



Characterisation and quality assessment of surface and groundwater in and around Lake Bosumtwi impact craton (Ghana)

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Abstract

Conventional graphical methods have been used to classify water in Lake Bosumtwi and groundwater around the lake. The study also assessed the suitability of these water resources for agricultural use. Results indicate slightly acidic, moderately hard to very hard groundwater with alkaline earth concentrations exceeding alkali metals. In contrast, the lake water is alkaline, showing alkalis in excess over alkaline earth metals. Weak acids exceed strong acids in both lake/groundwater. Rock weathering largely controls groundwater and lake water chemical compositions, resulting mainly in Ca–Mg–HCO₃ groundwater and Na–HCO₃ lake water types. Thus, suggesting that there is no apparent incipient relationship, which benefits the primary aquifer system in terms of recharge. Water quality indices suggest groundwater of good to excellent quality for human consumption and other domestic use. An evaluation of lake/groundwater based on salinity, sodicity and bicarbonate hazard reveals that the groundwater is generally suitable for irrigation while the lake water is not suitable for irrigation. However, the lake water may be used in generous amounts on highly permeable soils and salt-tolerant crops under special soil and water management practices.

Keywords Lake Bosumtwi · Water quality · Irrigation · Birimian

Introduction

The use of hydrochemical datasets in hydrological and hydrogeological studies to characterise water resources, establish hydrological relationships and track hydrological processes is conventional. For instance, researchers have utilized such datasets in characterising the hydrogeology of watersheds, trace groundwater flow paths in aquifers (Flusche et al. 2005; Rouabhia et al. 2009; Busico et al. 2018; Asante and Kremer 2018; Yidana et al. 2018) and to evaluate water quality (Milovanovic 2007; Yidana et al. 2008; Anku et al. 2009; Egbi et al. 2018; Rotiroti et al.

2019). The approach is based on the fact that certain chemical characteristics of water bodies are essential indications of the water sources and evolution processes in transit. Careful analyses of the variations in such parameters in light of the underlying lithology, vegetation, and climatic conditions provide very useful leads to groundwater evolutionary trends. Through this methodology, distinct groundwater flow paths have been defined to help conceptualise hydrological systems and processes (Schilling et al. 2006; Kumar and James 2019; Ballesteros-Navarro et al. 2019).

Lake Bosumtwi has attracted international attention due to its scientific value. Much of the research in the area has been focused on establishing its origin and evolution through time (Jones 1985; Koeberl et al. 2007a, b; Loh et al. 2016). Although the people living around the lake have depended on groundwater for their drinking and domestic uses over the years, very little work has been done regarding the quality of groundwater resources within the area. However, the lake has seen gradual depletion (Adu-Boahen et al. 2015) and some deterioration due to the use of agrochemicals by the fisher folks (Mensah et al. 2018) and indiscriminate discharge of domestic effluents. The effect of these indiscriminate discharge of effluents is being felt as there has been a

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decline in fish catch and delay of the peak season (Mensah et al. 2018). Growing concerns over the reduction in the fish catch of the Lake Bosumtwi has also been attributed to climate change (Russell et al. 2003; Mensah et al. 2018).

Various researchers (e.g. Milovanovic 2007; Yidana et al. 2008; Anku et al. 2009; Diaconu et al. 2019; Kattel, 2019) concur that water of good quality is essential for good health, ecosystems, economic development and social prosperity. Previous studies on the water resources within the basin focused on the hydrology and geochemistry of the lake and streams (McGregor 1937; Turner et al. 1996a, b). In recent times, Adu et al. (2011) assessed the water quality, emphasising on the radionuclide concentrations of the lake and the groundwater resources. A study on the physical and chemical properties of the lake water and groundwater resources in the area cannot be overemphasized. The Government of Ghana in its quest to reduce the country's steaming unemployment and increase the food basket to meet the demand of the growing population has initiated a flagship program of planting for food and jobs. This initiative will not only require water in high quantity but will equally need good quality water for year irrigation and improved crop yields. The realization and sustainability of this initiative and the Sustainable Development Goals; 1, 2, 3, 4 and 6 depend on the proper characterisation and assessment of the groundwater resources in the wake of global climate change and dwindling surface water resources to augment the rain-fed agriculture in the study area. This study is in such an endeavour.

In this paper, the physico-chemical parameters of lake and groundwater samples will be studied to classify these water resources into hydrochemical facies and determine their suitability for various uses. The groundwater's physical and chemical characteristics will be evaluated in terms of the water quality index (WQI) to determine its suitability for drinking and other domestic uses. This index is very useful in communicating to consumers and policymakers on the quality of drinking water and serves as an essential parameter in assessing and managing drinking water. As many countries, including Ghana, are moving away from rain-fed peasant farming to more mechanized irrigated commercial farming to meet the global demand for food, the study will also assess both lake and Groundwater suitability for irrigation use. Finally, since groundwater moves with very low velocities, degradation in quality may take a considerable length of time to notice, and with the current trend of human activities within the area, it is envisaged that the quality of the water resources could be compromised.

Thus, this research will establish background conditions (pristine or anthropogenically altered) on the quality of lake and groundwater resources within the basin needed by policymakers to make more informed water policy decisions.

