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Concentration of Inorganic Contaminants in Shallow Borehole Water in Chuka Sub-County, Kenya

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Abstract: Groundwater from shallow aquifers is an important source of portable water in Chuka Sub-County. However, most shallow boreholes in Chuka Sub-County are undocumented and susceptible to contamination by both geogenic and anthropogenic activities. This study was conducted to evaluate the quality of shallow boreholes water in Chuka Sub-County. Samples were collected from twenty boreholes in Chuka Sub-County during the dry and wet seasons. The temperature, pH and conductivity were determined *in situ* using a meter. The concentration of cations was determined using ICP-MS. The concentrations of anions were determined using standard APHA analytical methods. The temperatures and conductivities of borehole waters were within the limits set by KEBS and WHO. The pH of water in most boreholes during the wet season was within the limits set by KEBS and WHO for portable water. However, borehole water at Karandini (T15) was highly acidic (pH of 3.95) during the wet season. During the dry season, borehole waters were slightly acidic (4.42 - 6.44) except for the borehole at Ndagani market (T11), whose water was alkaline (pH = 8.75). The concentrations of trace and toxic cations and anions (NO_3^-, SO_4^{2-}, Cl^- and PO_4^{3-}) were within the limits set by KEBS and WHO. However, the concentration of nitrate in several boreholes during the dry season was within the range that cause chronic health effects. Groundwater from most boreholes in Chuka Sub-County is generally safe for domestic uses but require regular monitoring for quality.

Key words: Groundwater, borehole, inorganic contaminants, geogenic, anthropogenic

INTRODUCTION

In Kenya, 43% of the population does not have access to clean water [1]. The water crisis is more severe in rural areas where almost half of the population does not have access to clean water and relies on raw water from rivers, lakes and dams [1]. The water scarcity is poised to increase due to rapid population growth, urbanization, increasing per capita consumption rates, global warming and climate change and pollution of surface water resources [1], [2], [3].

Groundwater resources from deeper aquifers and shallow wells has considerable potential for enhancing water supplies in Kenya [4]. This is because groundwater is more resilient to climate variability and face minimal transmissions and storage loses compared to surface systems [5]. In rural areas, shallow groundwater resources are increasingly being used for provision of domestic water supply due to the ease of drilling and uplifting water from shallow hand-dug, hand-drilled and machine drilled wells [5]. Most of these shallow wells are undocumented because approval is not required to sink a shallow boreholes [6]. These boreholes are therefore highly susceptible to contamination by both geogenic and anthropogenic sources because their sitting does not require reconnaissance surveys and hydrogeological studies [6], [7].

Geogenic contaminants of groundwater include arsenic from volcanic rocks and deltaic sediments [8], [9], fluoride from fluoride-containing minerals (e.g., fluorite, biotites and topaz) in volcanic deposits [10], [11] and chloride ions from salt water intrusion in coastal areas [12]. Groundwater can also contain high concentrations of chromium and manganese weathered from ultramafic rocks, sandstones, granites and limestones [13], [14] and iron leached from rocks containing iron minerals such as hematite, scorodite, goethite, magnetite and ferromagnesian silicates [15]. The weathering of sedimentary rocks containing heavy metals can also cause pollution of groundwater by these metals [16].

Agricultural runoff containing fertilizers, agrochemicals and faecal matter is the major anthropogenic source of fluoride, nitrate, phosphate and heavy metals in groundwater [10], [17]. Other anthropogenic sources of contamination include animal feedlots, urban runoff, seepage from broken septic tanks and pit latrines, leachate from improperly constructed landfills and open dump sites, leakages from septic tanks and sewerage systems and contaminated soils [17], [18].

Groundwater pollution by inorganic contaminants can cause severe adverse health effects. Chronic exposure to high levels of arsenic causes arsenical dermatosis, skin, lung and urinary cancers, cardiometabolic diseases, respiratory disorders and gastrointestinal ailments [19]. Drinking water containing high concentrations of fluoride can cause dental and skeletal fluorosis [20] while the presence of nitrate in groundwater can cause infantile methaemoglobinaemia [21]. Several heavy metals are highly toxic and cause severe health effects, even in low concentrations. Adverse health effects of heavy metals include teratogenic effects, growth retardation in children, multiple organ damage and several types of cancers [22], [23].

The objective of this study was to determine the concentration of inorganic contaminants in groundwater from shallow boreholes in Chuka Sub-County of Tharaka-Nithi County, Kenya.

