19] [20]. **Table 3** showed that the average groundwater quality in the watershed. The water quality results were compared with WHO drinking water quality standards (**Table 2**, **Table 3**). The tested water quality parameters (Al, P, Fe, Ca, NO_3^-, TDS and EC) are within the acceptable range for the drinking water.

The Al, P, Fe, Ca, NO_3^-, TDS and EC concentrations of wells were independent of landscape positions and greater in the rain monsoon phase from June to September than during the dry phase in the remainder of the year (**Figure 5**, **Table 3**). Based on the two-way multivariate analysis, concentration was significantly different ($p < 0.05$) between the dry and the rainy monsoon phase (**Table 4**). Spatially P, Ca, Mg, EC, and TDS were significantly greater ($p < 0.05$) at bottom slope positions than at mid- and upper-slope positions (**Figure 5**, **Table 4**).

Table 1. Groundwater level and depth of monitored wells of Tikur-Wuha watershed (August 2014 and February 2015 of Tikur-Wuha watershed).

		Bottom Slope	Mid Slope	Up Slope
Groundwater level from the surface (m) (August)	Average	2.4	7.7	9.7
	Maximum	4.5	10	11.5
	Minimum	1.3	5.8	6.3
Groundwater level from the surface (m) (February)	Average	5.4	9	10.0
	Maximum	7.5	11.2	11.8
	Minimum	3.5	7	6.5
Well depth (m)	Average	6.8	10.4	11.4
	Maximum	9	13	13
	Minimum	5	8.5	8

Table 2. World health organization drinking water quality standards.

Parameters	Maximum WHO permissible limit
Al	0.2 mg/L
Ca	75 mg/L
Fe	0.3 mg/L
Mg	50 mg/L
NO_3	50 mg/L
pH	6.5 - 8
TDS	1000 mg/L
E. coli	0