The study area

Location

The study area is a well-preserved impact crater (Fig. 1) located about 32 km southeast of Kumasi, the capital of the Ashanti Region of Ghana. The crater is filled by Lake Bosumtwi and lies within latitude $06^{\circ}32'00''$ N and longitude $01^{\circ}25'00''$ W. Various authors have copiously described the physical structure of the crater (e.g. Jones et al. 1981; Reimold et al. 1998; Karp et al. 2002). The rim of the lake stands up to 300 m above present lake level. The irregularly circular shaped depression around the impact craton makes it a hydrologically closed basin with a rim-to-rim diameter of 10.5 km, as well as an outer ring of minor topographic highs with a diameter of about 20 km (Jones et al. 1981; Reimold et al. 1998). The inhabitants in and around the lake have always relied on fish catch from the lake as their primary source of livelihood until the fortunes in fishing started declining due to mass deaths of the fish (Turner et al. 1996) and overfishing from a growing population (Prakash et al. 2005). Consequently, many indigenes have resorted to the cultivation of various food crops for survival. Again, their dependence on local eco-tourism on the lake has seen many uncoordinated developments in the area.

Climate, vegetation and hydrology

The area is characterised by a tropical rain forest environment which has double maxima rainfall pattern. The rainfall amount is between 1600 and 1800 mm. The major rainfall season spans March to July, peaking in June, whereas the second season starts from September to November and peaks in October. Temperatures are relatively high and uniform, ranging from 32°C in March and 20°C in August with relative humidity in the range of 70% and 80% (Turner et al. 1996; Adu-Boahen et al. 2015; Adom 2018). Due to extensive and repeated farming, illegal mining and lumbering, the original vegetation cover of semi-deciduous and rain-forest have been degraded to a mosaic of secondary forest. Even though the drainage pattern of Bosumtwi District is dendritic, there is internal drainage around the lake, where the streams flow from surrounding highlands into the lake, forming a dense network due to the double maxima rainfall regime.

Geology and hydrogeology

The area is underlain by rocks of the Birimian Supergroup comprising Birimian metasediments and metavolcanics (Kesse 1985) of early Proterozoic age (Fig. 2). These rocks

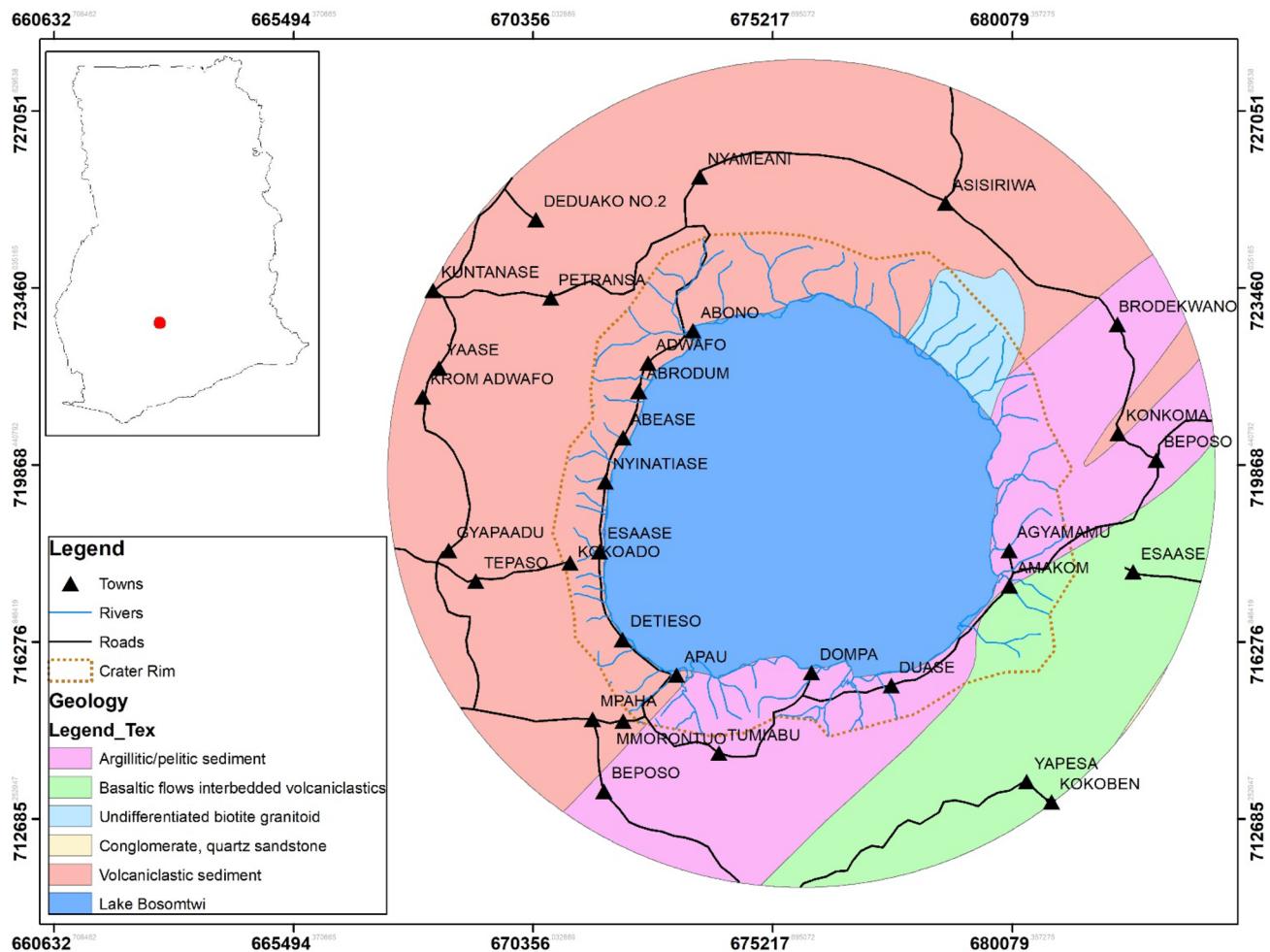


Fig. 1 Study area map showing location of communities

have been extensively studied by various workers (Leube et al. 1990; Hirdes et al. 1992) since most of Ghana's mineral deposits (e.g. gold and diamond) are located in them. These rocks have been folded, metamorphosed under greenschist-facies conditions, and intruded by various generations of granitoids during the ca 2.1 Ga Eburnean orogenic event. At the northern sector of the study area, rock types ranging from hornblende-to-biotite–muscovite granite and dolerite (Koeberl et al. 1998) are seen occurring. However, just around the lake, the geology consists of meta-sandstones, shales, phyllites and schist (Leube et al. 1990; Hirdes et al. 1992). These metasediments are rich in quartz, feldspars (plagioclase and alkali feldspars) and micas (biotite, muscovite).