MATERIALS AND METHODS

Study Area: The study was conducted in Chuka Sub-County, Tharaka-Nithi County, Kenya.The sub-county covers an area of 316 Km^2 and is sub-divided into three wards (Karingani, Magumoni and Mugwe) as shown in Figure 1. The total population of the Chuka sub-county is 83, 824 people [24].

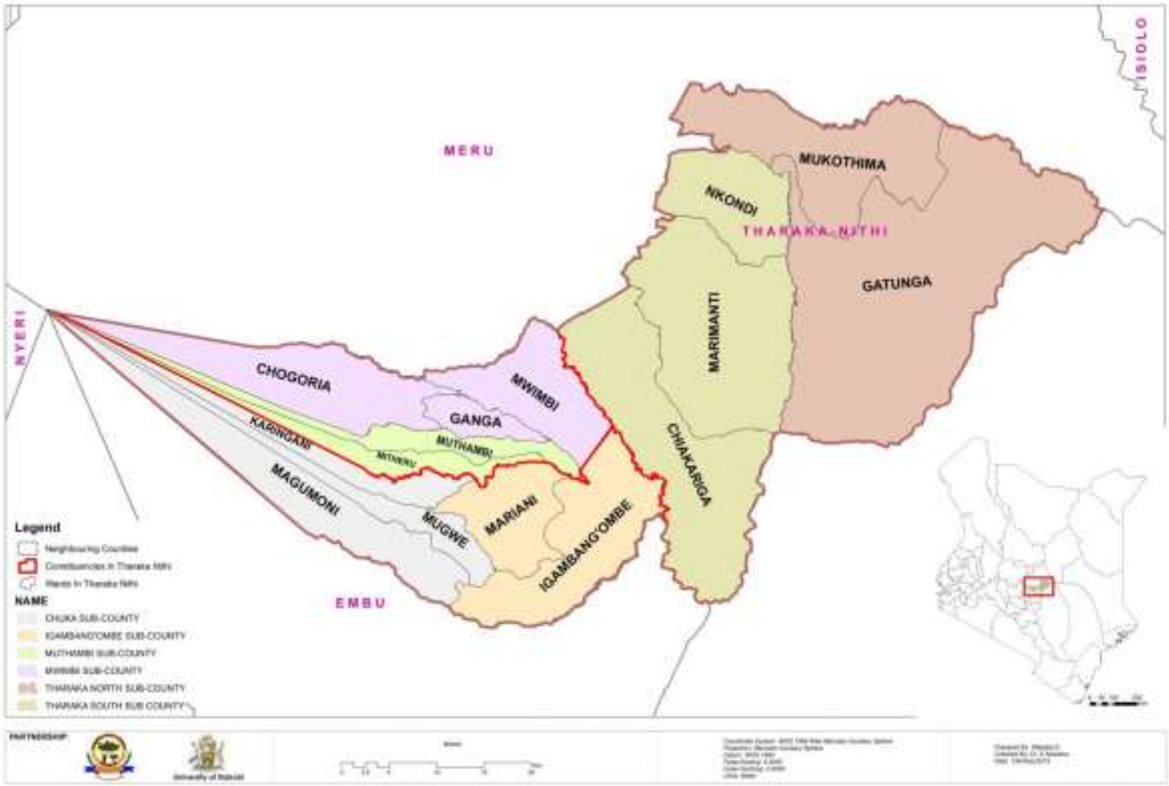

Figure 1: Map of Tharaka Nithi County (Source: https://tharakanithi.go.ke).

Chuka sub-county is located on the wind-ward side of Mt. Kenya and receive an average annual rainfall of 1400-1800 mm [25]. The rainfall pattern is bimodal with long rains occurring between the months of March and May and the short rains falling between the months of October and December. Temperatures in the sub-county range between 14ºC and 30ºC. The area slopes from West to East and is drained by five major rivers (i.e. Thuci, Mara, Nithi, Mutonga, Naka and Ruguti rivers). The geology of the area is greatly influenced by the volcanism of Mount Kenya with Lahars containing phenolites and trachytes forming the bulk of the rock types [25]. The area has deep red soils composed of volcanic ashes and weathered materials from the lahars. Aquifers occur at several depths everywhere in the lahar area between depths of 7-120 m.

