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Spatial and Temporal Dynamics of Irrigation Water Quality in Zeway, Ketar, and Bulbula sub-Watersheds, Central Rift Valley of Ethiopia

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Abstract

Scarcity of information apprehending the current situation and spatial variation of water quality has limited our understanding on to what extent the current intensive human activities in the Central Rift Valley are affecting the natural resource base. This study investigated hydrochemistry, spatial and temporal quality variation of water from different sources, and their implications for agricultural uses. Water samples from rivers (Meki, Ketar, and Bulbula), Lake Zeway, and borehole or hand-dug (BH/HD) wells were analyzed for selected quality parameters following standard procedures. Historical data and current analysis results were used to analyze temporal changes using Mann-Kendall test statistics, while analysis of *variance was used to detect spatial variation. The hydrochemistry analysis result showed that* Na^+ *followed by* Ca^{2+}, *except for Ketar River where* Ca^{2+} *followed by* Na^+, *dominates among cations. Bicarbonate dominated among anions in all water samples. In Lake Zeway, no statistically significant spatial variations were evident for sampling locations, while electrical conductivity (EC) and iron showed a statistically significant increasing trend from 2005 to 2016. Iron in Lake Zeway; total dissolved solids, EC and* Na^+ *in BH/HD wells, and* K^+ *in all water sources were partly beyond the maximum permissible limit for drinking. Considering salinity effect on crop water availability, at least 60% of the water samples from rivers and Lake Zeway were in "none" restriction, while it was in "slight to moderate" restriction category in about 50% of water samples from BH/HD wells. Over 37% of the water samples from BH/HD wells in Zeway and Bulbula sub-watersheds showed high to very high alkali hazard. The RSC* > 2.5 *meq* L^{-1} *in most water samples of Lake Zeway, and BH/HD wells in Zeway and Bulbula sub-watersheds hastens sodium hazard rate. The study results suggest the need to adapt compatible management options on use and emplace strong water quality monitoring program to reduce risks.*

Introduction

Planning safe water use and management requires beforehand knowledge on spatial and temporal quality dynamics of the available water sources. The quality of water is a function of both natural processes and anthropogenic influences (Tenalem, 2005). The Central Rift Valley (CRV) of Ethiopia, a high potential area for irrigated agriculture development, is endowed with different sources and variable qualities of water for irrigation, and other agricultural and domestic use. Estimates made by Francisco (2008) indicate that around 42 and 31% of irrigated agriculture area ranging from smallholder farmers to large-scale export-oriented producers in the area rely on surface water diverted from nearby rivers and Lake Zeway, respectively. The remaining 25 and 2% of the irrigated land uses groundwater extracted through existing boreholes (BH) and hand-dug (HD) wells, and spring water, respectively.

Competing demands for the available water resources are projected to limit the potential expansion of irrigated agriculture in the CRV of Ethiopia (Francis and Lowe, 2015). The Irrigated Agriculture Development (IAD) district offices of Dugda, Zeway Dugda, and Adami Tulu Jiddo Kombolcha (ATJK) also witnessed that the problem has already compelled farmers and investors to start using water previously thought to be of marginal quality for irrigation. Currently, BH/HD wells are among the major sources of irrigation water for the newly expanding irrigated agricultural lands unreached either by water from Meki and Ketar rivers or Lake Zeway.

The existing agricultural practices with poor quality irrigation water under the changing climate will undoubtedly lead to large-scale negative consequences on the fragile Rift Valley environment unless their quality and required management options are known and managed as required. Farmers in some locations in the CRV of Ethiopia witness the prevalence of negative impacts on soils and crop performance when water from BH/HD wells is continuously used for irrigation over three to four production seasons. With the expansion of irrigated agriculture, the amount and types of agrochemicals particularly chemical fertilizers and pesticides use in the CRV of the country have continuously increased. For instance, fertilizer use for vegetable production has exceeded 800 kg ha^{-1} of fertilizer product (urea and DAP) (Putter *et al.*, 2012; Edossa *et al.*, 2013), while it far exceeds in floricultures (Sahle and Potting, 2013). This intensive and excessive use of agrochemicals in the proximity of Lake Zeway was repeatedly reported as potential source of pollution (Hengsdijk and Jansen, 2006; Jansen and Harmsen, 2011; Berhan *et al.*, 2015) through release of residues into the lake. Previous water quality studies in the area have depicted pollution of Lake Zeway and some inflow rivers with residues of pesticides (Yared *et al.*, 2014; Teklu *et al.*, 2016). Climate change in the study sub-watersheds, manifested by a linear increase of temperature with no significant change in precipitation (Belay, 2014; Mezegebu *et al.*, 2014), could potentially contribute to evaporative ion concentration of Lake Zeway (Croley and Lewis, 2006).

The CRV of Ethiopia lacks water quality from regular monitoring data to study the temporal change (change trend) of water quality. However, piecemeal studies on water quality of different water sources (Lake Zeway, rivers, and BH/HD wells) in the CRV of Ethiopia were made since the 1940s (Wood and Talling, 1988). The studies revealed some concerns on the quality of water for irrigation and domestic use (Wood and Talling, 1988; Kebede *et al.*, 1994; Zinabu *et al.*, 2002; Teklu *et al.*, 2016; MoWR, 2008a). Some of these studies were limited to the lakes, while some have covered larger area. The number of samples collected from water sources in those previous specific studies was not sufficient to show adequately the spatial variation. In the absence of long-term water quality data from continuous and regular monitoring, combined use of existing historical data from the past studies with current assessment study can provide insights about the temporal changes particularly for lake water and spatial variation for other water bodies. The main objective of this study was therefore to assess hydrochemistry of different water sources in the study sub-watersheds, spatial and temporal variation of water quality, and suitability for irrigation use.

Material and Methods

The study area

Location and topography

The Rift Valley in Ethiopia, part of the East African Rift Valley, consists of three main sections: the northern, the southern, and the central or main portion (Billi, 2015). The current study area is within the Central Rift system that encompasses three interconnected sub-watersheds: Zeway, Ketar, and Bulbula (Figure 1). The study area is located between 7°22′N-8°13′N and 38°27′E-39°24′E at about 120 km south of Addis Ababa, the capital city of Ethiopia. The altitude of the study sub-watersheds varies from 1600 meters in the Rift Valley floor to above 3700 m on the eastern escarpment of the Rift Valley.