Detailed petrographical, mineralogical and geochemical studies on the lithologies of the Bosomtwi structure have been comprehensively discussed by various researchers (e.g. Koeberl et al. 1997, 1998; Reimold et al. 1998; Boamah and Koeberl, 2002; Karikari et al. 2007). Various accessory minerals in these rocks include carbonates, Fe-oxides,

secondary sericite and chlorite and some opaque minerals, notably sulfides (Karikari et al. 2007).

The study area falls within the Birimian hydrogeological Province (Banoeng-Yakubo et al. 2011). Groundwater occurrence and movement in aquifers of this province are associated by secondary porosity and permeability in the rocks, which were created in the wake of the Eburnean orogenic event some 2.1 Ga ago (Kesse 1985) and impact cratering (Reimold et al. 1998). Detailed hydrogeological characteristics of the rocks in the area have been copiously documented (Loh et al. 2016). The rocks, especially the micaceous and feldspathic schists, usually weather to clays, which reduce the permeability. Geophysical (resistivity) studies for groundwater prospection in the region and well logs from boreholes and wells collated from consultants in the study area indicate that the stratigraphy of the aquifer is made up of three layers. These comprise upper, intermediate and lower layers of humic or lateritic soils, highly weathered rocks and moderately weathered to fractured fresh rocks, respectively.

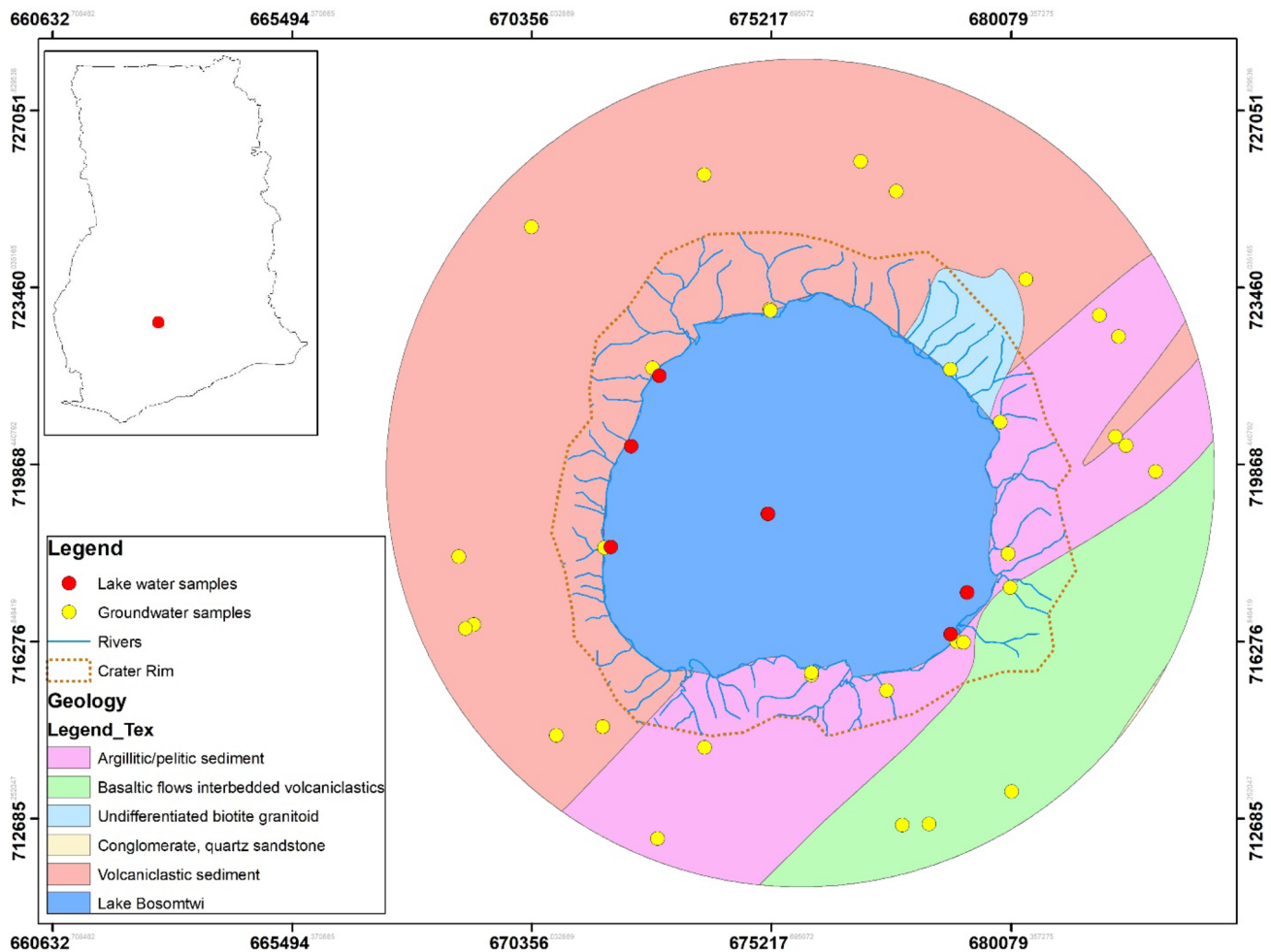


Fig. 2 Geological map of the study area showing sample points

Borehole depths in the area are in the range of 26–64 m, with an average of 43 m. The depth to the water level in the area varies between 3 to 43 m below ground level. Borehole yields observed in the area are dependent on the topographic setup, lithology and degree of weathering and range between 0.6 m³/h and about 9.0 m³/h with specific capacities in the range of 0.027–18.18 m³/h/m (Banoeng-Yakubo 2010).