Collection of Samples: The purposive sampling technique was used to collect water samples from twenty shallow boreholes in the study area during the wet and the dry season. The sampling sites and their geographic coordinates, located using a global positioning system (GPS), are shown in **Table 1.**

The groundwater samples were collected in triplicate using PET bottles. The bottles were rinsed three times with respective borehole water prior to sampling. The pH and temperature of the water samples were measured on-site using a portable digital pH meter (H198107, HANNA instruments). The conductivity of the samples was also measured onsite using a portable Hanna conductivity meter (HI9033 EC, HANNA instruments). The samples were then transported to the laboratory in ice boxes and stored at -4ºC prior to analysis.

Table 1: Geographic coordinates of the sampling sites

Sampling site	Code	Latitude (º)	Longitude (º)
Mungoni	T1	-0.3239489	37.6557212
Kibumbu	T2	-0.3335136	37.6437504
Ikuu Boys	T3	-0.3479525	37.6233826
Ndagani Slaughter	T4	-0.3367368	37.6499972
Kiandogo Village	T5	-0.3502179	37.6393124
Ndagani Marine	T6	-0..3086445	37.6743652
Njaina	T7	-0.30894876	37.6757678
Kirege	T8	-0.3479532	37.6233826
Iruma	T9	-0.3495257	37.6255826
Ndagani Tumaini	T10	-0.3343615	37.6740452
Ndagani Market	T11	-0.3365329	37.6451324
Kirigi Village	T12	-0.3485243	37.6244724
Kirubia	T13	-0.3349398	37.645954
Kangoro	T14	-0.3499825	37.6288856
Karandini	T15	-0.3602106	37.6341194
Kagumo	T16	-0.3452342	37.646274
Ikuu Market	T17	-0.3602106	37.6341194
Rukindu	T18	-0.3207712	37.6607199
Kathigirini Village	T19	-0.2491951	37.73082228
Karigini Village	T20	-0.3455232	37.6249728

Sample Analysis: Elemental analysis of the water samples was performed using an Agilent 7900 Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) system. The concentration of chloride ions was determined following the argentometric method (APHA Method 4500-Cl^- B) described in the literature [26]. The concentration of nitrate ions was determined by the APHA (APHA Method 4500-NO_3^- B) spectrophotometric method, using a Shimadzu 1800 Ultraviolet-Visible Spectrophotometer [26]. The concentration of sulphate ions was determined by the APHA turbidimetric method (APHA method 4500-SO_4^{2-} E) using a Shimadzu 1800 Ultraviolet-Visible spectrophotometer [26]. The concentration of phosphate ions was determined using the APHA colorimetric method (APHA Method 4500-P E) using a Shimadzu 1800 Ultraviolet-Visible spectrophotometer [26].

RESULTS AND DISCUSSION

Physico-Chemical Parameters: The temperature, pH and conductivity of borehole waters during the wet and dry seasons are given in Table 2. During the wet season, the lowest and highest temperatures were recorded at T1 (23.3ºC) and T7 (29.0ºC) sites, respectively. The mean temperature for the wet season was 25.75°C while the standard deviation was 1.84. The lowest and highest temperatures were recorded at T17 (24.8°C) and T7 (32.1°C) during the dry season. The mean temperature and the standard deviation for the dry season were 29.1°C and 1.83, respectively.

Table 2: Physico-chemical parameters of borehole waters

Site	Physico-Chemical Parameters					
	Temperature (°C)		pH		Conductivity (μs/cm)	
	WS[a]	DS[b]	WS	DS	WS	DS
T1	23.3	27.3	8.52	5.44	37	34.1
T2	23.9	27.8	7.51	5.17	40.5	42.4
T3	23.3	29.1	8.08	4.98	36.9	37.7
T4	26.8	29.0	7.96	4.96	62.9	63.4
T5	26.3	29.4	7.0	4.77	57.8	55.2
T6	24.0	30.5	5.91	6.44	16	540
T7	29.0	32.1	6.61	4.8	31.3	22.5
T8	27.3	30.3	9.06	4.83	40.1	38.2
T9	26.8	30.7	8.1	5.15	53.5	52.9
T10	26.2	30.0	5.94	4.96	33.8	32.9
T11	27.7	31.4	7.49	8.75	1150	1208
T12	27.6	31.1	8.57	4.9	21.4	19.5
T13	27.4	30.6	5.96	5.3	100.8	39.9
T14	27.2	29.3	8.47	4.97	20.6	24
T15	27.2	29.3	3.95	4.72	30.5	27.1
T16	23.8	27.1	6.1	5.01	61	76.7
T17	24.1	24.8	5.89	4.42	60.9	59.4
T18	23.5	27.3	6.35	5.88	58.9	119.2
T19	23.7	26.8	9.3	5.18	63.8	58.8
T20	25.9	28.6	7.57	4.66	81.5	59.1
Mean	25.75	29.125	7.217	5.2645	102.96	130.55
Min	23.3	24.8	3.95	4.42	16	19.5
Max	29	32.1	9.3	8.75	1150	1208
St. dev	1.837189	1.830696	1.356536	0.933175	247.3636	277.3128

