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Groundwater quality composition and its suitability for drinking in long-term irrigated area

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Abstract

This study presents the hydrochemical composition of groundwater under long-term irrigation of Wonji plain (Ethiopia) and its quality status for drinking purpose. Groundwater samples were collected from 30 groundwater monitoring tube wells installed at different parts of the sugarcane plantation and then analysed for the major physico-chemical quality parameters (pH, *EC*, major cations and anions) following standard test procedures. The status of groundwater for drinking was compared with WHO and other quality standards. Analytical analysis results indicated that majority of the considered quality parameters are rated above the prescribed tolerable limits for drinking set by WHO. About 97% of the water samples has water quality index in the range of very poor to unfit for drinking. The contamination index is in the ranges of low (–1.0) to high (3.6). In general, the groundwater of the area is unsuitable for human consumption without proper treatment such as boiling, chlorination, filtering, distillation, desalinaization, defluoridation, deionization, demineralization (ion-exchange) and membrane processes. Since the TDS concentration is relatively small (<2000 ppm), demineralization process alone can be sufficient to bring the water to an acceptable level.

Key words: *contamination, drinking, groundwater, quality index, quality parameters, Wonji*

INTRODUCTION

In the recent few decades, there has been a remarkable increase in the demand for fresh water due to the rapid growth of population coupled with an accelerated pace of industrialization [RAMAKRISHNAIAH *et al.* 2009; KUMAR *et al.* 2015; CHAUDHARY *et al.* 2011]. But the available freshwater resources are declining and becoming a scarce resource. In arid and semi-arid environments, water quality is limited by its quality than quantity [MACHIWAL, JHA 2015]. In recent period, groundwater has become the most important resource used for various sectors (domestic, industrial and agricultural) in many countries of the world [SELVAKUMAR *et al.* 2017]. Globally, it is estimated that about one-third of the worlds' population are depending on groundwater supply [WHO 2011]. In irrigated areas, groundwater is often an important source of drinking. This is attributed to the fact that groundwater is typically of more stable quality and often require little or no treatment than surface waters [DAVIS 2010]. Natural groundwaters are usually free from contamination compared to surface waters [AKOTEYON 2013].

Groundwater storage represents about 97% of the global unfrozen freshwater reserves and its quality is relatively good compared to surface waters. Despite these facts, groundwater replenishment is finite and its quality can be deteriorated [AKOTEYON 2013; FALKENMARK 2005]. In shallow groundwater irrigated agriculture areas like Wonji sugarcane farm, the downward mobility of various contaminants (organic and inorganic) is very fast, causing several problems on humans and the environment. Once groundwater is contaminated, it becomes very difficult to remediate as the result of its large storage, long residence time [KUMAR *et al.* 2015] and physical inaccessibility [FOSTER 2006]. FOSTER [2006] indicated that the widespread pollution of groundwater due to inadequate protection from urbanization processes, industrial discharges and agricultural intensification is of great concern. Thus, protection of groundwater quality is very important to protect the public health [WHO 2011] and the environment. It is important to maintain a regular monitoring and assessment of groundwater quality and to device ways and means to protect it [RAMAKRISHNAIAH *et al*. 2009].

Groundwater hydrochemistry and its suitability for various purposes is affected by many factors such as: lithology, residence time of groundwater in the host rock, chemical composition of the aquifer, climatic conditions, and quantity of water available in the aquifer and its circulation rate [TODD, MAYS 2005]. Groundwater hydrochemistry is mostly influenced by the mineral weathering processes [YIDANA *et al*. 2012]. The physico-chemical quality of drinking water is also influenced by its hydrogeology [KELMENDI *et al*. 2018]. In shallow aquifer areas, saline intrusion and anthropogenic activities also play a significant role in the contamination of groundwater [AKOTEYON 2013].

In the arid and semi-arid climatic regions, groundwater quality assessment and sustainability considerations are extremely important due to its socio-economic significance [HOSSEINIFARD, AMINIYAN 2015]. In these regions, for instance, groundwater is often the main source of water supply [BAGHVAND *et al*. 2010] for irrigation and drinking [SRINIVAS *et al*. 2013]. Therefore, a continuous groundwater assessment and monitoring is an imperative and mandatory in order to minimize the groundwater pollution and have a control on the pollution causing agents [NWANKWOALA *et al*. 2014].

Wonji-Shoa Sugar Estate (WSSE), located in semi-arid climatic region (Ethiopia), has been under continuous supply of irrigation and agro-chemicals since its establishment in the 1950s. The sugar estate has been using various agro-chemicals (herbicides, pesticides, fungicides, insecticides, inorganic fertilizers, and organic compounds) for quite long-period of time. Such intensive activities can introduce a number of potential contaminants into groundwater system of Wonji plain. The leaching of agro-chemicals to groundwater system in such agricultural area is of great concern to human health in particular and sustainability of agriculture and environment of the region in general. As indicated by FOSTER [2006], the widespread pollution of groundwater due to inadequate protection from urbanization processes, industrial discharges and agricultural intensification is of great concern [DINKA 2019].

There is no critical research that has been reported so far in Wonji plain regarding the groundwater quality assessment for drinking purpose. There is little information available on the hydro-chemical composition of groundwater of the study area [DINKA 2019]. DECHASA [1999] studied the groundwater quality of the Ethiopian Rift Valley, including Wonji area, from few boreholes and hand-dug shallow wells and gave a general highlight about the water quality of the area [DINKA, NDAMBUKI 2014]. His work was done approximately 16 years ago, while groundwater quality assessment is a continuous process. There is an urgent need to have information of the prospective groundwater quality of the area with regard to its usage for drinking purpose. Therefore, the main goal of this study was to evaluate the hydrochemical composition of groundwater of WSSE and its quality status for drinking purposes. The status of groundwater was compared with WHO and other standard guidelines. Moreover, the feasible treatment options are suggested.

MATERIALS AND METHODS

BRIEF DESCRIPTION OF THE STUDY AREA

Wonji-Shoa Sugar Estate is located in the Awash River basin at about 110 km South-East of the capital city of Ethiopia. The sugar estate is crossed by Awash River, the only perennial river in the Awash basin and the source of irrigation in the sugarcane plantation. The long-term average annual rainfall and wind speed are about 832 mm and 2.81 $m \cdot s^{-1}$, respectively. The mean temperature of the area is in the range of 12.6–28.5°C, which is specifically suitable for sugarcane crop, the main crop grown in the area. The soils of WSSE area are generally classified as light and heavy textured soils. With the exception of the recent under expansion at outgrowers plantation sites (Wake Tio and Dodota), the sugar estate uses furrow irrigation system, where water is diverted from the Awash River. The new under development in outgrowers plantation areas are using dragline sprinkler irrigation systems. Detailed information about the study area can be obtained from recent publications [DINKA 2019; DINKA *et al*. 2013; 2014; DINKA, NDAMBUKI 2014]. Especially, DINKA and NDAMBUKI [2014] provides detailed information about the study area: location and topography, climate, soils and geology, land use/cover and irrigation water management.