Materials and methods

Standard water sampling protocol was followed to collect 41 representative water samples comprising 34 groundwater and 7 lake water (Fig. 2) for laboratory analyses. The samples were filtered through a 0.45 µm cellulose acetate membrane into two 50-ml sterilized polypropylene tubes, one of which was acidified with pure nitric acid (HNO₃) to pH < 2 for cations and trace element analyses, while the other unacidified filtered samples were used for anion

analysis. Acidification was necessary to restrict bacterial action, block oxidation reactions, and prevent adsorption or precipitation of cations (Chapman 1996). The sample bottles were rinsed with distilled water and later with portions of the filtrate before they were filled. Collected samples were tightly capped and sealed with an electric insulating tape and were labelled with unique sample IDs. The samples were then stored in iceboxes. A hand-held Garmin-eTrex Vista HCx global positioning system (GPS) was used to take the coordinates (latitude and longitude) and elevations of sample locations. Physical parameters such as electrical conductivity (EC), total dissolved solids (TDS), salinity (Sal), water temperature (T), pH, oxidation–reduction potential (ORP), and dissolved oxygen (DO) were measured in situ with an HI 98,280 GPS Multiparameter Meter manufactured by HANNA Instruments. The alkalinity (Alk) (as HCO₃⁻) was measured with the Hatch digital titrator in the field. A water sample location map showing the spatial distribution of sample points was generated from the GPS locations using

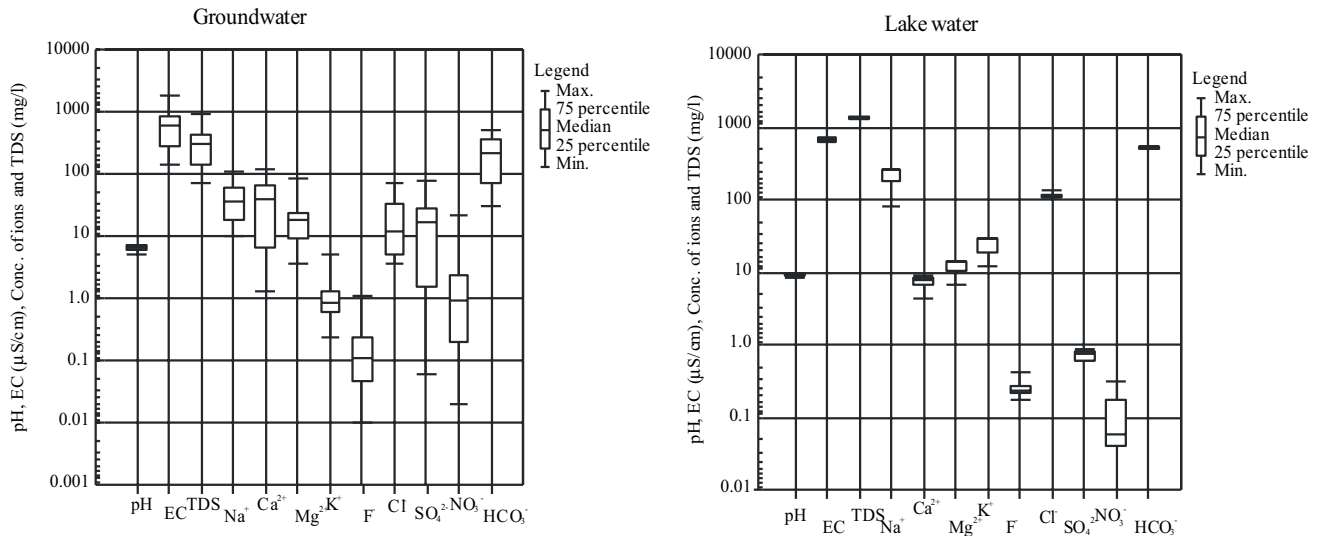


Fig. 3 Boxplot of physical and chemical parameters for the various water samples

ArcGIS ArcMap10 software (Fig. 3). The samples were analysed at Activation Laboratories Ltd in Canada. Major cations and trace elements were analysed by an Inductively Coupled Plasma- Mass Spectrometer (ICP-MS). Samples that had concentrations above the detection limit (i.e. > 25 ppm of Na, K, and Sr; and > 100 ppm of Ca, Mg and Si) of the ICP-MS were reanalysed by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) in milligram per liter (mg/l). Using Dionex DX 120 Ion Chromatograph (I.C), anions including Chloride (Cl^-), sulfate (SO_4^{2-}), and nitrate (NO_3^-), fluoride (F), nitrite (NO_2^-), and phosphate (PO_4^{3-}) in milligram per liter ((mg/l) were analysed. Charge Balance Error (CBE) was calculated to check the accuracy of the laboratory (analytical) results was generally within $\pm 10\%$ based on ions expressed in meq/l (Appelo and Postma 2005). Even though the global standard limit is 5%, Ghana standards Authority guidelines accept limit within $\pm 10\%$.