[a]Wet Season, [b]Dry Season

Temperatures were significantly higher during dry season than during the wet season presumably due to inflow of water from rainfall [27]. Cool water is generally more palatable than warm water because temperature affects several factors that determine the odour and taste of water [20], [27]. Higher water temperatures also reduces dissolved oxygen, accelerates chemical reactions and enhances microbial growth [20].

During the wet season, the lowest pH of 3.95 was recorded at site T15 while the highest pH of 9.3 was recorded at the T19 site. The mean pH and the standard deviation during the wet season were 7.2 and 1.36, respectively. The pH of several boreholes during the wet season is within the limits (5.5-9.5) set by the Kenya Bureau of Standards (KEBS) for natural portable water [28]. However, the borehole water at site T15 (3.95) is highly acidic. During the dry season, the pH ranged from 4.42 to 8.75. The mean pH and the standard deviation were 5.3 and 0.93, respectively. The borehole waters were slightly acidic (4.42-6.44) except for site T11 (8.75), whose water was alkaline. The pH of water in most boreholes were outside the lower limit set by KEBS. The pH of water is influenced by several factors including dissolved gases (e.g. carbon dioxide), dilution and dissolved chemical species of both geogenic and anthropogenic origins [29]. Highly acidic water can cause adverse health effects such as irritation, gastro-intestinal disorders and redness of the eyes [27]. High acidity can also cause corrosion of several metals [27].

The electrical conductivity of the water samples ranged from 16-1150 µs/cm during the wet season, with a mean of 102.96 and a standard deviation of 247.36. During the dry season, the electrical conductivity ranged 19.5 to 1208 µs/cm with a mean of 130.55µs/cm and a standard deviation of 277.31. The borehole water at site T11 had remarkably higher conductivities that the other boreholes in the study area during both the wet (1150 µs/cm) and the dry (1208 µs/cm) seasons indicating a higher amount of ionic substances in the water [29]. The conductivities of the waters in all boreholes during both the wet and the dry seasons are within the upper limit of 1400 µs/cm set by the WHO and 2500 µs/cm set by KEBS [20], [28].

Concentration of cations: The concentrations of trace cations in borehole waters are shown in **Table 3.** The concentrations of manganese during the dry season ranged from zero to 13924.34 ppb with a mean concentration of 764.33 ppb. The concentration of manganese in all boreholes was zero except T6 (13924.34 ppb), T14 (20.95 ppb) and T18 (1341.27 ppb). The concentrations of manganese during the wet season ranged from zero to 203.89 ppb with a mean concentration of 25.94 ppb. The concentrations in all boreholes were zero except T3 (15.03 ppb), T4 (58.64 ppb), T5 (7.49 ppb), T13 (203.89 ppb), T16 (196.33 ppb), T18 (33.45 ppb) and T20 (3.98 ppb). The concentration of manganese in all boreholes during both the dry and the wet season is significantly lower than the maximum allowed value of 0.1 mg/L set by the Kenya Bureau of Standards [28] and the health-based value of 0.4 mg/L set by the World Health Organization for portable water [20]. In addition, the concentrations are lower than levels with potential to cause neurotoxicity in children [30].

Manganese is usually found in groundwater due to the weathering and leaching of manganese-bearing minerals and rocks in the aquifers [31]. Dissolution of manganese from minerals and rocks is favoured by low pH (< 7), anoxic conditions and the presence of micro-organisms that degrade organic carbon [31]. The site and seasonal variations in concentrations of manganese can therefore be attributed to localized hydrogeochemical processes since the boreholes are located in the same geological zone.