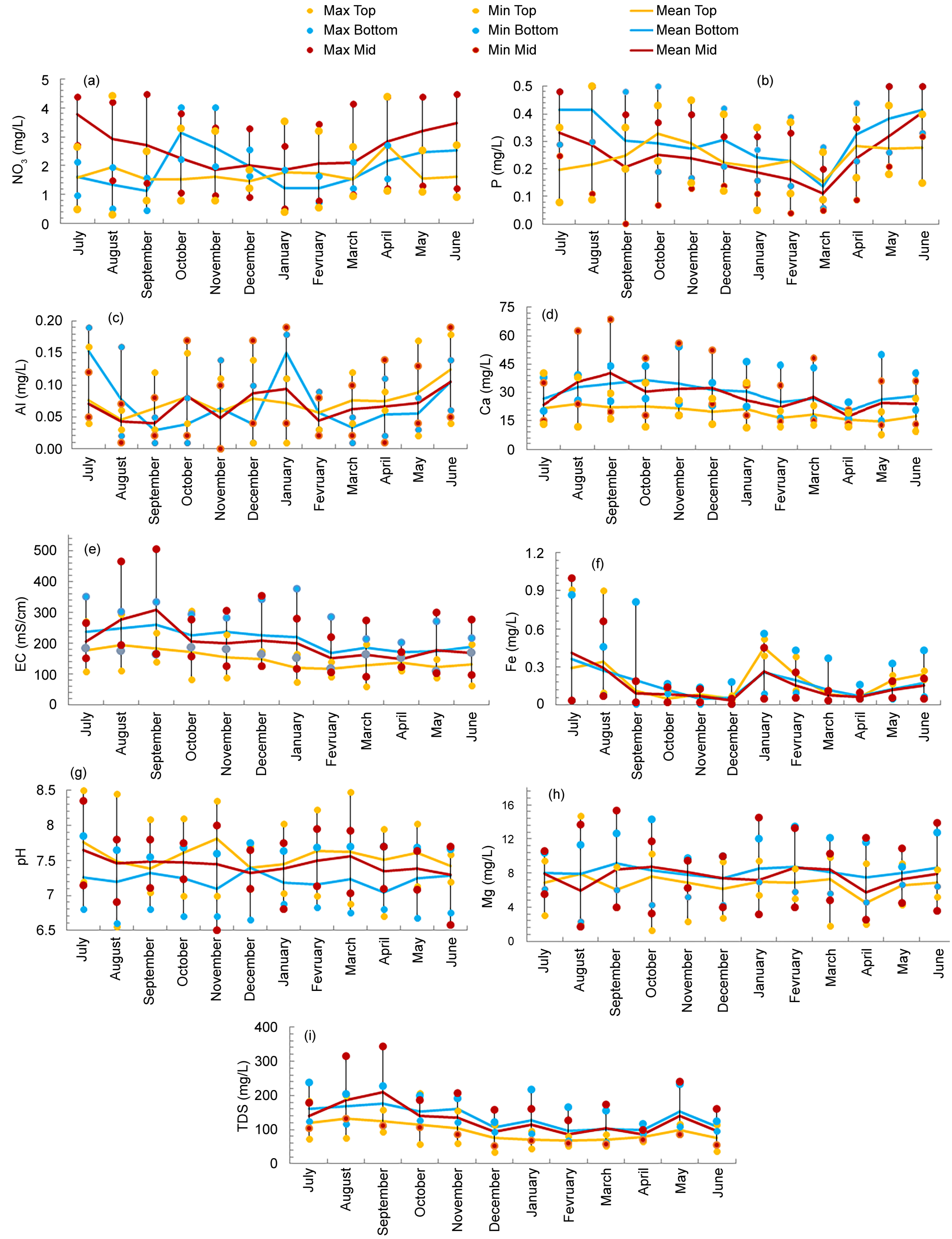

Figure 5. Shallow groundwater quality for the three slope positions of Tikur-Wuha watershed. (a) Nitrate-N, (b) Phosphorus, (c) Aluminum, (d) calcium, (e) Electrical conductivity (EC), (f) Iron, (g) pH, (h) Magnesium, (i) Total dissolved solids.

Table 3. Average, maximum, minimum and standard error (S. E) of shallow groundwater quality for distinct wet and dry season in the Tikur-Wuha watershed (July 2014-June 2015).

Season	Statistics	Al (mg/L)	Ca (mg/L)	EC (μS/cm)	Fe (mg/L)	Mg (mg/L)	NO_3 (mg/L)	P (mg/L)	pH	TDS (mg/L)
Wet	Average	0.09	28.29	219.24	0.25	7.66	2.43	0.31	7.42	144.97
	Maximum	0.19	68.50	505.90	1.00	15.30	4.47	0.50	8.50	344.00
	Minimum	0.01	9.80	62.20	0.01	1.70	0.32	0.00	6.55	36.10
	S. E	0.01	1.25	8.99	0.03	0.34	0.13	0.01	0.05	6.41
Dry	Average	0.06	25.27	175.68	0.13	7.52	2.01	0.24	7.40	109.39
	Maximum	0.17	56.00	376.30	0.57	14.50	4.40	0.50	8.48	240.40
	Minimum	0.00	8.00	59.50	0.01	1.30	0.41	0.04	6.50	34.50
	S.E	0.00	0.78	4.79	0.01	0.21	0.08	0.01	0.03	3.30

Table 4. Seasonal and spatial two-way multivariate analysis of shallow groundwater quality of Tikur-Wuha watershed (July, 2014-June, 2015).

	Source	Al	Ca	EC	Fe	Mg	NO_3	P	pH	TDS
Season	df	1	1	1	1	1	1	1	1	1
	F	31.9	4.5	22.4	23.9	0.2	7.2	16.5	0.1	29.8
	Sig.	0.00*	0.03*	0.00*	0.00*	0.63	0.01*	0.00*	0.79	0.00*
Slope	df	2	2	2	2	2	2	2	2	2
	F	2.0	18.9	18.6	0.4	4.3	22.4	10.9	12.1	15.2
	Sig.	0.14	0.00*	0.00*	0.64	0.01*	0.00*	0.00*	0.00*	0.00*

*Significant at $p < 0.05$.

In contrast, NO_3^- concentrations were significantly greater at mid-slope positions than bottom and upper-slope positions (Table 4, Figure 5(a)).

The microbiological water quality of the groundwater was in Table 5. The results of the samples were compared with WHO water quality standards for drinking water (Table 5). Ninety percent of wells were contaminated with E. coli in the rain monsoon phase (*i.e.*, September and June), which exceeds from WHO standard for drinking water. In the dry phase (*i.e.*, December and March), 45% of the sampled wells ($n = 19$) were contaminated. Similar to most of the dissolved ion concentrations, E. coli contamination was more severe in the downslope than the upslope positions (Table 5).

3.2. Discussion

In general, the dissolved ions and NO_3^- concentrations in groundwater (Figure 5, Table 3) were below WHO drinking water quality standards. This is in line with few other studies conducted in the Ethiopian highlands [12] [13] [21].

EC, (mainly mid-slope and valley bottom) and TDS of the sampled groundwater in the wet phase significantly exceeded that of the dry phase ($p < 0.001$, Table 4, Figure 5(e), Figure 5(i)). In the rainy phase, the fertilizers and other

Table 5. Spatial and temporal variation of microbiological water quality (E. coli) of shallow groundwater (September and December 2014 and March and June 2015).