Various statistical methods have been applied to the data set using SPSS, Microsoft Excel and other software with statistical packages to assess the variables independently and determine the relationships between variable pairs. In addition, conventional graphs and spatial distribution maps have been made to aid interpretation. These spatial distribution maps were made by fitting an optimal variogram model for the obtained EC and estimated water quality index (WQI). Rigorous cross validation was conducted for different models. Variogram parameters were constantly adjusted until all criteria for an optimal model was achieved. The spherical model proved to be the best model predictor for the obtained EC and estimated WQI for the study area.

Water Quality Index (WQI) provides a single value that is used to express the overall groundwater quality at a specific location and time based on certain essential water

quality parameters. This method has been employed by many researchers with the objective of turning complex water parameters such as the pH, TDS, Na^+ , Ca^{2+} , Mg^{2+} , Cl^- , SO_4^{2-} , NO_3^- , F^- , Fe, As, Mn, Cu, Zn, Pb, Ni and Cd were considered in calculating the WQI in three steps. In the first step, each of these physical and chemical parameters was assigned a weight (w_i) based on their perceived effect on primary health, with the highest weight of 5 assigned to parameters such as Pb, NO_3^- and F^- that are considered to have significant effects on water quality for drinking purposes. The weight (w_i) assigned to all other parameters used in this study is shown in Table 1. It is important to note that the index is subjective as it depends on the parameters chosen and their weights assigned by the researcher. The second step computes the relative weight (W_i) for each parameter as contained in (Eq. 1).

$$W_i = \frac{w_i}{\sum w_i}, \quad (1)$$

w_i the weight of each parameter, and $\sum w_i$ the sum of the weight of all parameters.

Table 1 presents the w_i , W_i and WHO guideline values for each chemical parameter used in this study. The third and final step then computes a rating scale q_i , for each parameter using the following equation:

$$q_i = \frac{C_i}{S_i} \times 100, \quad (2)$$

C_i the concentration of each parameter and S_i WHO guideline value.

The water quality sub-index SI_i for each parameter is then computed from Eq. 3 with the overall sum (Eq. 4), giving the

Table 1 WHO guideline values, weight and relative weight of each of the chemical parameters used for the WQI determination

Parameter	WHO (S_i)	Weight (W_i)	Relative weight (W)
pH	7.5	4	0.0741
TDS	500	4	0.0741
SO	250	3	0.0556
Cl	250	3	0.0556
NO ₃	50	5	0.0926
F	1.5	5	0.0926
Ca	75	2	0.0370
Mg	30	2	0.0370
Na	200	2	0.0370
As	0.01	4	0.0741
Cd	0.003	3	0.0556
Cu	1	2	0.0370
Fe	0.3	3	0.0556
Mn	0.1	3	0.0556
Ni	0.02	2	0.0370
Pb	0.01	5	0.0926
Zn	3	2	0.0370
$\Sigma (w_i) = 54$			

WQI that reflects the composite influence of different water quality parameter.

$$SI_i = W_i \times q_i, \quad (3)$$

$$WQI = \sum_{i=1}^n SI_i. \quad (4)$$

The sodium adsorption ratio (SAR) to determine the suitability of the water for irrigation. The SAR measures the sodium hazard/sodicity in relation to calcium and magnesium concentrations as shown in the equation below (Eq. 5) (Fetter 1994):

$$SAR = \frac{(Na^+)}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}}. \quad (5)$$

Another classification scheme, Wilcox diagram, engineered by Wilcox (1955) was utilized to assess the quality of the water for irrigation. This classification scheme measures the sodium percent (Na %) defined by the following equation:

$$Na\% = \frac{(Na^+)}{Na^+ + K^+ + Ca^{2+} + Mg^{2+}} \times 100. \quad (6)$$

Results and discussion

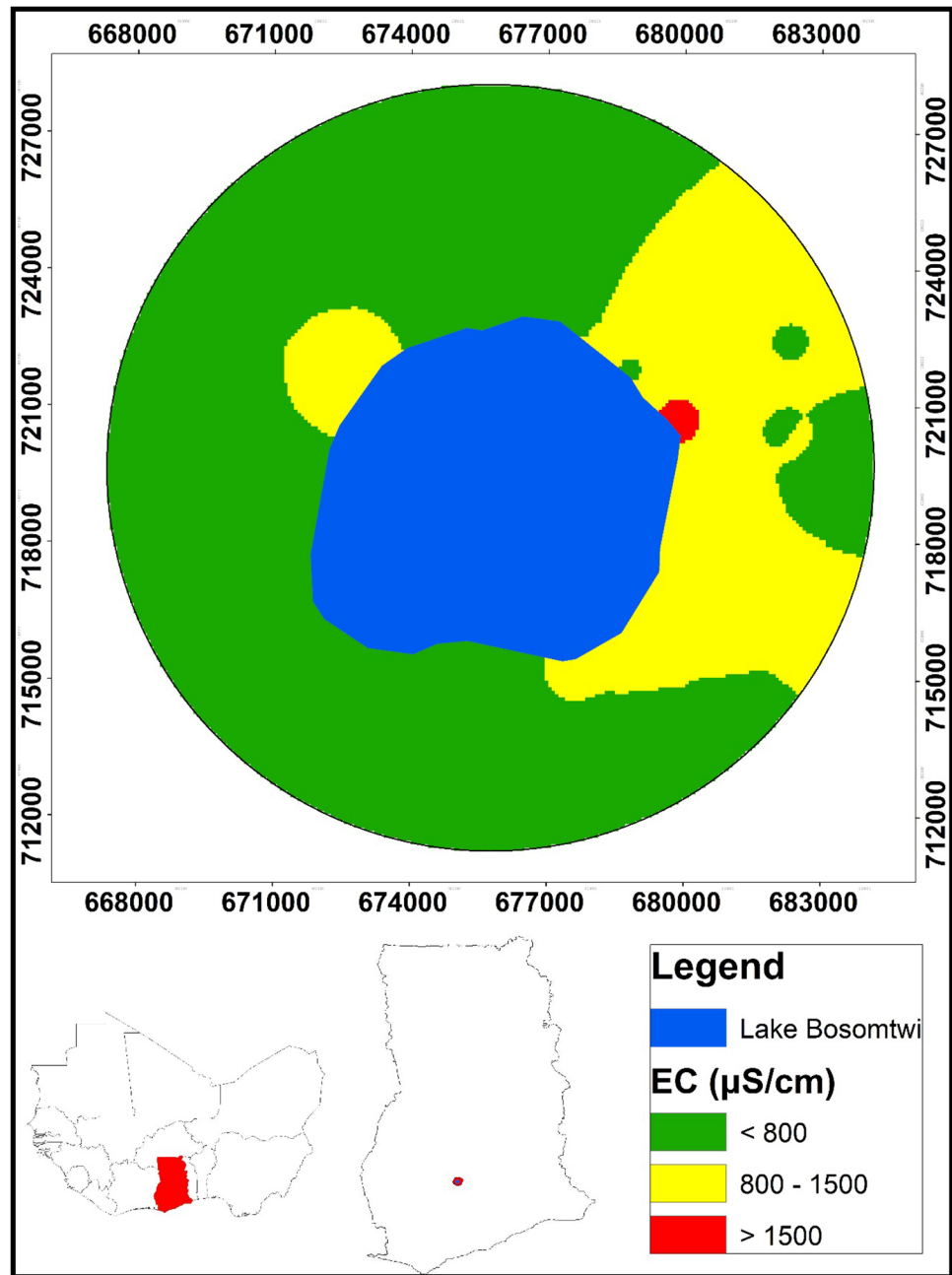
General hydrochemical distribution

Box and whisker plots of the physicochemical parameters measured in the groundwater and lake water samples of the study area are presented in Fig. 3. The mean values calculated for most measured parameters are generally within the World Health Organisation (WHO 2017) acceptable limits for drinking. A pH range of 5.08–7.25, with a mean of 6.37 classifies the groundwater as slightly acidic. It has been observed that aquifers underlying areas covered by dense tropical rainforest, high rainfall, warm climate and high organic activity are slightly acidic (Collins and Kuel 2000). The study area is characterised by heavy rainfall (1600–1800 per annum), giving rise to typical dense tropical rainforest. The decomposition of organic matter to carbon dioxide and carbonic acids diminishes alkalinity and this get to the groundwater reservoir through recharge mechanisms. This may have given the groundwater in the area its slightly acidic nature. On the other hand, the lake water is alkaline, with a mean pH value of 8.86.

The electrical conductivity (EC) values of groundwater from the area are generally low, ranging from 138 $\mu\text{S}/\text{cm}$ to 1746 $\mu\text{S}/\text{cm}$ with a mean of 623 $\mu\text{S}/\text{cm}$. This suggests diluted or slightly mineralised groundwater. The groundwater of this nature is usually pristine and has a shorter residence time (Freeze and Cherry 1979). From the spatial EC map (Fig. 4), most part of the study area has EC values less than 800 $\mu\text{S}/\text{cm}$ while a portion of the eastern part has EC values ranging from 800 to 1500 $\mu\text{S}/\text{cm}$. Also, just around the lake EC value greater than 1500 $\mu\text{S}/\text{cm}$ is seen. Even though WHO guidelines stipulate EC value of 1500 $\mu\text{S}/\text{cm}$ as acceptable for drinking, the indigenes preferred drinking water from the boreholes with EC values below 800 $\mu\text{S}/\text{cm}$ and mostly avoided. The groundwater with EC values greater than 800 $\mu\text{S}/\text{cm}$. The areas with EC values greater than 800 $\mu\text{S}/\text{cm}$ were low-lying areas with average elevation of 163 masl. These EC values could possibly be as a result of prolong water–rock interaction, and thus increase the mineral content of the groundwater in those areas.

The lake water, on the other hand, has a mean EC value of 1313.29 $\mu\text{S}/\text{cm}$. The lake water's high EC values may be due to indiscriminate discharge of wastewater into the lake, as observed during the field campaigns. The ion concentration percent frequency diagrams (Fig. 5) are useful in defining the relative concentration of cations or anions as percentages of total cations and anions, respectively (Kortatsi, 2006). Results of the analyses (Fig. 5) show that sodium, calcium and magnesium ions are fairly represented, and no cation dominates in the Groundwater except in a few

Fig. 4 Spatial distribution of electrical conductivity (EC) for the groundwater samples



cases where these cations extend to the zone of dominance (i.e., % meq/l > 50). Among the major cations, however, Na^+ , on the average amounts to about 37% in abundance, followed by Ca^{2+} which is approximately 32% with Mg^{2+} and K^+ , respectively, representing 30% and 1% of the total cations. Bicarbonate (HCO_3^-) ions, among the major anions, constitute about 78% of total anions followed by Cl^- ions, (14%) with SO_4^{2-} ions representing 7%. On the other hand, Na^+ contributes as much as 82% of total cations with Mg^{2+} , K^+ and Ca^{2+} , respectively, representing 9%, 6% and 3% in the lake while HCO_3^- and Cl^- , dominate the major anions with relative percentage contribution of about 73% and

27% respectively of total anions in the lake. The order of relative abundance of major cations in the groundwater samples is $\text{Na}^+ > \text{Mg}^{2+} > \text{Ca}^{2+}$ while that of the anions is $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-} > \text{NO}_3^-$ thus, bicarbonates of calcium, magnesium and sodium generally dominate the groundwater and lake. The trace elements measured in both the groundwater and the lake were below the WHO guideline limits for such elements and therefore was not considered for further analysis. However, nickel, iron and manganese showed elevated concentrations in some of the boreholes. The areas with these elevated ionic concentrations are underlain by mafic volcanic rocks in the study area (Fig. 2).