The concentrations of iron during the dry season ranged from zero to 3368.8 ppb with a mean of 209.68 ppb while during the wet season, the concentrations ranged from zero to 715.17 ppb with a mean concentration of 35.76 ppb. These concentrations are lower than levels of 0.5 to 50 mg/L usually found in natural fresh waters and the 2 mg/L allocated to drinking water as part of the minimum daily dietary requirement for iron [20]. The levels of iron in borehole waters therefore do not present aesthetic problems or health hazards. The low levels further suggests that iron in boreholes waters is of geogenic origin. The concentration of cobalt during the dry season ranged from zero to 14.77 ppb with a mean concentration of 1.73 ppb. Moreover, the concentrations ranged from zero to 320.52 ppb during the wet season with mean concentration of 29.92 ppb. The concentrations of cobalt in all samples were within the maximum admissible limit of 100 µg/L set by US EPA [32].

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Table 3: Concentrations of trace cations in borehole waters

Site	Concentration (ppb)									
	Mn		Fe		Co		Cu		Zn	
	DS[a]	WS[b]	DS	WS	DS	WS	DS	WS	DS	WS
T1	0.00	0.00	0.00	0.00	0.15	32.85	0.00	0.00	0.00	1166.13
T2	0.00	0.00	0.00	0.00	1.13	2.90	0.00	0.00	0.00	0.00
T3	0.00	15.03	0.00	0.00	0.00	4.00	0.00	0.00	0.00	0.00
T4	0.00	58.64	0.00	0.00	0.06	2.37	0.00	0.00	0.00	51.06
T5	0.00	7.49	163.68	0.00	1.09	0.89	0.00	0.00	0.00	0.00
T6	13924.34	0.00	3368.82	0.00	9.88	26.93	0.00	0.00	0.00	114.20
T7	0.00	0.00	0.00	0.00	0.06	1.24	3.21	0.00	0.00	12.33
T8	0.00	0.00	0.00	0.00	0.00	1.84	0.00	0.00	0.00	19.25
T9	0.00	0.00	0.00	0.00	3.87	0.35	0.00	0.00	0.00	0.00
T10	0.00	0.00	0.00	0.00	2.49	5.08	0.00	21.90	0.00	0.00
T11	0.00	0.00	0.00	0.00	0.00	0.70	0.00	0.00	0.00	0.00
T12	0.00	0.00	0.00	0.00	0.40	2.07	26.68	1.79	0.00	77.24
T13	0.00	203.89	0.00	0.00	0.00	0.05	13.11	0.00	0.00	27.50
T14	20.95	0.00	0.00	0.00	0.00	2.42	0.00	0.00	0.00	62.90
T15	0.00	0.00	0.00	0.00	0.00	1.72	0.00	0.00	0.00	0.00
T16	0.00	196.33	0.00	0.00	14.77	37.94	0.00	0.00	0.00	47.73
T17	0.00	0.00	0.00	0.00	0.17	320.52	0.00	0.00	0.00	4.37
T18	1341.27	33.45	661.10	715.17	0.50	151.92	0.00	0.00	0.00	146.44
T19	0.00	0.00	0.00	0.00	0.00	0.74	0.00	0.00	0.00	0.00
T20	0.00	3.98	0.00	0.00	0.00	1.89	0.00	0.00	0.00	36.12
Mean	764.33	25.9405	209.68	35.7585	1.7285	29.921	2.15	1.1845	0.00	88.2635
Min	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00
Max	13924.34	203.89	3368.82	715.17	14.77	320.52	26.68	21.90	0.00	1166.13
St. dev	3111.969614	61.350504	159.916874	758.581727	3.839707	76.513021	6.495134	6.49513021	0.00	257.104001

[a] Dry season, [b]Wet Season

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The concentrations were within the range for naturally occurring cobalt in groundwater from geogenic sources [33]. Cobalt is a constituent of several minerals including smeltite, cobaltite and linneite that are abundant in the nickel-bearing laterite deposits, sedimentary copper deposits and the nickel-copper sulphide deposits hosted in mafic and ultramafic rocks [33].

The concentrations of copper during the dry season ranged from zero to 26.68 ppb with mean concentration of 2.15 ppb. During the wet season, the concentrations were between zero and 21.90 ppb with mean concentration of 1.18 ppb. These concentrations are significantly lower than the maximum allowable concentration of 1.000 mg/L set by the Kenya Bureau of Standards [28] and the WHO health-based value of 2 mg/L [20]. These very low concentrations suggests that groundwater in the study area is not contaminated by copper from anthropogenic sources.The concentration of zinc during the dry season was zero in all samples. The concentrations during the wet season ranged from zero to 1166.13 ppb with a mean concentration of 88.26 ppb. These concentrations are all within the maximum allowable concentration of 5 mg/L set by the Kenya Bureau of Standards [28]. The higher concentrations of zinc during the wet season are presumably due to geochemical conditions than enhance mineralization from zinc bearing minerals [34].