WATER SAMPLING AND ANALYSIS

A total of 70 groundwater samples were collected from 30 groundwater monitoring hand dug tube wells distributed throughout the sugarcane plantation area (Fig. 1). The depth of the tube wells are from 2–3 m bellow the ground. The water sampling was done in the months of May (2009, 2010 and 2014) using clean polyethylene bottles (0.5 dm^3). All groundwater samples were collected early in the morning and analysed on the same day, following standard test procedures [APHA 2005; DINKA *et al*. 2015; WHO 2011]. The pH and electrical conductivity (*EC*) values were measured using pH and conductivity meters, respectively. Calcium (Ca) and magnesium (Mg) ions were determined by EDTA titration; sodium (Na) and potassium (K) by flame photometric; carbonate (CO_3), bicarbonate (HCO_3) and chloride (Cl) by titrimetric; sulphate (SO_4) by spectrophotometeric; flouride (F) and boron (B) by potentiometric; and turbidity by turbidometer methods. Other parameters total dissolved solids (TDS) and total hardness (TH) were derived from measured physico-chemical parameters. TDS was determined from the measured *EC* value by the empirical formula (Eq. 1) [DINKA *et al*. 2015; PRADHAN, PIRASTEH 2011] since the *EC* value in groundwater of the

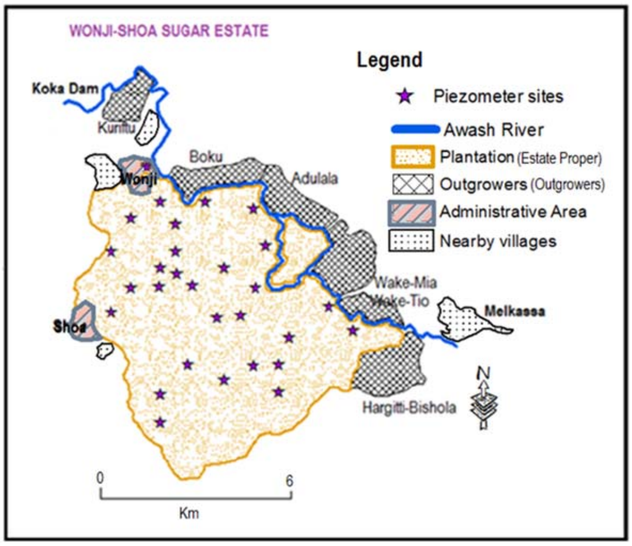

Fig. 1. Wonji-Shoa Sugar Plantation (estate proper and outgrowers) showing GW sampling sites, the Awash River, administrative areas, and villages/towns; source: own elaboration

study area is less than 5 dS·m^{-1}. TH (Eq. 2) was determined by the methods suggested by RAGHUNATH [1987] and adopted by others (SARKAR and HASSAN [2006]; DINKA *et al.* [2015]; CHAUDHARY and SATHEESHKUMAR [2018]).

$$TDS = 640EC \tag{1}$$

$$TH = 2.497Ca + 4.11Mg \tag{2}$$

Where: TH, Ca and Mg values are expressed in mg·dm^{-3}, *EC* in dS·m^{-1} and TDS in ppm.

WATER QUALITY ANALYSIS AND INTERPRETATION

Analysis and interpretation of the analytical water quality results for drinking purposes were done following the standard guidelines for drinking purpose: World Health Organization [WHO 2011], European standards [Council Directive 80/778/EEC], U.S. Environmental Protection Agency [USEPA 2000], Health Canada [2008], standards used in Russia [CHAPMAN (ed.) 1996], and Ethiopian standards [MoH 2011. Emphasis was given to WHO standards since most developing and other developed countries use the WHO standards for drinking water [WHO 2011].

The characteristics of each of the considered physico-chemical constituents are described briefly in terms of the WHO standards (desirable and permissible). The potential sources of chemicals and their possible effects on health, water acceptability and water supply systems are presented. Moreover, the treatment processes are suggested for some of the individual quality parameters specifically and for the whole parameters in general. The quality rating of each quality parameters and general suitability of the water for drinking purpose was estimated using the water quality index (*WQI*) adopted by others [ASADI *et al.* 2007; DINKA 2010; DAS *et al.* 2001; JAGADEESWARI, RAMESH 2012; RAMAKRISHNAIAH *et al.* 2009].

The water quality index WQI was calculated using the weighted arithmetic water quality index method proposed by TIWARI and MISHRA [1985] and adopted by others [ASADI *et al.* 2007; DINKA 2010; DAS *et al.* 2001; RAMAKRISHNAIAH *et al.* 2009; TYAGI *et al.* 2013]. The quality rating (q_i) (Eq. 3) for the considered i^{th} parameter is calculated as follows:

$$q_i = 100\left(\frac{V_i - V_o}{S_i - V_i}\right) \tag{3}$$

Where: V_i and S_i are the analytical value and the standard value for the i^{th} parameter, respectively, V_o is the ideal value of the i^{th} parameter in pure water (V_o = 0, except pH = 7.0). The standard value is considered as the maximum permissible level set by WHO [2011].

The sub-index (*SI*) quality parameter was calculated as [RAMAKRISHNAIAH *et al.* 2009]:

$$SI_i = W_i q_i \tag{4}$$

Where: W_i is the relative weights for various water quality parameters, assumed to be inversely proportional to the recommended standards for the corresponding parameters; W_i is computed using Eq. (5).

$$W_i = \frac{w_i}{\sum w_i} \tag{5}$$

Where: w_i = unit weight of each parameter according to its relative importance in the overall quality of water for drinking purposes, adopted from JAGADEESWARI and RAMESH [2012]. The $\sum w_i$ should be equal to 1. In this study, the $\sum w_i = 48$.

The aggregated *WQI* (Eq. 6) was calculated for each of the water sources by aggregating the quality rating (q_i) linearly and taking their weighted mean.

$$WQI = \sum_{i=1}^{n} SI_i \tag{6}$$

The *WQI* classes used were from the works of TIWARI and MISHRA [1985] and adopted by others [ASADI *et al.* 2007; DINKA 2010; DAS *et al.* 2001; RAMAKRISHNAIAH *et al.* 2009; TYAGI *et al.* 2013]. *WQI* classes are as follows: 0–25 (excellent, grade A), 26–50 (good, grade B), 51–75 (poor, grade C), 76–100 (very poor, grade D), >100 (unfit for drinking, grade E).