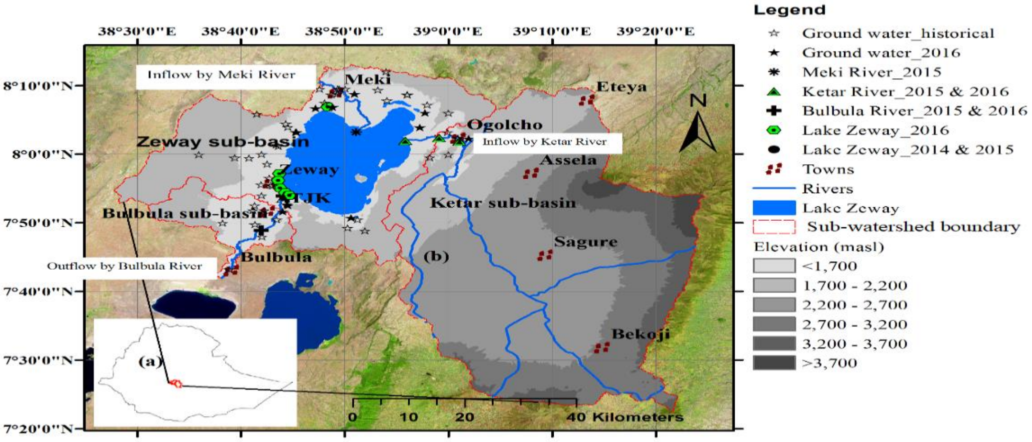

Figure 1. Location map: the study area in Ethiopia (a) study sub-watersheds, elevation and water sampling locations (b).
Ground water = BH/HD wells, ATJK=Adami Tulu Jido Kombolcha, m.a.s.l= meters above sea level

Climate

The annual average minimum and maximum temperatures of the central lowlands (1600-1750 m.a.s.l) are 13.4-14.2 °C and 27.5-28.7 °C, respectively, while it is 8.9 °C and 21.4 °C at Assela, which is located in the eastern escarpment of the CRV. Mean annual precipitation varies from less than 700 mm in the central lowlands to about 1100 mm in the highlands such as at Assela (Figure 2). The main rainy season, which spans from June to September, receives about 70% of the precipitation. The short rainy season stretches from March to May (Belay, 2014).

Geology, Hydrogeology and Hydrology

The geology of the area is the result of Cenozoic volcano-tectonic and sedimentary processes (Azeb *et al*., 2015). The hydrogeology of the rifted volcanic terrain in Ethiopia is complexed due to disruption of the lithologies by cross cutting faults and the variability of volcanic structures (JICA, 2012). The western escarpment is characterized mainly by the Tertiary volcanic composed of basalts, rhyolites, ignimbrites and tuffs while pyroclastic deposits such as tuff and ignimbrite dominate the eastern boundary. The entire area of Lake Zeway plain is covered by lacustrine sediments mixed with pyroclastic fall deposits (MoWR, 2008b). These variations are attributed to the heterogeneity of aquifer composition, presence of variable groundwater chemistry, and groundwater depths (JICA, 2012).

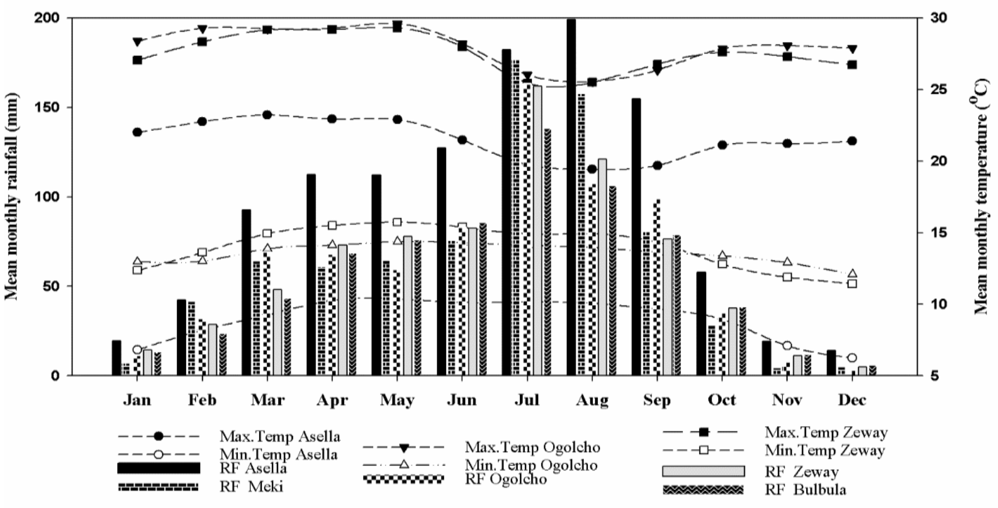

Figure 2. Mean monthly rainfall, and mean monthly maximum and minimum temperature at Asella, Ogolcho, Zeway, Meki and Bulbula stations of the study area.

Max=maximum, Min=minimum, Temp=temperature and RF=rainfall; Data source: National Meteorology Agency (1984-2014), Ethiopia.

The CRV comprises a chain of three major lakes namely Lake Zeway, Lake Abijata and Lake Langano. Lake Zeway (included in the study sub-watersheds) is fed by Meki River that drains from the northwestern plateau (the Gurage Mountains and the swamps), and Ketar River that drains from the Eastern and South-eastern Plateaus (Mount Kakka). Lake Zeway is further connected and drained to Lake Abijata through Bulbula River. The study area is endowed with diverse soil types; namely Vitric Andosols, Vertisols, Calcaric Fluvisols and Eutric Nitisols (Makin *et al.*, 1975; FAO/UNESCO, 1977).

Land-use and farming system

The land-use of the study sub-watersheds is dominated by mixed farming under open canopy of remnant acacias principally *Acacia tortilis* (Forssk.). The major crops produced under rain-fed agriculture include maize, common bean, wheat, *tef* and barley. In the past two decades, smallholder and export oriented large scale vegetable, fruit and flower production under irrigation have boomed in the study sub-watersheds (Teklu *et al.*, 2016). The natural vegetation is largely dominated by deciduous Acacia woodland and wooded grasslands on the Rift floor, while the Rift shoulders are characterized by bushed grassland.

Data Sources

Current analysis and empirical literatures (Table 1) were used as data sources. Water quality data selected from empirical literatures were limited to dry season sampling particularly from January, February, March, and April to minimize seasonal variations from the current study-sampling month, April 2016.

Table1. Empirical literatures used as water quality data sources for different water sources

Water sources	Literature sources of water quality data	Remarks[1]	Purpose
Lake Zeway	Current study (April, 2016)	Sampling sites and time are inline to HoAREC and N monitoring data	For temporal trend and spatial variability analysis
	HoAREC and N monitoring data (February, 2011, 2013, 2014 and 2015)	The 2011 and 2013 lacks some trace elements and nutrient data	
	Literatures (MoWR, 2008a, 2008b; Tewodros *et al*., 2010a; Alemayehu *et al*., 2011) for 2005 to 2013 sampling events	The 2009 and 2012 data are not available. Sampling months aligning with the monitoring data of HoAREC and N and current study were selected	
BH/HD wells[2]	Literatures (Haile, 1999; MoWR, 2008a, 2008b; Tewodros *et al*., 2010a) and current study	Sampling date was not available for Haile, 1999.	For spatial variability and status
Ketar River	Literatures (MoWR, 2008a; Tewodros *et al*., 2010a) and current work		For variability and status analysis
Meki River	Literatures (von Damm and Edmond, 1984; Haile, 1999; MoWR, 2008a; Tewodros *et al*., 2010a) and HoAREC and N.	Meki river during 2016 was not conveying any water due to climate anomalies of the 2015 rainy season (El Ninos)	
Bulbula River	Literatures (Haile, 1999), HoAREC and N from 2015 and current work		

[1] *HoAREC and N= Horn of Africa Regional Environment Centre and Networking*

[2] *The BH/HD wells' depth (farmers indicated 7-12 meter) and water quality parameters measured were within the same range; hence data were presented in combination.*

Water sample collection

Twenty-two water samples were collected in April 2016 from Lake Zeway, BH/HD wells, and rivers (Ketar and Bulbula) in the three sub-watersheds. The offshore open part of Lake Zeway along its western shore was considered for sample collection, as this part is more accessible for irrigation and other human impacts. The sample collection points for the lake and rivers were arranged to capture some critical areas suspected to cause local pollution to the water body. Water sample collections were from active pumping sites at about 30 to 40 cm depth from the water surface level. Pre-washed one liter polyethylene bottles rinsed with double distilled water were used for sample collection (APHA, 1999). The containers were rinsed with water three times at sampling and were tightened with plastic caps after complete filling.