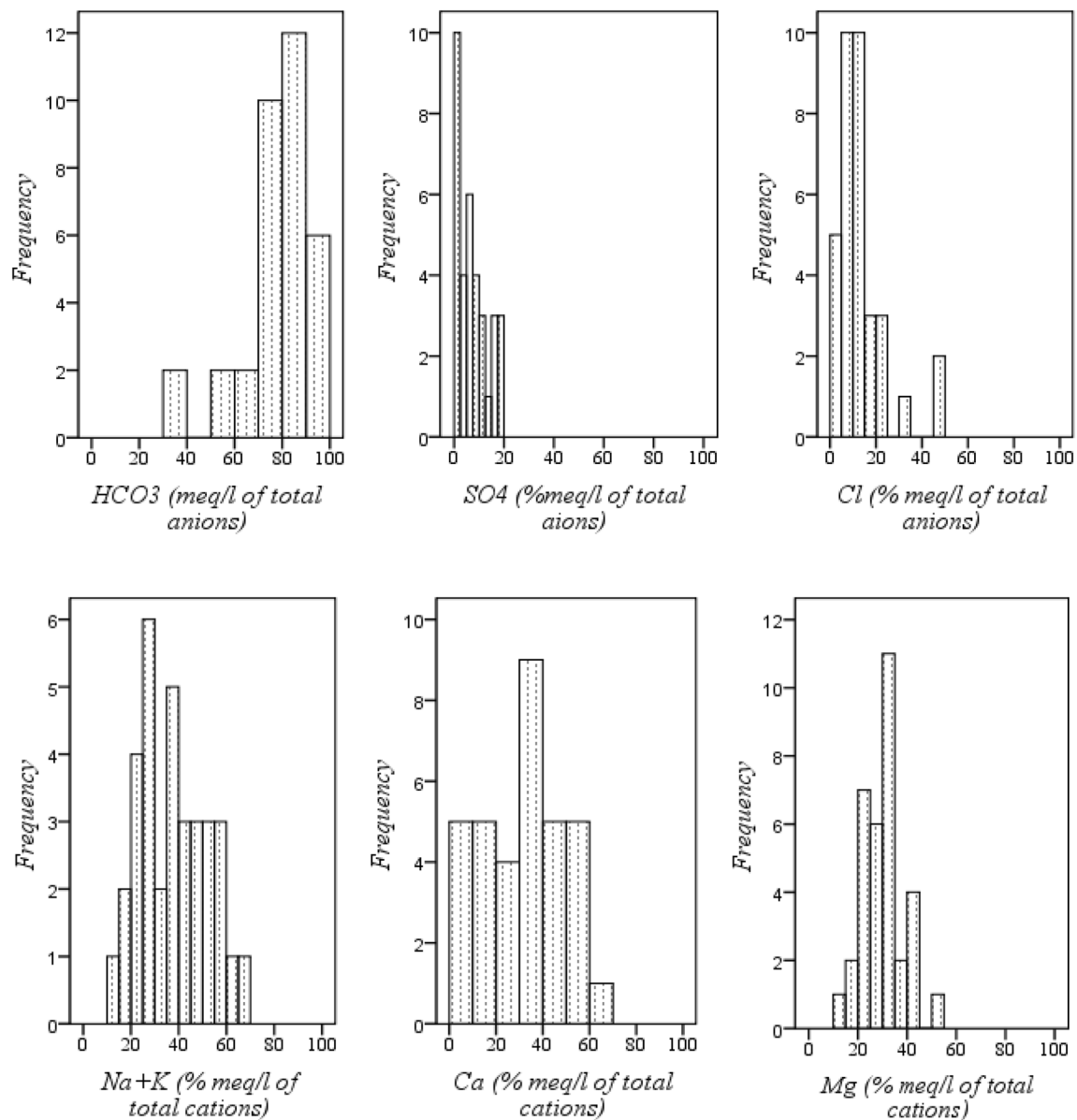


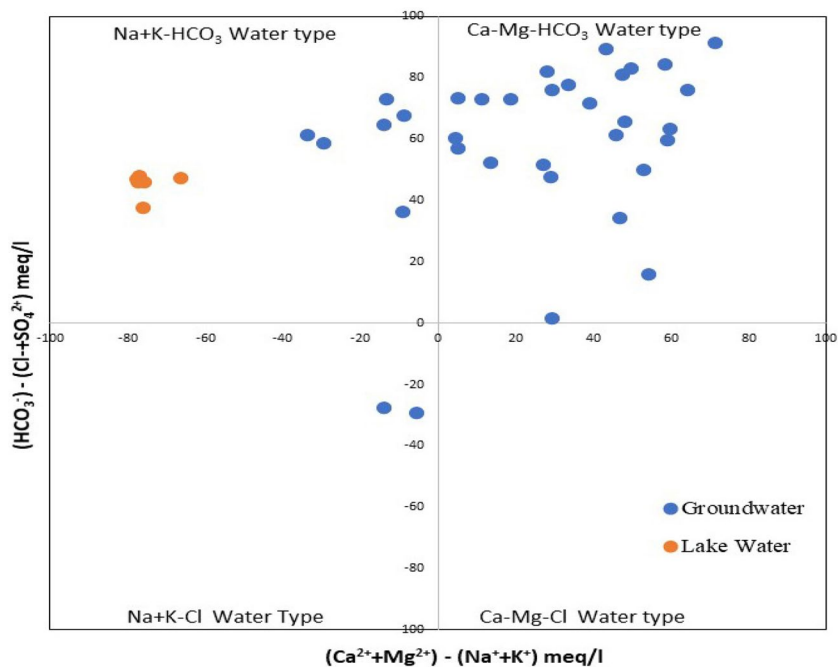
Fig. 5: Percentage frequency distribution of the major ion concentrations in the groundwater samples