Finally, the contamination factor for each parameter (CI_i) and the overall contamination index (C_d) were calculated as shown in Equations 7–8 [EDET, OFFIONG 2002]. The contamination index is classified as: low (C_d < 1), medium (1 < C_d < 3) and high (C_d > 3) contamination [EDET, OFFIONG 2002].

$$CI_i = \frac{V_i}{S_i} - 1 = \frac{q}{100} - 1 \tag{7}$$

$$C_d = \sum_{i=1}^{n} CI_i \tag{8}$$

RESULTS AND DISCUSSION

COMPOSITIONAL VARIABILITY AND COMPARISON WITH STANDARD GUIDELINES

The analytical analysis results of physicochemical parameters compared to permissible limits of various drinking water standard guidelines are presented in Table 1. Table 1 also provides the probability of groundwater quality parameters exceeding WHO [2011] (desirable and permissible) drinking water standards. The distribution patterns of each quality variables compared to the WHO's maximum permissible limit (MPL) and the highly desirable limit (HDL) standards for drinking water are plotted and presented in Figure 2.

Analytical analysis results indicated that all quality parameters (except CO_3 and turbidity) do not completely satisfy the WHO MPL and HDL standards. Only few parameters (pH, CO_3, turbidity and K) are within the WHO acceptable MPL standards. Also Na, Ca, Mg, SO_4, TDS and *EC* almost satisfy the WHO MPL standards, except 8 (20%), 4 (10%), 4 (10%), 4 (10%), 4 (10%) and 7 (17.5%) samples, respectively. The percentage of samples within the HDL limits for pH, Ca, Mg, Cl, and SO_4 are 95%, 80%, 80%, 92.5%, and 80%, respectively. Majority of the samples (70%) are above the acceptable WHO HDL limits for TDS. The measured pH value is in the range of 6.8 to 8.0. A pH above 8.2 is a measure of the dominance of CO_3 ion and that below 8.2 is a measure of HCO_3 ion [DINKA *et al.* 2015]. This study result is in line with this argument: the pH value is <8.2 and CO_3 ion is almost nil, and hence, HCO_3 ion is the dominant anion. In general, Na and Ca are the dominant cations and HCO_3 is the dominant anion. HCO_3 ions are usually dominant in groundwaters with low to medium mineralization. Thus, it is possible to suggest that groundwater of the area is undergoing mineralization process. The mineralization process is indicator for an anthropogenic origin [BRAHMIA *et al.* 2018]. The soluble cations and anions can be arranged according to their dominance as Na > Ca > Mg > K and HCO_3 > SO_4 > Cl > CO_3, respectively.

Another interesting feature which can be observed from Figure 2 is that water quality of the area varies from location to location. Groundwater samples with relatively high *EC* values also have relatively high TDS values. This is actually expected since *EC* and TDS values are interrelated. In general, plantation fields with relatively high content of cations have showed relatively high values of anions, and vice versa (Fig. 2). Moreover, plantation fields with relatively high concentration of soluble salts (*EC* and TDS) have relatively high values of other parameters (Na, Ca, K, HCO_3, Cl and TH), and vice versa. This means that the latter ones are the main responsible for the quality status of water in the study area. The large variation in the quality parameters are mainly attributed to the variation in geological formations, and hydrological processes.

Table 1. Comparison of the obtained results with the different drinking water standards and the probability of groundwater quality parameters exceeding WHO drinking water standards (average values for 2009, 2010 and 2014 measurements)

Parameter	Standard concentration							Results obtained				
	WHO 1)		USA 2)	Europe 3)	Russia 4)	Canada 5)	Ethiopia 6)	Range (average)	sample percentage compared to WHO			
	HDL	MPL							p < HDL	p > HDL	p < MPL	p > MPL
pH (–)	7.0–8.5	6.5–8.5	6.5–8.5	6.5–8.5	6.0–9.0	6.5–8.5	6.5–8.5	6.8–8.02 (7.5)	95	5	100	0
EC ($\mu S \cdot m^{-1}$)	300	1400	–	–	2000	–	–	117–3002 (1046)	5	95	82.5	17.5
Na^+ ($mg \cdot dm^{-3}$)	–	200	–	–	200	20	358	30–496 (174)	–	–	80	20
Ca^{2+} ($mg \cdot dm^{-3}$)	75	100	–	–	–	–	75	22–168 (59)	80	20	90	10
Mg^{2+} ($mg \cdot dm^{-3}$)	30	50	–	–	–	–	50	5–76 (24)	80	20	90	10
K^+ ($mg \cdot dm^{-3}$)	–	200	–	–	–	–	1.5	1–70 (10)	–	–	100	0
Cl^- ($mg \cdot dm^{-3}$)	200	250	250	250	350	250	533	27–308 (68)	92.5	7.5	95	5
CO_3^- ($mg \cdot dm^{-3}$)	–	45	–	–	–	–	–	0–44 (23)	100	0	100	0
HCO_3^- ($mg \cdot dm^{-3}$)	–	500	–	–	–	–	–	218–1933 (619)	–	–	45	55
TH ($mg \cdot dm^{-3}$)	200	500	–	–	–	300	392	105–604 (320)	7.5	92.5	82.5	17.5
B ($mg \cdot dm^{-3}$)	–	2.4	–	1.0	0.3	5.0	0.3	2–6.0 (3.3)	–	–	30	70
F ($mg \cdot dm^{-3}$)	1.0	1.5	2.0	1.5	1.5	1.5	3.0	1.5–6.4 (3.8)	0	100	0	100
SO_4^- ($mg \cdot dm^{-3}$)	200	250	250	250	500	250	483	30–208 (96)	80	20	90	10
TDS (ppm)	500	600	500	–	1000	500	1776	112–1872 (645)	30	70	90	10
Turbidity (NTU)	5	10						2.0–9.0 (6.0)	90	10	100	0

Explanations: the values in parentheses are average values; p – probability (%); HDL= highest desirable limit; MPL = maximum permissible limit.
Source: own study and: 1) WHO [2006, 2011], 2) USEPA [2000], 3) Council Directive 80/778/EEC, 4) CHAPMAN (ed.) [1996], 5) Health Canada [1980], 6) MoH [2011], MoWR [2001].