Laboratory analysis

Laboratory analysis of all the selected parameters was done following established analytical methods of APHA (1999). Electrical conductivity (EC) and pH were measured by direct reading in the water samples using an EC meter and an electrode pH meter, respectively. Total dissolved solids (TDS) was determined by weighing the solid residue obtained by evaporating the filtrate (filtered through 2.0 µm filter paper) followed by drying to a constant weight at 105 °C. Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) analysis (Garbarino and Struzeski, 1998) was used to measure Ca, Mg, Na, K, S, P, Cu, Fe, Mn, Zn, and B concentrations in unfiltered water samples. Chloride was determined with the argentometric method by titration of samples against

$AgNO_3$ solution, while carbonate and bicarbonates were determined by titration with H_2SO_4 solution. Ammonium and nitrate (NH_4^+ and NO_3^-) were measured by spectrophotometer. The hardness of the water was computed using Equation 1 from the results of separate determinations of calcium and magnesium (APHA, 1999):

$$Hardness_{calc}, mg\ equivalent\ CaCO_3\ L^{-1} = 2.497\left[Ca, mg\ L^{-1}\right] + 4.118\left[Mg, mg\ L^{-1}\right] \quad (1)$$

Sodium adsorption ratio of irrigation water samples (SAR_{iw}) was calculated as indicated in Equation 2 after Ayers and Westcot (1985):-

$$SAR_{iw} = \frac{Na^+}{\sqrt{\left(Ca^{2+} + Mg^{2+}\right)/2}} \quad \cdots\cdots\cdots\cdots \quad (2)$$

The calculation for adj R_{Na} as an improvement to the older SAR (Suarez, 1981) was made using Equation 3 (Ayers and Westcot, 1985).

$$adjR_{Na} = \frac{Na^+}{\sqrt{\left(Ca_x^{\ 2+} + Mg^{2+}\right)/2}} \cdots\cdots\cdots (3)$$

where Na and Mg are respectively sodium and magnesium concentration in the irrigation water, Ca_x is a modified calcium value as indicated in "Table 11"of Ayers and Westcot (1985) accounting for ionic strength and HCO_3/Ca ratio. The concentrations are all in meq L^{-1}.

The adj R_{Na} procedure adjusts the calcium concentration of irrigation water to the expected equilibrium value following an irrigation, and includes the effects of carbon dioxide (CO_2), bicarbonate (HCO_3) and salinity of irrigation water (EC_{iw}) upon the calcium originally present in the applied water but later becomes a part of the soil-water.

High concentration of HCO_3 in water encourages Ca and Mg to precipitate as CO_3. As a result, the relative proportion of Na in the form of sodium bicarbonate in water and soil will increase. Hence, Residual Sodium Carbonate (RSC) was computed to determine the CO_3 and HCO_3 indirect hazard effect on soil quality from its long-term use for irrigation using Equation 4 (Eaton, 1950), where the concentrations are all in meq L^{-1}.

$$RSC = \left(CO_3^{\ 2-} + HCO_3^{\ -}\right) - \left(Ca^{2+} + Mg^{2+}\right) \cdots\cdots \quad (4)$$

Data analysis and interpretation

Descriptive summary statistics and graphical representation were used to visualize physicochemical characteristics and spatial variation of water quality data. One-way analysis of variance was applied to analyze variation of different water quality parameters along sampling locations of Lake Zeway. Mann-Kendall test (Mann, 1945; Kendall,

1970) and Sen's slope estimator (Sen, 1968) test at $P<0.05$ level were performed using XLSTAT statistical package for trend analysis. Missing data, irregularly spaced measurement periods, which are common limitations to environmental data such as water quality measurements, are permitted in these tests. They are robust to outliers, non-detects, and data need not conform to any particular distribution (Gilbert, 1987; Gibbons *et al.*, 2009). The Mann-Kendall test statistics (S) was computed using the relationship:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(Y_j - Y_i) \tag{5}$$

where, Y_j and Y_i, are the annual values in years j and i, respectively; n is the number of measurements available for the period, and sgn (Y_j-Y_i) is the sign function given as:

$$\operatorname{Sgn}(Y_j - Y_i) = \begin{cases} +1 \text{ if } (Y_j - Y_i) > 0 \\ 0 \text{ if } (Y_j - Y_i) = 0 \\ -1 \text{ if } (Y_j - Y_i) < 0 \end{cases} \tag{6}$$

where sign(y_j - y_i), is equal to +1, 0, or -1 as indicated above.

A positive value of S indicates an upward while a negative value indicates a downward trend. Sen's Slope estimator, a non-parametric test by which true slope (change per year) is estimated (Sen, 1968; Gilbert, 1987; Gibbons *et al.*, 2009), was used assuming the trend to be linear, i.e,

$$f(t) = Qt + B \tag{7}$$

where, *f(t)* = increasing or decreasing function of time, i.e, the trend; Q= the slope and

B= intercept (constant)

This approach involves computing slopes for all the pairs of time points Qi and then using the median of these slopes as an estimate of the overall slope Q. The slope of each data pair Q_s was calculated as:

$$Q_s = \frac{Y_j - Y_i}{j - i} \tag{8}$$

where j > i and, if there is n number of x_j in the time series, we get as many as $N = \frac{n(n-1)}{2}$ slope estimates Q_s.

Then, values of Q_s are ranked from small to large; the median of which is the Sen's Slope (Q)

$$Q = \begin{cases} Q_{\left[\frac{(N+1)}{2}\right]} \text{ if N is odd} \\ \frac{1}{2}\left(Q_{\left[\frac{N}{2}\right]} + Q_{\left[\frac{(N+2)}{2}\right]}\right) \text{if N is even} \end{cases} \tag{9}$$

Water quality or suitability for specific use was evaluated on potential severity of problems that could develop during long term use. Water quality in the present study, which is commonly used for domestic uses too, was evaluated based on established Maximum Permissible Limits (MPL) of WHO (2011) and the Ethiopian drinking water quality standards (ESA, 2013). Major quality indices of irrigation water including EC and TDS for crop water availability, SAR/adjR_{Na}, and RSC for water infiltration rate to soil, and toxicity of specific ions (B, Cl) to sensitive crops were evaluated against the FAO (Ayers and Westcot, 1985) guideline.