Slope position	Month	September	December	March	June
Bottom slope	Number of samples	6	6	6	6
	Free E. coli	0	2	3	0
	Contaminated samples with E. coli	6	4	3	6
	% polluted	100%	67%	50%	100%
Mid slope	Number of samples	8	8	8	8
	Free E. coli	1	5	7	0
	Contaminated samples with E. coli	7	3	1	8
	% polluted	88%	38%	13%	100%
Upper slope	Number of samples	5	5	5	5
	Free E. coli	1	4	5	1
	Contaminated samples with E. coli	4	1	0	4
	% polluted	80%	20%	0%	80%

minerals from the surface dissolved and infiltrated into the groundwater. Some of the other elements related to fertilizer application follow this general trend as well, such as nitrate in the wells located in the upslope and mid-slope, but not in a wells located in valley bottom (orange and red lines and points in **Figure 5(a)**) and the phosphorus in the bottom and mid-slope wells (**Figure 5(b)**). Ca (especially the upland wells, **Figure 5(d)**) and magnesium (**Figure 5(h)**) remain relatively constant throughout the year while Al (**Figure 5(c)**) and Fe (**Figure 5(f)**) were elevated during some of the dry months, indicating that the sources of these four elements were in the subsurface and not a result of processes at the soil surface [22].

The TDS and EC concentrations at the upper slope position (Orange line in **Figure 5(e)**, **Figure 5(i)**), were generally less than mid-slope and downslope because a relatively large portion of area was covered with shrubs [23]. The concentration of TDS (blue line and point in **Figure 5(i)**) and EC (blue in **Figure 5(e)**) are slightly greater in the valley bottom (except during the end of rain monsoon phase in August and September) despite most agricultural activities taking place in mid-slope. The reason for the greater concentration during the dry phase, the groundwater level relatively shallow in the valley bottom and it can evaporate [24] that increased concentration. Groundwater depth on the other landscape position is too deep for evaporation. During the rain phase, concentration at mid slope are greater because salts in the cropland easily dissolved by the rainwater and infiltrating to the groundwater.

The trend of concentrations of the two dissolved nutrients (NO_3^- and P) varies with slope position. Nitrate is greater at mid-slope position and phosphorus is greater at the valley bottom. However, both have the lowest concentration at the up-slope position (**Figure 4**). The greater nitrate concentration at mid-slope position can be explained by the existence of agricultural lands in the mid slope where applied fertilizers leached down to the groundwater [16] [25] [26] [27]. The saturated condition in the bottom slope position favors denitrification and contributes to the lower NO_3^- content in shallow wells, located in the valley bottom [27] [28]. Similarly, [29] [30] [31] detected higher concentrations of nitrate in the parts of a watershed where croplands dominate, while lower concentrations of nitrate were detected at the bottom-slope positions of the watershed.

The greater P concentration at the bottom slope position is related to both sediments accumulation at the bottom slopes from the fertilized agricultural land [32] [33] and the water table being near the soil surface causing reduced soil conditions. Reduced conditions increases dissolved P [18] [32] [34] [35] [36]. In addition, grazing cattle defecating on the bottomlands may cause increases in P concentration. Some animals are also in the top part of the watershed and could explain the greater P concentrations. However, the manure is often collected as fuel and the ashes from the burned manure are applied to the cultivated land.

The primary source of the E. coli contamination is human and animal feces [37]. The contamination is most severe during the wet phase due to the leaching of the waste into shallow groundwater via preferential flow paths short-circuiting the surface with the groundwater. The greater contamination of E. coli in groundwater of the valley bottomlands (**Table 5**) is caused likely by the majority of the cattle grazing and defecating on those periodically saturated lands and thereby causing high levels of E. coli bacteria in the water recharging the groundwater [38].

The shallow groundwater is the response of the rainfall and any change in the rainfall will affect the ground water level and the water quality [39]. Similarly, [40] found that increase in rainfall increased human exposures to agricultural contaminants like waterborne pathogens. Nitrate concentrations in the valley bottom may increase when rainfall decreases because the groundwater might not rise to the surface reducing the effect of denitrifcation.

4. Conclusion

Groundwater quality in the Tikur-Wuha watershed at the headwaters of the Blue Nile in the Lake Tana basin was monitored. Shallow groundwater quality is influenced by landscape position, season and associated agricultural management practices. The concentration of dissolved ion species and E. coli level of groundwater is greater in the rainy season than in the dry season. The concentration of dissolved ion species and E. coli levels increased from the top of the watershed to the valley bottom of the watershed. However, nitrate concentration is an exception with greater values at the mid slope position than up slope and bottom slope of the watershed. The elevated concentrations of E. coli suggest that remedial action should be undertaken to improve groundwater quality that is a major source of drinking water in most developing regions of the world such as the Lake Tana watershed. From this study, we can conclude that installation of wells for water supply should consider the relationship of landscape position and water quality. In addition, water quality in wells should be monitored for the impact of agricultural inputs and any improvements due to best management practices.

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