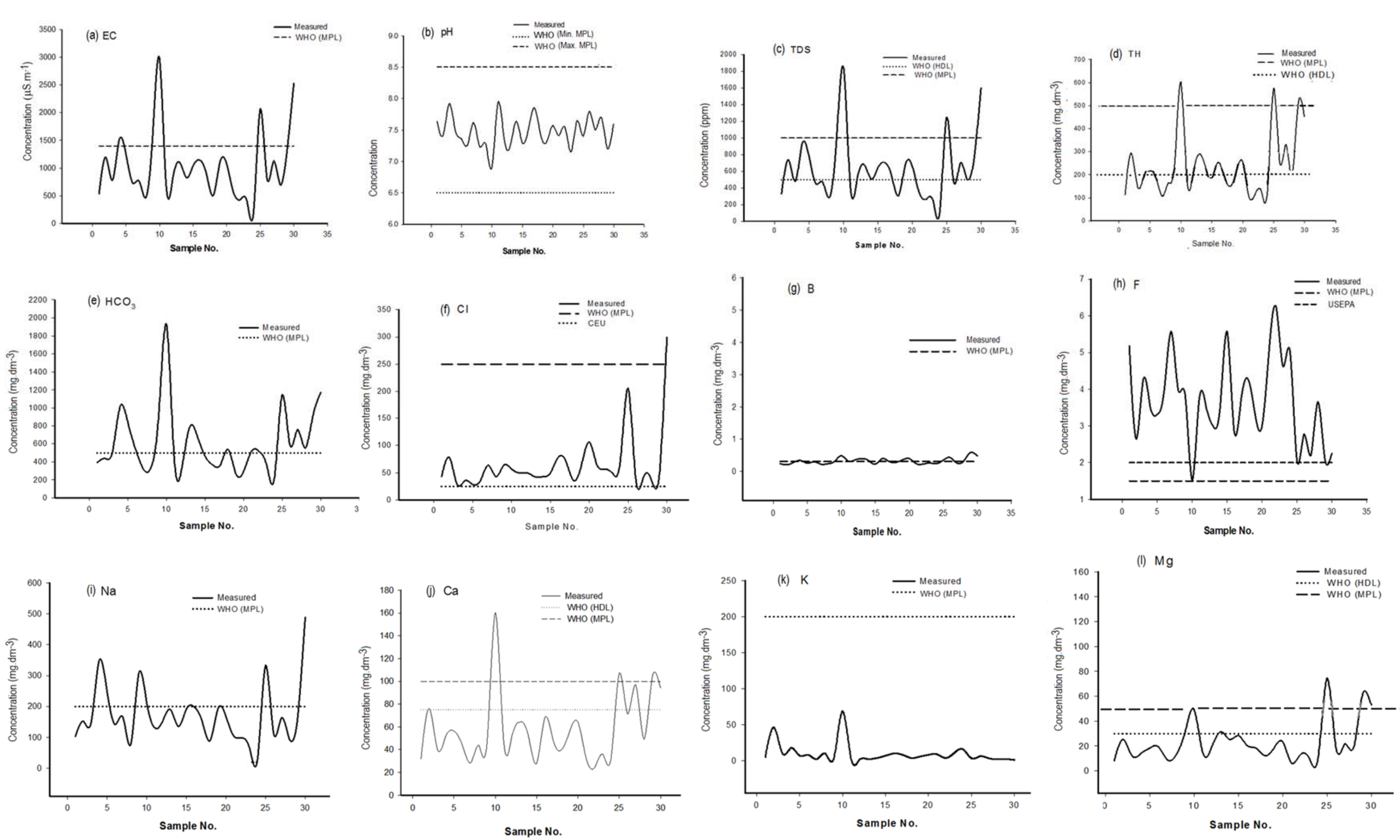

Fig. 2. The variation and distribution pattern of the water quality parameters compared to standard WHO guidelines (2009–2010); source: own study

CHARACTERIZATION OF INDIVIDUAL QUALITY VARIABLES

Under this section, the characteristics of each of the considered physic-chemical constituents are described briefly. The measured water quality for each of the considered parameters is presented compared to the prescribed WHO standards (HDL and MPL). Brief discussions were presented for the potential sources of chemicals and their possible effects on health and water supply systems.

The pH value. Eventhough pH has no direct health effects, it can affect the acceptability of water due to its indirect health effects via metal solubility [DWAF 1996] and its effects on water treatment processes and water supply equipments. Extremely high pH can result in the solubilisation (i.e. redox reaction) of toxic heavy metals (like Fe, As, Mn, Pb, etc.) and the deprotonation of other ions or compounds. The pH value <6.5 or >9.2 can impair the potability of drinking water significantly [WHO 2011]. Thus, water pH can affect the toxicity level of other elements and has very pronounced effects on many chemical reactions which are important to water treatments for various purposes [PRADHAN, PIRASTEH 2011]. The pH value governs the behaviour of several other processes of water treatment such as proper coagulation, water softening, acid base neutralization, precipitation, disinfection, corrosion control, stabilization, ammonia toxicity, chloride disinfection efficiency, and metal solubility [DAVIS 2010; DWAF 1996]. The pH value also affects the taste of water (high pH gives the basic/bitter taste and low pH gives acidic/sour taste), the corrosivity, solubility and speciation of metal ions [DWAF 1996], and increases the scale formation in pipe systems [JAMSHIDZADEH, MIRBAGHERI 2011].

Higher pH affects the chlorination efficiency. For adequate disinfection, alkaline water requires a longer contact time or a higher free residual chlorine level at the end of the contact time [WHO 2011]. For effective disinfections with chlorine, WHO [2011] set the value of pH < 8.0. Fortunately, all the groundwater samples of the area satisfy this condition. The pH values obtained (6.8–8.0) are within the range of MPL (6.5–8.5) set by WHO for drinking purpose (Fig. 2b, Tab. 2). The highest and lowest values of pH were recorded for samples No. 11 (field 18) and No. 10 (field 63). Only 2 samples are found to be below the minimum WHO HDL limit (7.0–8.5). In general, all the groundwater samples of the area (except 2 samples with pH of 6.8 and 6.9) are slightly alkaline/basic in nature (pH > 7). According to the various standards shown in Table 1, the groundwater of the study area is safe for drinking as far as pH is concerned. The potential sources of alkaline pH in the study area can be the levels of hard-water minerals (bicarbonate, borates, silicates and phosphates), nutrient recycling and release of basic effluents from industries (paper and sugar factory) and agriculture (use of fertilizer like urea). High pH can be adjusted by addition of an alkaline reagents ($NaCO_3$, $NaHCO_3$ or lime); whereas a low pH can be increased by adding acidic reagents (CO_2, HCl or H_2SO_4). The stabilization of water pH to within acceptable range can be done by the careful addition of buffering reagents such as Na, CO_3, HCO_3, SO_4 and Cl [DWAF 1996].