Results and Discussion

Physicochemical characteristics

Minimum, maximum, and mean values for water quality parameters are summarized in Table 2. The pH value of Ketar River was near neutral, while it was in alkaline range for Lake Zeway, Bulbula River and BH/HD wells. The result concurs with previous result (MoWR, 2008a; Azeb *et al.*, 2015). Relatively higher mean values of TDS, EC, HCO_3^-, Cl^- and major cations were found in water samples from BH/HD wells as compared to other water sources. Concentrations of NO_3^-, NH_4^+ and phosphorus were generally low for all water samples except in some samples from Lake Zeway, and BH/HD wells. Previous water quality assessment studies on Lake Zeway, Ketar, Meki and Bulbula rivers showed further low concentration of NO_3^- (Elizabeth *et al.*, 1994; MoWR, 2008a; Tewodros *et al.*, 2010a) and NH_4^+ in Lake Zeway (Elizabeth *et al.*, 1994; Zinabu, 2002). Other BH/HD wells' water quality studies (Reimann *et al., 2003;* MoWR, 2008b*)* however showed lower concentrations of NO_3^- in general, although the concentrations were yet greater in BH/HD wells than in the rivers and Lake Zeway.

The result, where concentrations of Ca^{2+}, Mg^{2+}, Cl^-, Zn and Cu were found within the MPL, while Fe and K^+ exceeded the MPL, was consistent with other water quality study results in the study area (Tewodros *et al.*, 2010a; Alemayehu *et al.*, 2011; Teklu *et al.*, 2016). Manganese, Cu, and Zn in Lake Zeway were reported to be predominantly present as high molecular mass indicating that they are less available to organisms (Alemayehu *et al.*, 2011) that may reduce risks related to their uptake. Furthermore, the MPL values assigned to TDS, Na^+, K^+, Ca^{2+}, NH_4^+, Fe and Mn are known mainly to affect the palatability of water for consumption (WHO, 2011; ESA, 2013).

Sodium was found to be the predominant cation followed by Ca^{2+} in the total cations in all water samples except for Ketar River. Bicarbonate was the dominant anion followed by Cl^- except for BH/HD wells' water in Ketar sub-watershed where SO_4^{2-} follows the HCO_3^- (Figure 3). This study result is in agreement with previous finding on the hydrochemical characteristics of water in the study sub-watersheds which was reported as Na^+-Ca^{2+}-HCO_3^- type for Meki and Bulbula rivers, Lake Zeway, and BH/HD wells and Ca^{2+}-Na^+-HCO_3^- type for Ketar River water(Haile, 1999; Tewodros *et al.*, 2010b).

The higher Na:Ca ratio in water samples from BH/HD wells (9.99), Lake Zeway (4.49) and Bulbula River (5.97) might be attributed to alkali element leaching from volcanic parent rocks (Azeb *et al.*, 2015) and hydrolysis of silicate minerals (Alemayehu *et al.*, 2011). Silicate mineral hydrolysis and volcanic activity aided by high rate of CO_2 flux encourages Ca carbonate precipitation (Berhanu, 1996; Haile, 1999; Tenalem, 2005) that contributes to higher ratio of Na^+ to Ca^{2+}. The process could increase the HCO_3^-, Na^+ and K^+ concentrations in water with increasing residence time and water-rock interaction. The strong positive correlation ($r=0.81$ and $P<0.01$) between Na^+ and HCO_3^- in all the water samples also supports the above finding.

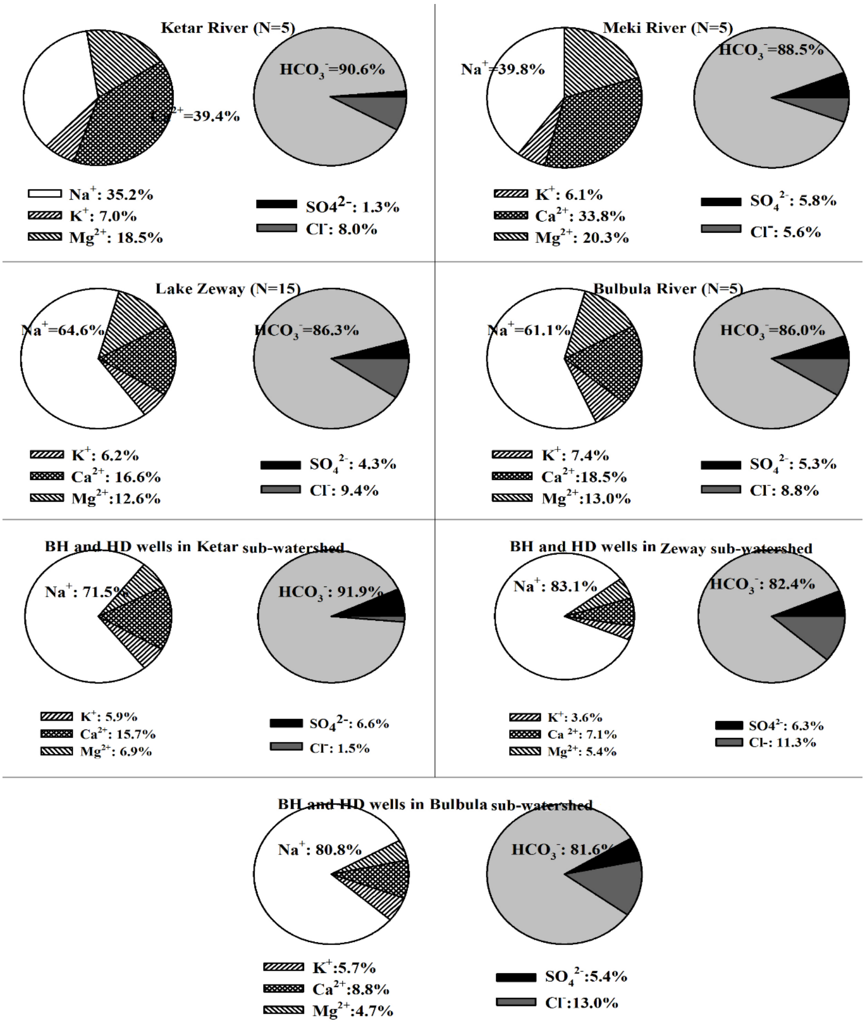

Figure 3. Mean values including historical data of major ions of water samples in different sub-watersheds

Table 2. Selected physical and chemical characteristics of water samples from the study sub-watersheds in the CRV of Ethiopia; units are in mg L^{-1} unless stated