The concentrations of toxic cations in borehole waters are shown in **Table 4**. The concentration of lead during the dry season ranged from zero to 108.3 ppb with a mean concentration of 11.79 ppb. During the wet season, the concentrations ranged from zero to 6.45 ppb with a mean concentration of 0.32 ppb. These concentrations are within the maximum concentration limit of 0.01 mg/L set by KEBS and the guideline value of 0.01 mg/L set by the WHO [20], [28]. Moreover, the concentrations of lead are two orders of magnitude lower than the maximum concentration limit suggesting that the groundwater is not contaminated with lead from anthropogenic sources. The concentrations of lead were generally higher during the dry season than in the wet season presumably due to enhanced solubilisation from lead-bearing minerals and rocks at low pH in the boreholes [35].

The concentration of cadmium during the dry season was below the detection limit while concentrations during the wet season ranged from zero to 0.22 ppb with a mean concentration of 0.02 ppb. These concentrations are about four orders of magnitude lower than the maximum concentration limit of 0.003 mg/L set by KEBS and the guideline value of 0.003 mg/L set by the WHO [20], [28].

The concentration of mercury during the dry season ranged from zero to 0.1 ppb with a mean concentration of 0.01 ppb. The concentration during the wet season was below the detection limit. These concentrations are several orders of magnitude lower than the maximum concentration limit of 0.001 mg/L set by KEBS and the guideline value of 0.006 mg/L set by the WHO for inorganic mercury [20], [28].

The concentrations of arsenic during the dry season ranged from zero to 1.4 ppb with a mean concentration of 0.07 ppb. In addition, the concentrations during the wet season ranged from zero to 0.43 ppb with a mean concentration of 0.02 ppb. These concentrations are significantly lower than the maximum concentration limit of 0.01 mg/L set by KEBS and the guideline value 0.01 mg/L set by the WHO [20], [28]. The concentrations are also within those found in natural groundwater in volcanic regions [20]. The concentrations of boron in groundwaters ranged from zero to 75.59 ppb during the dry season and zero to 45.85 ppb during the wet season. The mean concentrations were 12.54 and 5.39 ppb during the dry and the wet season, respectively. The concentrations are within the guideline maximum value of 2.4 mg/L set by the WHO for portable water [20]. The very low values also suggests that the boron in groundwaters is of geogenic origin presumably as a result of leaching from rocks and soils containing borates and borosilicates [20].

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Table 4: Concentrations of toxic elements in borehole waters

Site	Concentration (ppb)													
	Pb		Cd		Hg		As		B		Sr		Ba	
	DS[a]	WS[b]	DS	WS	DS	WS	DS	WS	DS	WS	DS	WS	D	WS
T1	5.54	0.00	0.00	0.00	0.06	0.00	0.00	0.00	11.20	9.09	7.97	9.41	0.00	0.00
T2	0.00	0.00	0.00	0.22	0.02	0.00	0.00	0.00	7.00	0.00	14.50	11.33	0.00	0.00
T3	22.81	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	23.29	18.88	0.00	0.00
T4	62.80	0.00	0.00	0.00	0.03	0.00	0.00	0.00	11.10	0.00	23.01	26.78	0.00	0.00
T5	2.31	0.00	0.00	0.03	0.00	0.00	0.02	0.00	21.95	0.00	26.86	25.59	0.00	0.00
T6	0.00	0.00	0.00	0.02	0.00	0.00	1.40	0.00	3.43	0.00	240.01	0.00	201.91	0.00
T7	2.20	0.00	0.00	0.10	0.00	0.00	0.00	0.00	1.30	0.00	5.05	4.10	0.00	0.00
T8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.43	0.00	10.82	5.64	0.00	0.00
T9	15.58	0.00	0.00	0.00	0.00	0.00	0.05	0.00	8.43	0.00	14.97	9.22	0.00	0.00
T10	5.79	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.97	4.17	0.00	0.00
T11	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.43	75.59	45.85	12.57	9.36	0.00	0.00
T12	4.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.76	0.00	1.56	4.64	0.00	0.00
T13	0.00	6.459335	0.00	0.00	0.00	0.00	0.00	0.00	1.20	0.00	12.67	34.76	0.00	0.00
T14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.40	2.07	13.32	12.39	0.00	0.00
T15	3.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.11	0.00	21.57	6.34	0.00	0.00
T16	108.30	0.00	0.00	0.02	0.00	0.00	0.00	0.00	17.51	0.00	53.02	18.71	0.00	37.11
T17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.08	0.00	40.66	23.07	0.00	0.00
T18	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	34.70	87.91	11.58	0.00	0.00
T19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.59	0.00	11.09	4.42	0.00	0.00
T20	2.52	0.00	0.00	0.03	0.00	0.00	0.00	0.00	37.79	16.11	18.65	14.21	0.00	0.00
Mean	11.79	0.32	0.00	0.02	0.01	0.00	0.07	0.02	12.54	5.39	32.32	12.73	10.10	1.86
Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.56	0.00	0.00	0.00
Max	108.3	6.45	0.00	0.22	0.1	0.00	1.4	0.43	75.59	45.85	240.01	34.76	201.91	37.11
St. dev	26.92	1.44	0.00	0.05	0.03	0.00	0.31	0.10	17.46	12.71	52.72	9.19	45.15	8.30