Total soluble salts: *EC* and TDS. The *EC* values of the groundwater samples are within the ranges of 117–3002, with average value of 1046 $\mu S \cdot cm^{-1}$. The highest *EC* value was recorded for sample No. 10 (field 63) and the lowest *EC* value was recorded for sample No. 24 (field 11). About 83% of the samples have *EC* in the range of suitable for drinking (*EC* < 1400 $\mu S \cdot cm^{-1}$ [WHO 2011]) and the remaining proportion (17%) is above the recommended WHO permissible limit (Tab. 1). Surprisingly, about 95% of the samples have *EC* greater than the WHO HDL limit (*EC* < 300 $\mu S \cdot cm^{-1}$), and hence is of great concern for the area. High value of *EC*, for drinking use, denotes the proportionally high value of dissolved ions, especially cations. The *EC* value also reveals the mineralization of water types [MALEK *et al.* 2019]. Based on *EC* values, four types of mineralization can be identified in the groundwater samples of the study area [KABBOUR, ZOUHRI 2005]. About 5%, 20%, 30% and 45% of the water samples showed a weak, marked, significant and high mineralization, respectively. That means more than 75% of the groundwater of the area are undergoing medium to high rate of mineralization. This condition further strengthens the rate of mineralization suggested earlier under the preceding sub-section "Compositional variability and comparison with standard guidelines".

The TDS values varying from 115 to 1872, with an average value of 645 ppm. Considering the TDS limits for drinking purpose (Tab. 1), only 30% of the samples are in

Table 2. Frequency of samples within the water quality index (*WQI*) for each quality variables (average of 2009 and 2010), numbers of samples – 60.

WQI	Status[1)]	Samples	pH	*EC*	Na	K	Ca	Mg	HCO_3	SO_4	Cl	TDS	TH	F	B	Turbidity
0–25	excellent	number %	21 35	3 5	3 5	57 95	30 50	54 90	–	12 20	38 63	3 5	–	–	–	43 72
26–50	good	number %	30 50	15 25	9 15	3 5	24 40	6 10	2 3	38 63	18 30	23 38	16 27	–	–	11 18
51–75	poor	number %	9 15	16 27	14 23	–	4 7	–	16 27	8 13	–	20 33	20 33	–	8 13	6 10
76–100	very poor	number %	–	16 27	22 37	–	2 3	–	8 13	2 3	2 3	8 13	14 23	–	20 33	–
>100	unfit for drinking	number %	–	10 17	12 20	–	–	–	34 57	0 0	2 3	6 10	10 17	60 100	32 53	–

1) Acc. to ASADI *et al*. [2007].
Explanations: *EC* = electrical conductivity, TDS = total dissolved solids, TH = total hardness.
Source: own study.

the safe WHO HDL limit (TDS < 500 ppm). However, about 90% of the samples are within the WHO MPL limit (TDS < 1000 ppm) and categorized as fresh water and the remaining samples (10%) are classified to be brackish (TDS > 1000 ppm), which likely to contain enough of certain constituents to cause noticeable taste or otherwise make the water undesirable or unsuitable for drinking. Four samples in 3 different fields (63, 201 and 52) have TDS > 1000 ppm. High values of TDS above the safe HDL limit (TDS > 500 ppm) indicates the presence of slightly elevated concentrations of soluble salts and is related to the other problems such as hardness [HEROJEET *et al.* 2013]. Eventhough there is no direct health effects associated with the ingestion of TDS in drinking water, its objectionability is due to its causes of water hardness and its effects on water supply systems. Higher TDS (>500 ppm) can cause excessive scaling in water pipes, water heaters, boilers and household appliances [GODGHATE *et al.* 2013]. High TDS can cause undesirable taste and gastrointestinal irritation [SELVAKUMAR *et al.* 2017]. It can also cause excessive water hardness, unpalatability, mineral deposition and corrosion [DWAF 1996]. TDS is a measure of the amount of dissolved (inorganic) salts in water and is directly proportional to *EC* values. The *EC* and TDS concentrations in water can be reduced by distillation and highly sophisticated separation technologies [DWAF 1996] such as demineralization (ion-exchange, reverse osmosis, electrodialysis) or deionization processes. However, the sophisticated technologies are characterised by high cost of processing and/or high energy consumption. Fortunately, the TDS value in the area is less than 2000 and hence, desalinization process (reverse osmosis) alone can be sufficient.

Major soluble cations. The average values of soluble cations and anions are relatively low in concentration in groundwater of the area. However, the concentrations of Na and HCO_3 ions in some fields (48, 66, 101, 153, 63, 169, 131, 105, 195, and 189) are very high compared to the others (Fig. 2). The measured K ion concentration is in the range of 1–70, with average value of 10 mg·dm^{-3}. All the water samples are within the WHO MPL limit for K. Sodium ion content is found to be in the range of 30–496, with average value of 174 mg·dm^{-3}. Accordingly, about 80% of the samples are not suitable for drinking as its quality rating for Na is above the permissible limit (200 mg·dm^{-3}) – Table 1. Most salts of Na are not active in chemical reactions eventhough they are readily soluble in water [PRADHAN, PIRASTEH 2011]. Excess Na consumption can exacerbate certain disease conditions such as hypertension, cardiovascular or renal diseases [DWAF 1996]. Especially, it affects persons suffering from heart, kidney or circulatory ailments [DAVIS 2010]. Therefore, some of the groundwater samples of the area are undesirable for infants and/or persons on a sodium-restricted diet. The dominance of Na concentration in some of the groundwater samples of the study area could be due to the weathering of Na bearing minerals/rocks, halite dissolution, cation-exchange process, pollution from industrial effluent and domestic sewage, and/or discharge from agricultural activities (use of agrochemicals). Na can be removed by distillation and the sophisticated physico-chemical separation techniques such as demineralization or membrane technique. However, since TDS in the area is less than 2000 ppm, demineralization process alone is sufficient.

The concentration of Ca ion is in the range from 22 to 168, with average value of 59 mg·dm^{-3}. Ninety and eighty percent and of the samples are below the specified HDL (75 mg·dm^{-3}) and MPL (100 mg·dm^{-3}) limits for Ca, respectively. Eventhough Ca concentration has no health effects, it can make the water unpalatable due to its effects on water supply system. While high concentration of Ca (>100 mg·dm^{-3}) has scaling problems and impaired lathering of soaps; low concentration of Ca (<16 mg·dm^{-3}) can cause possible corrosive effects. Fortunately, all the water samples have Ca concentration above 16 mg·dm^{-3}.

High Ca concentrations usually impair the lathering of soap by the formation of insoluble Ca salts of long chain fatty acids that precipitate as scums, resulting in excessive soap consumption used in personal hygiene and, in rare cases, household cleaning operations [DWAF 1996]. However, Ca has some beneficial effects in natural water bodies. It plays an important role in the health of natural water bodies since it is known to reduce the toxicity of many other chemical compounds (e.g. NO_2) [WILLIAM *et al.* 1986]. The effect of $CaCO_3$ on water supply can be reduced by either of the following available techniques [DWAF 1996]: regular descaling of household appliances, treatment with mild acid (eg. acetic acid), and use of household (abrasive and alkaline) cleaning agents.