Parameters*	Ketar River (N=2)		Lake Zeway (N=15) except for others ⁑				Bulbula River (N=2)		BH/HD wells' water (N=12)				‡ESA/WHO MPL
	Upper stream of †	Lower stream of †	Min.	Mean	Max.	> MPL (%)	Upper stream	Lower stream	Min.	Mean	Max.	> MPL (%)	
pH	7.0	7.1	8.1	8.4	8.8	26.67	8.1	8.0	7.2	7.8	8.6	8.33	6.5-8.5
TDS	161.3	143.4	358.0	408.7	512.0	<MPL	488.0	404.0	266.0	1018.4	1848.0	50.00	1000.0
Na^+	20.7	19.3	3.2	84.4	127.6	<MPL	130.4	107.3	74.0	344.6	586.7	75.00	200.0
K^+	8.2	8.5	0.3	13.6	18.3	100.00	1.4	19.6	10.3	27.7	58.6	100.00	1.5
Ca^{2+}	21.7	17.5	0.4	18.8	23.8	<MPL	17.6	22.2	4.6	34.5	95.8	16.67	75.0
Mg^{2+}	5.1	4.9	0.4	8.6	10.7	<MPL	9.4	10.2	1.3	17.8	45.2	<MPL	50.0
TH (mg equivalent $CaCO_3$ L^{-1})	75.2	62.8	79.8	88.2	95.9	<MPL	82.6	97.6	16.4	156.4	385.6	16.67	300.0
TA (as $CaCO_3$)	118.0	104.0	288.0	339.3	548.0	100.0	248.0	360.0	232.0	876.2	1732.0	100.00	200.0/-
Sulfur as SO_4	1.4	2.5	6.0	11.7	17.7	<MPL	27.3	17.3	2.91	33.2	149.65	<MPL	250.0
HCO_3^-	144.0	126.9	235.5	294.9	380.6	-	325.2	439.2	283.0	1003.2	2113.0	-	NE
CO_3^{-2}	NIL	NIL	24.0	28.7	38.1	-	38	NIL	0.0	15.4	52.8	-	NE
Cl^-	4.0	3.5	0.4	17.4	23.5	<MPL	16.7	15.8	0.10	59.4	130.3	<MPL	250.0
EC (dS m^{-1}) at 25^{o}c	0.25	0.22	0.41	0.51	0.63	<MPL	0.64	0.68	0.26	1.52	3.08	58.3	1.0
SAR	1.0	1.1	2.6	4.2	6.2	-	6.2	4.7	4.1	14.8	31.6	-	NE
Adj R_{Na}	1.0	1.0	2.9	4.6	6.7	-	6.6	5.5	4.8	17.2	40.0	-	NE
RSC (meq L^{-1})	0.85	0.82	2.2	3.3	4.8	-	4.0	5.2	4.3	13.8	26.9	-	NE
NH_4^+	0.12	0.15	0.05	0.39	1.75	6.67	0.26	0.75	0.12	1.27	6.17	33.33	1.5/-
NO_3^-	8.61	7.96	0.06	13.71	20.81	<MPL	18.2	3.58	2.62	21.09	92.6	16.67	50
Total P	0.18	0.12	0.16	0.18	0.19	-	0.15	0.21	0.12	1.06	7.07	-	NE
Fe	1.19	2.63	0.60	3.3	4.8	100	2.07	0.69	0.001	1.71	9.8	25.00	0.3
Zn	<0.003	<0.003	0.00	0.01	0.01	<MPL	0.001	0.003	0.001	0.04	0.22	<MPL	5/3
Mn	<0.006	<0.006	0.01	0.03	0.09	<MPL	0.02	0.032	0.001	0.50	2.9	33.33	0.5/0.4
Cu	<0.001	<0.001	0.01	0.01	0.01	<MPL	0.01	0.013	0.002	0.01	0.04	<MPL	2/2
B	0.05	0.09	0.01	0.03	0.07	<MPL	<0.001	<0.001	0.001	0.12	0.54	16.67	0.3

*TH= total hardness; EC= electrical Conductivity; TA= total alkalinity; †Ogolcho town

⁑ N=15 for Lake Zeway includes data of 2014 and 2015 from HoARECandN database except for TDS. MPL= maximum permissible level for drinking; ‡NE =guideline values not established for some constituents that have no direct link to adverse health impacts.

Spatial variability

The spatial variation of water quality parameters of Lake Zeway was not statistically significant ($p<0.05$) (Figure 4). Nevertheless, there was clear indication of increase in concentrations for majority of the water quality parameters except for pH that showed slightly lower value for samples collected from the lake at "Loc-5" that is located near Sher Ethiopia PLC floriculture. This abrupt increase of the concentrations in water samples collected after Sher Ethiopia PLC floriculture farm might be attributable to the floriculture effluents entering the lake. The work done by Malefia (2009) also showed that the quality of water samples collected from areas where untreated effluent is discharged to the same lake was found deteriorating.

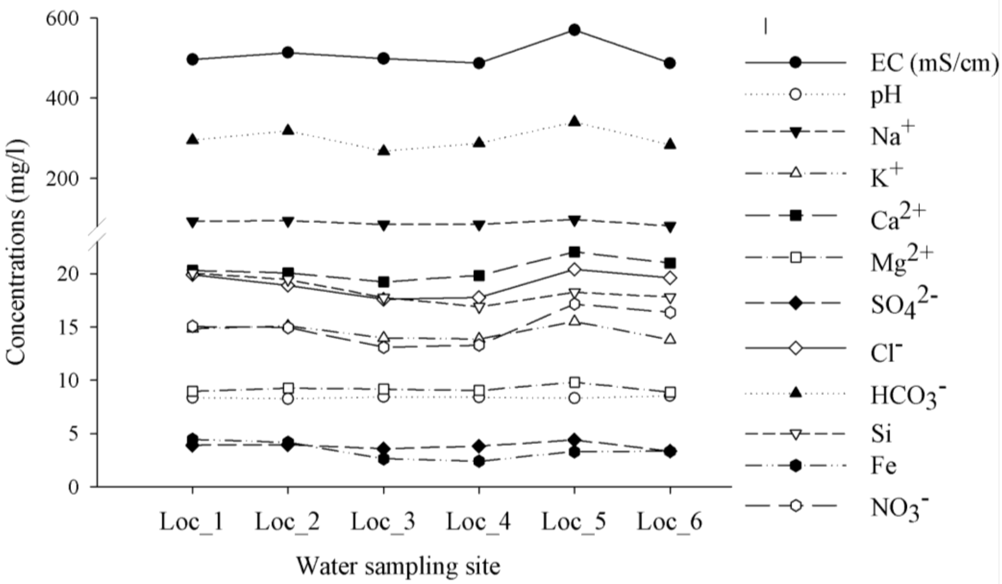

Figure 4. Spatial variation of selected water quality parameters along different sampling stations on western shore of Lake Zeway

Loc_1 = North West part of the lake near Korea irrigation project; Loc_2 = western part of the lake towards Abosa town, Loc_3 = near Kidane Miheret church; and Loc_4 = near Fishery Research Centre before Sher Ethiopia PLC; Loc_5 = after Sher Ethiopia PLC, and Loc_6 = south part of the lake at Bochesa.

The water quality variation of BH/HD wells' water is demonstrated in Figure 5 using analysis result from current study and historical studies presented by different scholars in different years. The available BH/HD wells' water quality data from literatures are limited to the lower part of the sub-watersheds probably due to availability of water at shallow depth (JICA, 2012) and irrigated agriculture in the area. The mean and median values of the selected water quality parameters were considerably high for the sub-watersheds located in the Rift Valley floor (Zeway and Bulbula sub-watersheds) except for Ca^{2+}, Mg^{2+}, and SO_4^{2-}. The higher alkalinity observed for BH/HD wells in Zeway and Bulbula sub-watersheds might be attributable to the higher bicarbonate concentration (Berhanu, 1996), which originates mainly from the water interaction with the alkaline volcanic rocks and their weathered products in the area (Alemayehu *et al.*, 2011; Azeb *et al.*, 2015).