[a]Dry Season, [b]Wet Season

The concentration of strontium during the dry season ranged from 1.56 to 240.01 ppb with mean concentration of 32.32 ppb. The concentrations during the wet season ranged from zero to 34.76 ppb with mean concentration of 12.73 ppb.

The concentration of barium ranged from zero to 201.91 ppb during the dry season and zero to 37.11 ppb during the wet season. The mean concentrations were 10.10 and 1.86 ppb during the dry and the wet season, respectively. These concentrations are all within the maximum concentration limit of 0.7 mg/L set by KEBS and the guideline value 1.3 mg/L set by the WHO [20], [28]. The primary source of barium in groundwater is leaching from barium compounds in ore deposits and rocks [20].

Concentration of anions: The concentrations of anions in borehole waters are shown in **Table 5**. The concentration of nitrate ranged from 0.186 to 2.831 mg/L during the dry season and 1.012 to 19.555 mg/L during the wet season. The concentration of nitrate is significantly higher during the wet season than the dry season in almost all boreholes. The higher nitrate concentrations during the wet season can be attributed to several factors including leaching of nitrate from agricultural fields, surface run-off into unprotected wells, sub-surface drainage into improperly cased wells and seepage of nitrate from latrines located close to boreholes.

The concentration of nitrate in all boreholes was within the WHO maximum acceptable limit of 50 mg/L for NO_3^- in portable water [20]. The water therefore does not pose adverse health effects (e.g. methaemoglobinaemia) associated with acute nitrate toxicity [20]. However, the concentration of nitrate in several wells during the dry season was within the range that has been shown to cause chronic health effects including colorectal, ovarian, thyroid, kidney and bladder cancers [36].

The concentration of orthophosphate during the dry season ranged from 0.041 to 0.150 mg/L with a mean concentration of 0.057 mg/L. During the wet season, the concentration ranged from zero to 0.139 mg/L with a mean concentration of 0.029 mg/L. These concentrations are significantly lower than the 2.2 mg/L maximum concentration permissible in natural portable water in Kenya [28]. Thus, the concentration of PO_4^{3-} in the groundwater does not pose any health or environmental problems.

The concentrations of PO_4^{3-} in almost all samples were significantly lower during the wet season. This suggests that surface run-off and leachate from soils containing phosphatic fertilizers or manure was not the major source of orthophosphate in the groundwater. The orthophosphate in these volcanic soils can be immobilized and retained by several processes including precipitation or co-precipitation by multivalent cations (e.g. Ca^{2+}) and adsorption by iron oxide minerals [37, 38]. Thus, the background concentration of orthophosphate in the groundwater can be attributed to dissolution of phosphate-containing minerals in aquifer sediments. The concentration of orthophosphate in aquifers decreases as the pH of the groundwater decreases due to enhanced adsorption and retention by iron oxide minerals in the sediments under acidic conditions [37, 38]. The lower concentrations of PO_4^{3-} ions during the dry season are therefore consistent with the higher acidity of the groundwater during this period.

The concentration of sulphate during the dry season ranged from 0.162 to 10.154 mg/L with mean concentration of 2.914 mg/L. Moreover, the concentration was between zero and 14.335 mg/L with mean concentration of 2.072 mg/L during the wet season. The concentration of sulphate in all boreholes was significantly lower than the maximum permissible concentration of 400 mg/L in natural potable water set by the Kenya Bureau of Standards [28]. The presence of sulphate ions in drinking water in concentrations greater than 250 mg/L causes objectionable taste [20]. In addition, concentrations of 1000-1200 mg/L can cause a laxative effect [20].