Magnesium ion content is in the ranges of 5–76, with average value of 24 mg·dm^{-3}. Similar to Ca, about 90% and 80% of the water samples are below the MPL (50 mg·dm^{-3}) and HDL (30 mg·dm^{-3}) limits for Mg, respectively. The objection of Mg in drinking water is based on both human health and aesthetic effects [DWAF 1996]. Higher Mg concentration makes the water unpalatable and act as laxative to human beings [CHOUDHARY *et al.* 2011]. Excess Mg intake is excreted by the kidney. Moreover, excess intake of Mg-SO_4 can result in diarrhoea. High Mg ion content, together with Ca, is responsible for scaling problems in appliances and plumbing, and also for inhibiting the lathering of soap which results in scum formation [DWAF 1996]. Scum deposits on enamelled surfaces of baths and hand basins are also related to the effects of Mg and Ca hardness. The most common Mg treatment method is lime softening followed by carbonation, precipitation of Mg as magnesium hydroxide and cation exchange processes.

Major soluble anions. The measured HCO_3 ion content is in the ranges of 220–1928, with average value of 617 mg·dm^{-3}. More than half (55%) of the water samples have HCO_3 exceeding MPL limits. The highest HCO_3 contents were observed on fields 63 and followed by fields 201, 52, 48, etc. The CO_3 content in the area is very low (0–44 mg·dm^{-3}) and all samples are within the recommended MPL limits. Both CO_3 and HCO_3 ions occur in the form of carbonate system of chemical equilibrium, usually associated with the high pH (alkalinity) and hardness of water, which gives an unpleasant taste to water [DINKA *et al.* 2015]. The sources of these ions could be dissolution of carbonate rocks (eg. limestone, dolomite, magnesites) [NI-

KANOROV, BRAZHNIKOV 2012] and carbonic acid (H_2CO_3) [RAMESH, JAGADEESWARI 2012].

The SO_4 concentration found in the water samples is in the ranges of 30 to 208, with mean value of 96 mg·dm^{-3}. Only 4 samples (10%) in fields 48, 153 and 201 exceeded the specified permissible limit (250 mg·dm^{-3}) for SO_4^{2-}. The sources of SO_4 could be natural and/or anthropogenic activities [DINKA *et al*. 2015; NIKANOROV, BRAZHNIKOV 2012]. The natural sources include weathering of rocks, volcanic activities, biochemical process [HEROJEET *et al*. 2013], decomposition and oxidation of substances containing SO_4 [DINKA *et al*. 2015], the leaching of natural deposits of Mg-SO_4 or Na-SO_4, and the sulphides of heavy metals [DWAF 1996]. Excess SO_4 content increases the erosion rate of metal fittings in water distribution systems and can cause acute health effects. SO_4 can also impart a salty or bitter taste to water. The health effects of SO_4 is usually associated with the concentration of cations (Na, Ca, and Mg). High concentration of Na-SO_4 and Mg-SO_4 is associated with respiratory illness and a laxative effect on some individuals. Excess Na-SO_4 should not be present in drinking water as they cause cathartic action. Redox reactions can change SO_4 to hydrogen sulphide (H_2S), especially in oxygen-poor environments in the presence of organic matter. The SO_4 in the form of H_2S will cause a distinct and unpleasant odour (rotten egg) even at very low concentrations (<10 mg·dm^{-3}) [DAVIS 2010]). The treatment options for SO_4 are ion exchange, demineralisation, membrane, distillation, precipitation, sedimentation and filtration [DWAF 1996].

Chloride (Cl) has little effect on the suitability of water for drinking, but can affect the palatability of water. Its excessive concentration above the MPL (250 mg·dm^{-3}) limit, depending upon water alkalinity can give rise to detectable salty taste in water [WHO 2011] and people who are not accustomed to high Cl may be subjected to laxative effect [GODGHATE *et al*. 2013; WHO 2011]. High Cl content can interfere with chlorination process [KELMENDI *et al*. 2018]. High Cl content can also cause a high blood pressure in people [GODGHATE *et al*. 2013] and increase rates of corrosion of metals in the distribution system [HOSSEINIFARD, AMINIYAN 2015; WHO 2011]. Corrosion, in turn, can lead to increased concentrations of metals in the water supply system making the water non-potable and corrosive. Chloride originates from $NaCl_2$ which gets dissolved in water from rocks and soil. Cl may be accumulated in groundwater from chloride-rich minerals or rocks, domestic sewage and agricultural activities [SELVAKUMAR *et al*. 2017]. The removal of $NaCl_2$ from water is difficult and too costly for most water uses. Fortunately, the concentration of Cl obtained in the study area varies between 27 and 308, with a mean value of 68 mg·dm^{-3}. Only 5% (2 sample) and 7.5% (3 samples) exceeds the recommended WHO [2011] MPL (250 mg·dm^{-3}) and HDL (200 mg·dm^{-3}) limits for Cl, respectively. However, all the water samples of the area exceeded the standard (25 mg·dm^{-3}) set by CEU. High Cl content was recorded for fields No. 52 and No. 201. The high Cl content in some fields could be due to pollution by agricultural activities (fertilizers and other agri-chemicals), domestic sewage, animal wastes (organic) and/or industrial effluents. Treatment options for Cl are electrolysis, anion exchange and desalinisation techniques.

Boron (B) is a natural component of freshwaters arising from the weathering of rocks, soil leaching, volcanic action and other natural processes [CHAPMAN (ed.) 1996]. It usually exists as undissociated boric acid and borax [WHO 2006]. Although some studies indicated that excessive amounts of B can cause nervous problems, its high concentration is a problem in irrigation than drinking water [DWAF 1996; WHO 2006]. Infants are usually more sensitive than adults to the effects of B compounds [WHO 2011]. The B ion concentration obtained was in the range between 2.0 and 6.0, with average value of 3.3 mg·dm^{-3}. Almost 70% of the samples exceed the WHO MPL (2.4 mg·dm^{-3}) for B concentration. However, the value is relatively safe compared to groundwater in Europe and Canada. All groundwater samples of the study area are below the standards set by Council of European Communities [Council Directive 80/778/EEC] and Health Canada [2008] (see Tab. 1). Thus, treatment for B is not required.

Fluoride (F^-), the most common occurring form of fluorine, is a natural contaminant of groundwater. High F content in groundwater is due to the bedrock containing F minerals. It is one of those chemicals given high priority by WHO [2006; 2011] and the other standards (USEPA, CEC, EC, Russia, Ethiopia, etc.) for their health effects on humans. Groundwater usually contains F dissolved by geological formations [ASADI *et al*. 2007]. Flourine is the most electronegative and reacts with most of the other elements [KARRO, UPPIN 2013]. This characteristics makes F content relatively high in drinking water obtained from groundwater. It is usually found in low quantities, but it can cause problems to humans upon consumption [ASADI *et al*. 2007]. Low concentration of F (0.6–1.0 mg·dm^{-3}) in drinking water is beneficial in growing children by hardening enamel and reducing incidence of tooth decay (i.e. dental caries) [KARRO, UPPIN 2013]. F < 2 mg·dm^{-3}causes dental cavities in children. However, high concentration of F in drinking water usually cause dental and skeletal fluorosis [WHO 2011; KARRO, UPPIN 2013]. Excessive consumption of F (>2 mg·dm^{-3}) causes a dental fluorosis (mottling of teeth), while regular consumption in excess may give rise to bone and skeletal fluorosis.