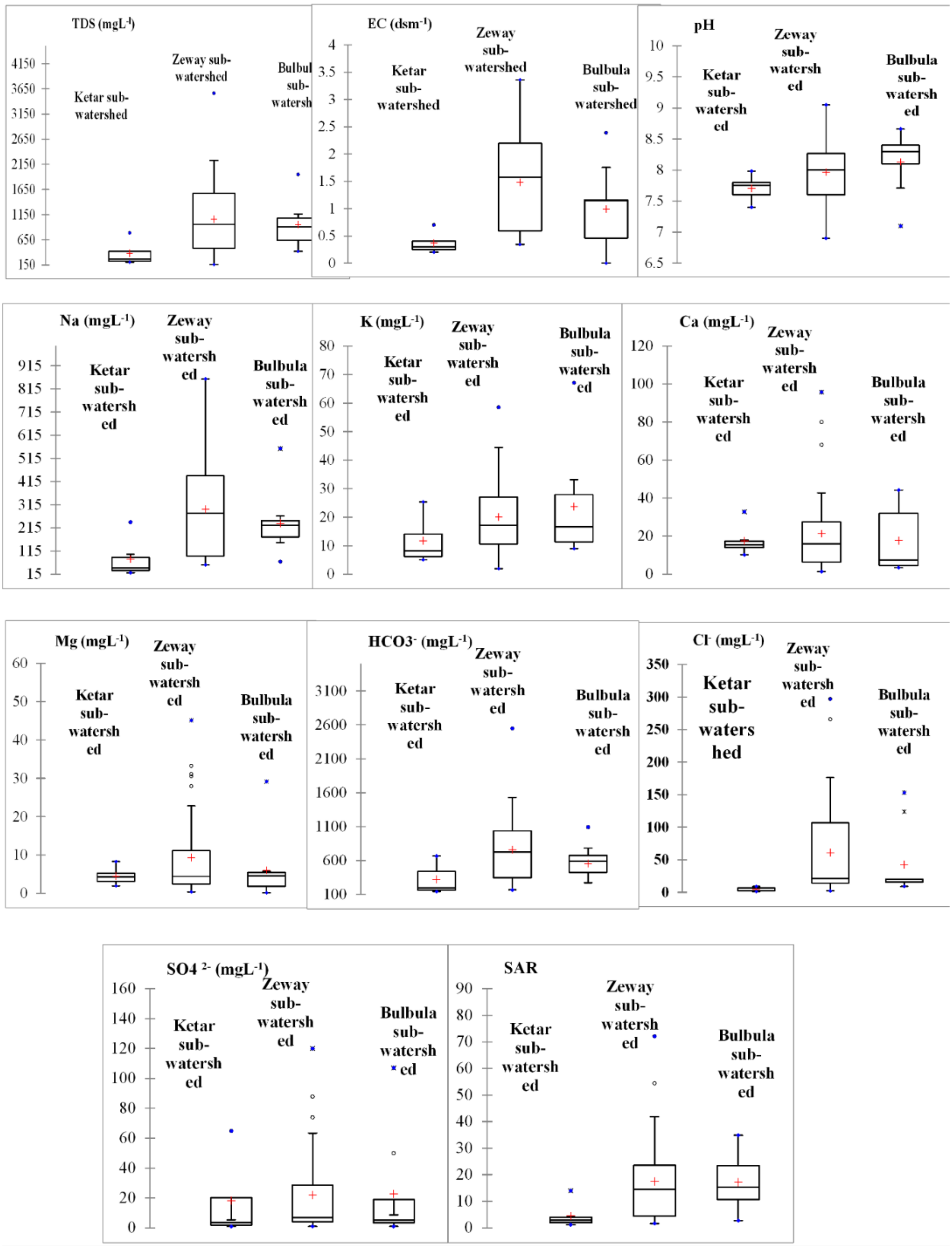

Figure 5. Spatial variation of selected water quality parameters visualized by box-and-whisker diagrm for BH/HD wells' water located in the three sub-watershedes

Lower and upper limits of the box are first and third quartile whereas the middle line and the cross mark in the box are median and mean respectively. Points are minimum and maximum values while open holepints above and below whisker's upper and lower boundary are outliers.

Temporal variation

The Mann-Kendall statistics (S) of Lake Zeway water quality showed upward trend (positive values) for majority of the parameters considered (Table 3). Nevertheless, the increasing trend was statistically significant ($P<0.05$) only for EC and Fe concentrations. The increase in EC may indicate increased solute inputs to the lake and less dilution from the likely decreasing inflow rivers due to increased abstraction for irrigated agriculture. The above processes with elevated temperature and hence evaporation (Belay, 2014; Mezegebu *et al.*, 2014) can potentially lead to further salinization of the lake in the future. The significantly increasing trend of EC with abrupt increases for water samples collected after Sher Ethiopia PLC Floriculture farm indicate the potential contribution of agricultural wastes to salinity of the lake (Malefia, 2009).

Table 3. Trends of water quality for Lake Zeway from 2005 to 2016

Variable	Minimum	Maximum	Mean± SD	S†	Q‡	P-value
TDS mg L^{-1}	324.00	408.67	366.46 ± 27.75	11.00	4.62	0.37
pH	8.04	8.90	8.53 ± 0.26	-3.00	-0.01	0.86
EC μs cm^{-1}	420.00	604.38	477.73 ± 55.14	25.00	11.66	0.03
Na^+ mg L^{-1}	59.93	124.91	75.34 ± 19.43	9.00	1.20	0.47
K^+ mg L^{-1}	11.00	17.76	13.31 ± 2.30	21.00	0.26	0.07
Ca^{2+} mg L^{-1}	14.40	27.30	20.07 ± 4.09	-17.00	-0.72	0.15
Mg^{2+} mg L^{-1}	7.54	10.80	8.84 ± 1.03	7.00	0.08	0.59
Fe mg L^{-1}	0.08	4.09	1.81 ± 1.59	25.00	0.43	0.03
Alkalinity (calc□) mg L^{-1}	166.36	275.31	215.66 ± 28.75	9.00	2.64	0.47
Hardness mg L^{-1} $CaCO_3$	46.14	102.16	82.77 ± 16.26	-15.00	-2.07	0.21
SAR	2.65	5.92	3.64 ± 0.97	17.00	0.17	0.15
NO_3^- mg L^{-1}	0.80	30.88	12.57 ± 11.78	11.00	2.04	0.37
SO_4^{2-} mg L^{-1}	2.92	15.03	6.53 ± 3.40	-21.00	-0.41	0.07
HCO_3^- mg L^{-1}	203.00	335.95	263.16 ± 35.08	9.00	3.22	0.47
Cl^- mg L^{-1}	10.00	22.77	15.72 ± 3.95	19.00	0.76	0.11

S† is Mann-Kendall statistics, Q‡ is Sen's slope of the trend, □ calc= calculated

Higher concentration of Fe in Lake Zeway, which was also reported in previous studies (Zinabu and Pearce, 2003; Kebede *et al.*, 2015), was confirmed in the current study as well. According to production manager of Castel Winery PLC farm (personal communication) that is established near Lake Zeway, the higher concentration of Fe is interfering with their drip system functioning. The farm started using Aquaphor filtering technology and backwash to reduce its interference. Identifying the sources of Fe to the water body requires detailed investigation. However, the natural weathering of Fe-compounds (oxyhydroxides) and ferrihydrite (the major secondary iron mineral in Andosol) (FAO, 2006) and its long-term interaction with water (Azeb *et al.*, 2015) might be considered among the potential sources. Furthermore, the domestic and irrigated agricultural wastes that are directly or indirectly connected to the lake might also have contributions. Vegetable producing commercial farmers and floriculture in the sub-watersheds apply micronutrients including iron.