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Table 5: Concentration of anions in borehole waters

Site	Concentration of Anions (mg/L)							
	Nitrate (NO_3^-)		Phosphate (PO_4^{3-})		Sulphate (SO_4^{2-})		Chloride (Cl^-)	
	DS[a]	WS[b]	DS	WS	DS	WS	DS	WS
T1	2.831	5.141	0.045	0.000	0.8887	0.370	0.720	1.000
T2	1.013	9.525	0.044	0.000	2.422	0.290	0.680	1.100
T3	0.299	3.412	0.068	0.050	7.019	0.230	0.640	1.000
T4	1.206	9.919	0.049	0.005	0.162	0.433	0.700	1.000
T5	1.396	10.855	0.049	0.004	0.218	0.407	0.720	1.100
T6	1.237	1.012	0.050	0.000	10.154	0.294	0.820	0.900
T7	0.754	5.521	0.043	0.000	0.918	0.094	0.840	1.050
T8	0.186	4.861	0.058	0.075	0.840	0.030	0.680	1.050
T9	0.571	4.714	0.062	0.112	2.428	0.019	0.680	1.650
T10	0.206	2.523	0.050	0.012	1.932	0.000	0.680	0.850
T11	0.306	2.422	0.150	0.139	8.339	14.335	1.240	1.750
T12	0.194	1.290	0.041	0.000	0.378	0.000	0.700	1.250
T13	0.196	1.152	0.043	0.018	0.362	0.000	0.660	1.250
T14	0.311	1.264	0.045	0.000	0.189	0.000	0.660	1.250
T15	0.347	2.427	0.043	0.000	0.278	3.000	0.680	1.000
T16	1.171	17.315	0.091	0.000	3.080	0.000	0.700	1.100
T17	1.954	19.555	0.043	0.000	0.3075	0.000	0.640	1.050
T18	0.418	4.378	0.052	0.020	9.101	12.906	0.660	0.950
T19	0.258	2.468	0.056	0.045	3.936	5.415	0.620	1.250
T20	1.026	3.578	0.056	0.090	5.332	3.615	0.740	1.150
Mean	0.794	5.667	0.057	0.029	2.914	2.072	0.723	1.135
Min	0.186	1.012	0.041	0.000	0.162	0.000	0.620	0.850
Max	2.831	19.555	0.150	0.139	10.154	14.335	1.240	1.750
St. dev	0.699	5.247	0.025	0.043	3.298	4.220	0.723	0.225

[a]Dry Season; [b]Wet Season

The concentrations of sulphate in groundwater in the study area do not pose any aesthetic or health hazards. The concentration of sulphate ions in groundwater during the wet season was significantly lower than corresponding concentrations during the dry season presumably due to dilution by external water that is abundant during this season. The lower concentration during the wet season suggests that the sulphate in groundwater is not anthropogenic but is derived from sulphate bearing minerals in the aquifers [20].

The concentration of chloride in the groundwater samples ranged from 0.620 to 1.240 mg/L during the dry season and 0.850 to 1.750 mg/L during the wet season. The mean concentrations were 0.723 and 1.135 mg/L during the dry and the wet season, respectively. These concentrations are very low compared the maximum permissible concentration of 250 mg/L set by the Kenya Bureau of Standards [28]. The concentrations are also significantly lower than the 200-300 mg/L taste thresholds for the chloride anion [20]. The concentrations of chloride in groundwater in the study area therefore do not pose any aesthetic or health hazards. The concentrations of chloride is considerably higher during the wet season. This suggests that agricultural run-off or leaching from soils is a possible source of chloride in addition to dissolution of chloride containing minerals.

CONCLUSIONS

The water is most boreholes in Chuka Sub-County meet the permissible maximum limits set the WHO and KEBS for portable water. Therefore, the water in most boreholes is generally safe for human consumption and shows minimal contamination from anthropogenic sources, especially during the dry season. However, nitrates levels are higher during the wet season suggesting contamination from agricultural run-off during the wet season. The concentrations of nitrate in several boreholes is at levels that can cause chronic health effects. In addition, water in some boreholes is highly acidic, which increases the risk of geogenic contamination through dissolution of minerals from rocks.

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