Unfortunately, all the water samples of the study area have F concentration exceeding the MPL limit (1.5 mg·dm^{-3}) set by WHO. Water samples have F content varying between 1.5 and 6.4 mg·dm^{-3}, with average value of 3.8 mg·dm^{-3}. The high F content in the area could be due to agricultural and industrial activities and the weathering of fluorine bearing minerals like fluoride and apatite. The use of water containing F above the MPL (1.5 mg·dm^{-3}) may cause mottling of the tooth enamel during formation of permanent teeth for children [HARITASH *et al*. 2008]. Majority of the children using water with F content as high as 4 mg·dm^{-3} may have mottled teeth enamel [HARITASH *et al*. 2008]. Almost 37% of the groundwater samples have F > 4 mg·dm^{-3}. The effect of F is clearly observed by the dental and skeletal fluorosis symptoms on some of the

Wonji population [DECHASA 1999]. People from Adama or Wonji area can be easily differentiated from the other parts of Ethiopia by their mottled teeth (i.e., brownish black streaks on their teeth). The problem of F is partly solved recently (about 4 years for Wonji and 8 years for Adama town) based on the newly established water supply system from Koka Dam (the Awash River), which has relatively low F content. However, the old water supply system is still in use for domestic purpose in some of the villages in the sugar plantation and its effect is not totally resolved. The content of F in groundwater of the area can be easily reduced to acceptable range by ion-exchange and membrane processes, deflouridation (adding alum), mixing it with fluoride free water, or by intake of vitamins (C & D) antioxidants.

Hardness and turbidity. The average value of TH obtained in this study was 214.8 mg·dm^{-3}, varying from 84 to 608 mg·dm^{-3}. TH values obtained indicates that twenty (50%), fourteen (35%), and six (15%) of the groundwater samples are moderately hard (101–200 mg·dm^{-3}), hard (201–300 mg·dm^{-3}) and very hard (>300 mg·dm^{-3}), respectively. About 50% of the water samples are above the WHO HDL (200 ppm) limits; but only 15% (6 samples) are above WHO MPL (500 ppm) limit for TH. Water hardness indicates the water quality, mainly in terms of Ca and Mg ions (Ca or Mg carbonates) [KUMAR *et al.* 2015]. High hardness can affect water acceptability for drinking purpose. It should be noted that TH in the range of acceptable MPL limit (150–300 ppm) can cause kidney problems and TH above MPL limits can cause gastro-intestinal irritation [GODGHATE *et al.* 2013]. The effects of hard water includes low suds production with soap and scale developed in water heater and plumbing.

Turbidity is defined as murkiness in water caused by colloidal and other suspended particles. Turbidity can also interfere with the treatability of water like disinfection processes. Moreover, harmful bacteria and other contaminants (such as excess nutrients and toxic materials) can be attached with the fine particles suspended in turbid water [DAVIS 2010]. Fortunately, the turbidity of all the water samples are within the recommended permissible range of WHO. Only 4 samples (10%) exceeded the recommended WHO HDL limit (5 NTU). The measured turbidity value is in the ranges of 2–9, with average value of 6 NTU.

WATER QUALITY INDEX (WQI)

It is difficult to quantify the overall suitability of water based on the various guidelines presented in Table 1. The interpretation of the various water quality parameters separately is usually a difficult task for general public as well as decision and policy makers. Therefore, the calculation of a general water quality index (WQI) is extremely important in order to communicate the quality of water in a better understandable way. The frequency of each water quality parameters within the specified range of WQI is presented in Table 2. The quality rating (q), sub-index (SI) and contamination index (CI) values for each of the considered quality parameters are presented in Table 3. In Table 4, the values of q, WQI and the general suitability of the water for drinking purposes are summarized for each of the groundwater samples. The results of the quality rating (q) (Tab. 3) and then general status (last column in Tab. 4) was made based on WQI categories shown in column 2 of Table 2.

The contamination index (last column of Table 3) is in the range of –1 (low) to 3.6 (high), with the overall C_d value of –1.3 (low). Majority of the considered quality parameters (EC, Na, HCO_3, TDS, TH, F, B) have WQI in the category of poor to UFD (Tab. 3). Others (pH, K, Ca, Mg, SO_4, Cl) are mostly categorized under excellent and good quality index. Surprisingly, the percentages of samples categorized under UFD are 53%, 57% and 100%, respectively for B, HCO_3, and F. As far as the general suitability is concerned (last column of Tab. 4), there is no sample categorized as excellent and good quality. Groundwater

Table 3. The quality rating (*q*), sub-index (*SI*) and contamination index (*CI*) values for each of the considered quality parameters

Parameter	Standard value *S*	Relative weight W_i	Measured value v_i		Quality rating q_i		SI_i		*CI*	
			range	mean	range	mean	range	mean	range	mean
pH	8.5	0.10	6.8–8.0	7.5	–6.3–170	45.6	–0.5–14.0	3.8	–0.2–(–0.1)	–0.12
EC	1400	0.08	117–3002	1046	13–214	74.3	0.8–13.3	4.6	–0.9–1.1	–0.26
TDS	500	0.08	112–1872	644	23–369	128.2	1.9–30.8	10.7	–0.8–2.7	0.28
Na	100	0.04	30–496	174	30–496	172.0	1.3–20.4	7.2	–0.7–3.9	0.72
Ca,	75	0.04	22–168	59	31–214	77.3	1.3–8.9	3.2	–0.7–1.1	–0.23
Mg	50	0.04	5–76	24	11–153	46.0	0.5–6.3	1.9	–0.9–0.5	–0.54
K	200	0.02	1–70	10	0.5–35	5.0	0.0–0.7	0.1	–1.0–(–0.7)	–0.95
Cl	250	0.08	27–308	68	11–121	26.4	0.7–7.5	1.7	–0.9–0.2	–0.74
CO_3	45	0.02	0–44	23	0–33	15.6	0.0–0.7	0.3	–1.0–(–0.7)	–0.84
HCO_3	500	0.06	218–1933	619	44–386	123.4	2.8–24.1	7.7	–0.6–2.9	0.23
SO_4	250	0.08	30–208	96	13–82	38.0	1.1–6.8	3.2	–0.9–(–0.2)	–0.62
TH	500	0.04	84–608	215	21–121	64.0	0.9–5.0	2.7	–0.8–0.2	–0.36
B	0.3	0.14	2–6	3.2	64–198	114.3	9.7–28.2	16.5	–0.3–0.9	0.13
F	1.5	0.12	1.5–6.4	3.8	120–430	249.8	12.5–52.5	30.8	0.0–3.20	1.47
Turbidity	5.0	0.08	2.0–9.0	6.0	40–180	120.0	3.3–15.0	10.0	–0.6–0.8	0.20
		Σ = 1.00	**Water quality index (*WQI*) = 105.2**				**Overall contamination index (C_d) = –1.30**			

Explanation: all values of *S* and v_i are in mg·dm^{-3}, except pH (–), *EC* (μS·cm^{-1}), and turbidity (NTU).
Source: own study.