Higher concentrations of NO_3^- were observed in recent (Teklu *et al.*, 2016) and current study results of water samples from Lake Zeway as compared to previous assessment study results of the same lake (Elizabeth *et al.*, 1994; MoWR, 2008b; Getachew and Seyoum, 2009; Tewodros *et al.*, 2010a). The effect was more noticeable in water samples from BH/HD wells where the concentration of NO_3^- and NH_4^+ was exceeding the maximum permissible limit (MPL) in some water samples. However it requires further investigation to confirm for the study area, as such occurrences have been reported as a common phenomenon for ground water located around irrigated agricultural fields (Suthar *et al.*, 2009; Lockhart *et al.*, 2013). According to survey work of Edossa *et al.* (2013) and irrigated agricultural field monitoring by Putter *et al.* (2012) in the current study area, continuously increasing nutrient use in irrigated agriculture might be among the likely reasons for the high concentration of NO_3^- and NH_4^+ recoded in the current study.

The fact that the historical water quality data were from different literatures, sampled and analyzed in different laboratories having different levels of capacities, limitations are expected. Nevertheless, use of these historical data with current work has given considerable insights about the trend of lake water quality and the need to monitor important water quality parameters at some important locations on the lake to aid proactive decisions as required.

Water suitability for irrigation

Electrical conductivity and TDS for crop water availability, SAR/adjR_{Na}, and RSC for infiltration rate, and toxicity of specific ions (B, Cl) to sensitive crops were variable for the different water sources (Table 4, 5 and 6). About 33% of the water samples from Lake Zeway and very few water samples in other sources had pH above 8.5. According to FAO guideline of water quality for irrigated agriculture (Ayers and Westcot, 1985), no restriction on use due to EC or TDS of irrigation water was found in all water samples (N=5) from Ketar River. The TDS was limiting for about 50% of the water samples from Meki River. Over 50% of the water samples from BH/HD wells were in the 'slight to moderate' restriction, while few water samples from BH/HD wells in Zeway sub-watershed were in 'severe' restriction category for use due to EC_{iw} or TDS.

All water samples from rivers (Meki, Ketar and Bulbula) and Lake Zeway were in "slight to moderate" restriction on use while 40-50% of the water samples from BH/HD wells were in "severe" restriction category due to SAR and EC_{iw} effect on water infiltration except for the BH/HD wells located in Ketar sub-watershed (Table 4 and 5). Soil structural dispersion effect due to sodium adsorbed to soil colloids results in reduced size of the conducting pores (Ayers and Westcot, 1985; Emdad *et al*., 2004). The relatively higher adjusted R_{Na} than the SAR_{iw} values (Table 2) are indications to the effect of carbon dioxide and bicarbonate on calcium and hence, higher adverse impact of the irrigation water on soil infiltration than estimated by SAR.

Water analysis on specific ion toxicity for sensitive crops was not evident for chlorides and boron in all water samples from all water sources considered except few instances for water samples from BH/HD wells in Zeway and Bulbula sub-watersheds (Table 4 and 5). Majority of the water samples from Lake Zeway, Bulbula River, and BH/HD wells were within “slight to moderate” restriction on use due to Na ion toxicity to plant. For surface irrigation, the dominant irrigation method used for vegetable production in the study area, the restriction on use even goes to “severe” level for water samples from BH/HD wells located in Zeway and Bulbula sub-watersheds (Table 5). Bicarbonate for overhead irrigation but not nitrate, poses “slight to moderate” restriction on use for irrigation water from the rivers and the lake, while it even has shown “severe” restriction on use in over 50% of the water samples from BH/HD wells except in Ketar sub-watershed. A high bicarbonate level (above 3.3 meq L^{-1}) is reported to cause lime (calcium and magnesium carbonate) deposition on foliage when irrigated with overhead sprinklers (Hopkins *et al*., 2007).

The divisions for “restriction on use” of irrigation water were based on intensive research trials, studies and observations applicable under normal field conditions prevailing in most irrigated areas in the arid and semi-arid regions of the world (Ayers and Westcot, 1985). It was also indicated that a change of 10 to 20% above or below a guideline value has little significance if considered in proper perspective with other factors affecting yield (Ayers and Westcot, 1985). Hence, a "restriction on use" doesn’t necessarily imply the water is unsuitable for use, but indicates that there may be a limitation in choice of crop, or special management may be needed to maintain full production capability.

Table 4. Degree of restriction (%) on use of irrigation water from Ketar, Meki and Bulbula rivers, and Lake Zeway

Evaluating parameters	Degree of restriction on use			Percent of water samples in each potential irrigation problem categories (FAO, 1985)											
				Ketar River (N=5)			Meki River (N=5)			Lake Zeway (N=15)			Bulbula River (N=5)		
	None	Sli-Mod	Sev	None	Sli-Mod	Sev	None	Sli-Mod	Sev	None	Sli-Mod	Sev	None	Sli-Mod	Sev
Salinity (affects crop water availability)															
EC_{iw} (dS m^{-1}) or	<0.7	0.7-3	>3	100.0	-	-	100.0	-	-	100.0	-	-	100.0	-	-
TDS (mgL-1)	<450	450-2000	>2000	100.0	-	-	60.0	40.0	-	86.7	13.3	-	80.0	20.0	-
SAR and EC_w together (affects infiltration rate of water into the soil)															
SAR = 0-3	EC_{iw}>0.7	EC_{iw} = 0.2 - 0.7	EC_{iw}<0.2	-	100.0	-	-	100.0	-	-	33.3	-	-	60.0	-
SAR = 3-6	EC_{iw}> 1.2	EC_{iw} = 0.3 - 1.2	EC_{iw}< 0.3	-	-	-	-	-	-	-	46.7	-	-	40.0	-
SAR = 6-12	EC_{iw}> 1.9	EC_{iw} = 0.5 - 1.9	EC_{iw}< 0.5	-	-	-	-	-	-	-	20.0	-	-	-	-
SAR = 12-20	EC_{iw}> 2.9	EC_{iw} = 1.3 - 2.9	EC_{iw}< 1.3	-	-	-	-	-	-	-	-	-	-	-	-
SAR = 20-40	EC_{iw}> 5.0	EC_{iw} = 2.9 - 5.0	EC_{iw}< 2.9	-	-	-	-	-	-	-	-	-	-	-	-
Total				**-**	**100.0**	**-**	**-**	**100.0**	**-**	**-**	**100.0**	**-**	**-**	**100.0**	**-**
Specific ion toxicity (affect sensitive crops) **Sodium (Na^+)**															
Surface irrigation (SAR)	< 3	3 - 9	> 9	100.0	-	-	100.0	-	-	33.3	66.7	-	60.0	40.0	-
Sprinkler irrigation (meqL^{-1})	< 3	> 3		100.0	-	-	100.0	-	-	33.3	66.7	-	60.0	40.0	-
Chloride (Cl^-)															
Surface irrigation (meqL^{-1})	< 4	4 - 10	>10	100.0	-	-	100.0	-	-	100.0	-	-	100.0	-	-
Sprinkler irrigation (meqL^{-1})	< 3	>3		100.0	-	-	100.0	-	-	100.0	-	-	100.0	-	-
Boron (mgL^{-1})	<0.7	0.7 - 3.0	> 3.0	100.0	-	-	100.0	-	-	100.0	-	-	100.0	-	-
Miscellaneous effects (affects susceptible crops)															
Nitrogen (NO3_N) (mgL^{-1})	<5	5 - 30	> 30	100.0			100.0	-	-	100.0	-	-	100.0	-	-
HCO_3^-(meqL^{-1}) (for overhead sprinkling)	<1.5	1.5 - 8.5	>8.5	-	100.0	-	-	100.0	-	-	100.0	-	-	100.0	-