Table 4. The quality rating (q), the general water quality index (*WQI*) and its status for each of the groundwater sample

Sample No.	Field No.	Quality rating (q_i)													*WQI*	Status
		pH	*EC*	Na	K	Ca	Mg	HCO_3	Cl	TDS	TH	F	B	SO_4		
1	29	43	38	52	3	32	5	78	17	33	38	346	78	33	86	very poor
2	41	28	86	76	23	76	17	88	31	74	98	176	67	30	68	poor
3	25	61	56	75	5	40	8	103	11	48	50	285	91	41	94	very poor
4	48	33	108	175	9	52	9	205	14	93	63	234	110	82	107	unfit for drinking
5	66	24	90	124	4	56	12	166	11	78	72	221	83	55	84	very poor
6	76	17	52	71	4	44	13	107	14	45	63	265	98	35	98	very poor
7	101	41	54	83	1	28	6	63	26	47	36	372	72	53	81	very poor
8	123	15	34	39	5	44	9	68	17	29	55	265	77	22	81	very poor
9	153	19	115	154	2	46	21	185	26	99	81	256	101	64	101	unfit for drinking
10	63	0	214	106	35	160	33	386	23	185	201	101	160	30	126	unfit for drinking
11	18	63	48	66	1	48	9	88	20	41	59	248	104	33	102	unfit for drinking
12	166	25	60	76	1	52	13	68	20	51	70	234	117	35	111	unfit for drinking
13	169	16	78	95	1	64	21	156	17	68	96	200	130	37	118	unfit for drinking
14	209	43	59	68	2	52	17	137	17	51	78	234	110	30	106	unfit for drinking
15	131	20	74	96	4	28	19	93	20	64	62	372	72	46	81	very poor
16	105	34	81	99	5	68	13	73	31	70	84	191	130	41	117	unfit for drinking
17	107	57	64	76	4	48	12	73	28	55	65	248	101	36	100	very poor
18	127	29	36	45	2	40	8	107	14	31	50	285	91	26	94	very poor
19	195	21	79	97	3	56	12	54	26	68	72	221	117	44	110	unfit for drinking
20	189	38	77	84	4	64	16	59	43	66	85	200	130	35	118	unfit for drinking
21	184	27	40	52	4	32	4	103	26	35	35	336	78	34	85	very poor
22	177	37	30	49	2	24	9	103	23	26	38	417	73	31	84	very poor
23	16	10	30	32	5	36	7	73	20	26	44	308	85	20	90	very poor
24	11	43	13	16	8	32	7	44	28	11	42	336	78	12	85	very poor
25	52	27	148	167	2	107	50	229	82	125	192	136	113	46	100	very poor
26	41	53	58	57	3	71	12	117	15	48	84	185	141	25	125	unfit for drinking
27	42	33	81	82	2	97	15	151	17	70	111	146	83	31	79	very poor
28	50	47	49	47	1	49	13	110	15	50	67	244	106	23	103	unfit for drinking
29	73	13	94	77	1	104	41	183	17	76	172	139	194	24	154	unfit for drinking
30	201	40	181	244	1	94	35	234	120	160	151	150	160	74	134	unfit for drinking
															***WQI* = 106**	

Explanation: *EC* = electrical conductivity, TDS = total dissolved solids, TH = total hardness.
Source: own study.

samples are generally categorized in the range of poor to UFD. Only 1 sample (3%, field 41) is generally categorized as poor. The other samples are categorized as very poor (50%) and UFD (47%). The general WQI value (WQI) for the area (Tab. 3) is calculated as 106, which is categorized as UFD. This means that the groundwater of the area is not suitable for drinking without treatment. Some of the treatment processes suggested by the author includes filtering, boiling, reverse osmosis, electro-dialysis, defluoridation, demineralization, ion-exchange, membrane processes, etc. Desalination techniques are usually require skilled manpower (for operation, control and maintenance) as well as a high cost (capital and operating).

CONCLUSIONS AND RECOMMENDATIONS

The study result inferred that the groundwater of the study area is slightly alkaline in nature, with Na and Ca ions as the dominant cations and HCO_3 ion as the dominant anion. The groundwater quality of the study area showed variations in composition from one location to another location. The variation could be the result of the respective groundwaters being in contact with different aquifer materials or minerals for significantly different periods of time.

The result also showed groundwater of the area is undergoing low to high level of mineralization. There are indicators for some of the quality variables are due to natural and anthropogenic sources. Some fields No. 63, 201, 52 and 48) have elevated concentration in almost all variables, indicating there is human induced pollution sources in these fields. The anthropogenic pollution sources in the area could be industrial effluents, agro-chemicals, domestic wastes, etc. The author would like to suggest that more attention should be given to effluent management by the managers of the sugar estate. The use of industrial effluent water and filterfcake for irrigation should be revised.

Analyses results further indicate that majority of the considered quality parameters do not completely satisfy the recommended WHO (MPL and HDL) standards. Majority of the considered quality parameters (*EC*, Na, HCO_3, TDS, TH, F and B) have *WQI* in the category of poor to unfit for drinking (UFD), and thus rated above the prescribed tolerable limits for drinking set by WHO. The obtained *WQI* for all samples was in the range of 68 (poor) to 154 (UFD), with average value of 106 (UFD). The contamination index is in the ranges of low (–1) to high (3.9). It is possible to infer that the groundwater of the area is at critical condition and hence, of great concern.

In general, groundwater of the area is not suitable for drinking without pre-treatment. Consumption of groundwater of the area has certain effects on human health, water acceptability and water supply systems. Therefore, a proper treatment would be necessary before its usage for drinking purpose. Some of the treatment processes, apart from chlorination, suggested by the author include filtering, boiling, distillation, desalinaization (reverse osmosis and electrodialysis), defluoridation, deionization, demineralization (ion-exchange), membrane processes, etc. Since TDS in the study area is less than 2000 ppm, demineralization process alone can be sufficient. However, it should be noted that the WQI in this study considers some of the important physico-chemical quality parameters only. Further study on the biological quality parameters is highly recommended before making the actual decision for treatment requirements.

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