Table 5. Degree of restriction (%) on use of irrigation water from BH/HD wells in Ketar, Zeway and Bulbula sub-watersheds

Evaluating parameters	Degree of restriction on use			Percent of water samples in each potential irrigation problem categories (FAO, 1985)											
				All BH/HD wells (N=41)			In Ketar sub-watershed (N=5)			In Zeway sub-watershed (N=31)			In Bulbula sub-watershed (N=5)		
	None	Sli-Mod	Sev	None	Sli-Mod	Sev	None	Sli-Mod	Sev	None	Sli-Mod	Sev	None	Sli-Mod	Sev
Salinity (affects crop water availability)															
EC_{iw}(dS m^{-1}) or	<0.7	0.7-3	>3	39.0	53.7	7.3	60.0	40.0	-	35.5	54.8	9.7	20.0	80.0	-
TDS (mgL^{-1})	<450	450-2000	>2000	31.7	63.4	4.9	80.0	20.0	-	25.8	67.7	6.5	20.0	80.0	-
SAR and EC_w together (affects infiltration rate of water into the soil)															
SAR = 0-3	EC_{iw}>0.7	EC_{iw} = 0.2 - 0.7	EC_{iw}<0.2	-	12.0	-	-	40.0	-	-	6.5	-	-	20.0	-
SAR = 3-6	EC_{iw}> 1.2	EC_{iw} = 0.3 - 1.2	EC_{iw}< 0.3	-	19.5	-	-	40.0	-	-	19.4	-	-	-	-
SAR = 6-12	EC_{iw}> 1.9	EC_{iw} = 0.5 - 1.9	EC_{iw}< 0.5	4.9	7.3	-	-	-	-	6.5	3.2	-	-	20.0	-
SAR = 12-20	EC_{iw}> 2.9	EC_{iw} = 1.3 - 2.9	EC_{iw}< 1.3	2.4	7.3	17.1	-	-	20.0	3.2	9.7	19.4	-	-	20.0
SAR = 20-40	EC_{iw}> 5.0	EC_{iw} = 2.9 - 5.0	EC_{iw}< 2.9	-	4.9	24.4	-	-	-	-	6.5	25.8	-	-	40.0
Total				**7.3**	**51.0**	**41.5**	**-**	**80.0**	**20.0**	**9.7**	**45.3**	**45.2**	**-**	**40.0**	**60.0**
Specific ion toxicity (affect sensitive crops) **Sodium (Na$^+$)**															
Surface irrigation (SAR)	< 3	3 - 9	> 9	12.2	26.8	61.0	40.0	40.0	20.0	6.5	25.8	67.7	20.0	20.0	60.0
Sprinkler irrigation (meqL^{-1})	< 3	≥ 3		17.1	82.9		40.0	60.0	-	12.9	87.1	-	20.0	80.0	-
Chloride (Cl$^-$) (meqL^{-1})															
Surface irrigation	< 4	4 - 10	>10	85.4	14.6	-	100.0	-	-	83.3	16.7	-	80.0	20.0	-
Sprinkler irrigation	< 3	≥3		73.2	26.8	-	100.0	-	-	73.3	36.7	-	60.0	40.0	-
Boron (mgL^{-1})	<0.7	0.7 - 3.0	> 3.0	92.0	4.0	4.0	100.0	-	-	94.4	-	5.6	60.0	40.0	-
Miscellaneous effects (affects susceptible crops)															
Nitrogen (NO3_N) (mgL^{-1})	<5	5 - 30	> 30	82.1	17.9	-	100.0	-	-	79.3	20.7	-	100.0	-	-
HCO_3^- (meqL^{-1}) (for overhead sprinkling)	<1.5	1.5 - 8.5	>8.5	-	43.9	56.1	-	80.0	20.0	-	41.9	58.1	-	20.0	80.0

The residual sodium bicarbonate of majority of the water samples from Lake Zeway, BH/HD wells particularly from Zeway, and Bulbula sub-watersheds exceeded 2.5. Bicarbonates and carbonates in irrigation water react with soil calcium and magnesium and form insoluble compounds (dominantly of calcium) that create more chance for sodium to accumulate on the soil colloid and raise the sodium hazard rate (Eaton, 1950; Ayers and Westcot, 1985; Hopkins *et al.*, 2007). Continuous use of water having RSC > 2.5 meq L^{-1} can lead to increased proportion of Na^+ and precipitation of Ca^{2+} and Mg^{2+} in the form of carbonates. This will impact the soil physical condition, and air and water movement by clogging the soil pores (Singh and Kumar, 2015; Abdel-satar *et al.*, 2017).

Conclusions and Recommendations

The water chemistry of water samples from Ketar sub-watershed are different from water sources located in Bulbula and Zeway sub-watersheds. Water from BH/HD wells in Bulbula and Zeway sub-watersheds share similar characteristics where $HCO_3^- > Cl^- > SO_4^{2-}$, while SO_4^{2-} was found to be dominant next to HCO_3^- for the samples collected from Ketar sub-watershed that may indicate the influence of hydrogeology. The spatial variation of water quality for Lake Zeway was not statistically confirmed. Nevertheless, the data showed clear indication of deterioration of water quality at sampling location after Sher Ethiopia PLC floriculture. The increasing trend of EC in the entire lake with abrupt increases after Sher Ethiopia PLC floriculture farm calls the regulatory body to do strict regulation on the farms or any business units releasing effluents near the lake.

Appreciable numbers of water samples from different water sources are in 'slight to moderate' restriction on use for irrigation either due to one or combinations of EC, TDS, SAR or RSC. Long term use of irrigation water from BH/HD wells, particularly located in Zeway and Bulbula sub-watersheds could develop high to very high alkali hazard to soils. The RSC, which was >2.5 for majority of water samples from Lake Zeway, BH/HD wells particularly in Zeway and Bulbula sub-watersheds, could further intensify the sodium hazard rate.

Existing irrigated agriculture and the future expansion has to consider the quality of irrigation water and the management required to reduce the adverse effects on soils. Furthermore, water quality monitoring program at strategically selected sites along Lake Zeway need to be established and existing ones must be upgraded considering the existing and upcoming development impacts in the area.

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