Hydrochemical facies

The Chadha diagram (Chadha 1999) (Fig. 6) was used to classify the overall chemical characteristic of the groundwater and used to conceptualize the possible relationship between the lake water and groundwater. Figure 6 shows that about 76% of groundwater samples have alkaline earth metals ($\text{Ca}^{2+} + \text{Mg}^{2+}$) exceeding alkali ($\text{Na}^+ + \text{K}^+$) metals. The remaining 24% of groundwater samples and all the lake water samples show an excess of alkali metals over the alkaline earth metals. Almost all the water samples except two (2) groundwater samples located at Timeabu (HW001) and Beposo (GW041) have weak acid (HCO_3^-) over the strong

acids ($\text{SO}_4^{2-} + \text{Cl}^-$). The overall enrichment of the groundwater with bicarbonate relative to chloride or sulphate may be attributed to recharge by rainwater. Bicarbonate ion concentration in groundwater generally results when silicate minerals weather in the presence of a weak carbonic acid obtained from rainwater (Appelo and Postma 2005; White & Brantley 2018; Cronan 2018). The hydrochemical processes that control the major ions concentration of the lake and groundwater in the area have been copiously discussed by Loh et al. (2016). A majority (~76%) of the groundwater samples are characteristically of Ca–Mg– HCO_3 water types. The remaining groundwater samples plot in fields defined by the Na–K– HCO_3 , and Na–K–Cl (Fig. 6), representing 18%

Fig. 6: Chadha diagram showing the hydrochemical facies of the study area



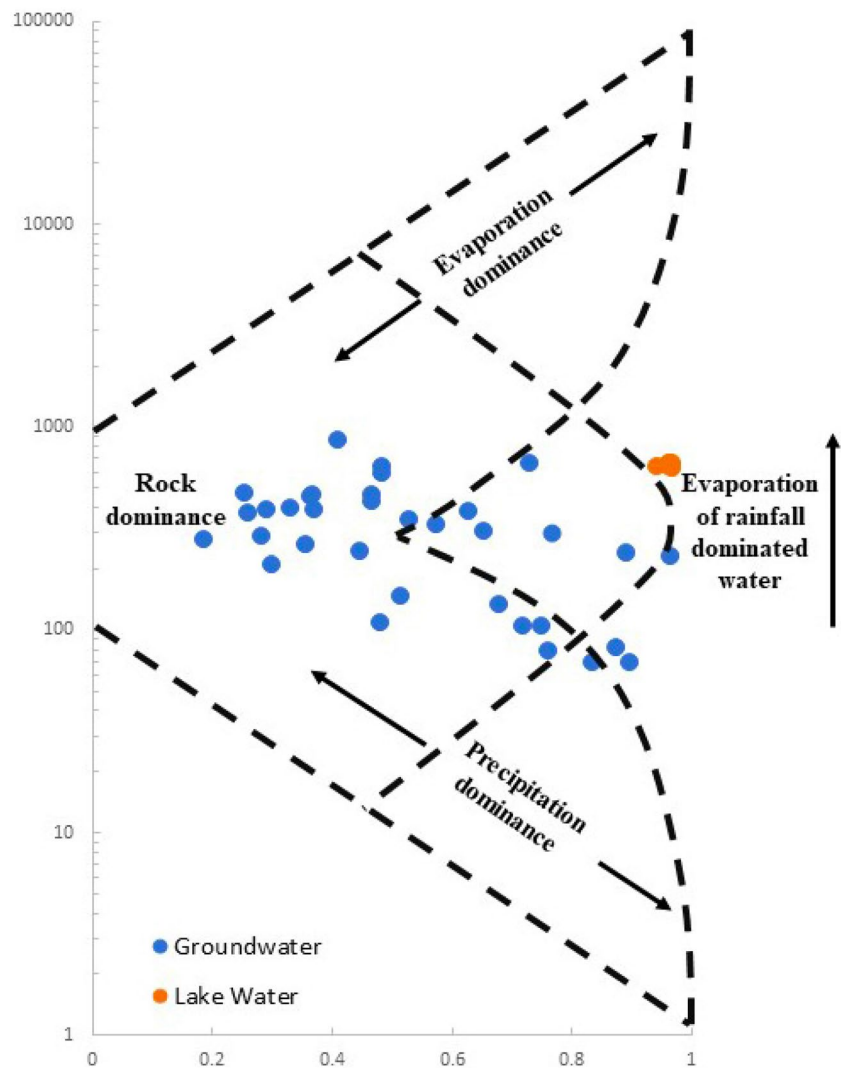
and 6%, respectively. The lake water is also characterised by Na–K–HCO₃ water type.

The Gibbs diagram (Gibbs 1970) (Fig. 7) further highlighted the evolutionary trends and the possible sources of variation in groundwater hydrochemistry in the area. The diagram is divided into regions based on a contribution from atmospheric precipitation, which is characterised by low to moderate TDS and high Na/(Na + Ca) weight ratio, rock dominance region; exemplified by moderate TDS and Na/(Na + Ca) ratio and an evaporation–crystallization region; typically, in the high TDS and Na/(Na + Ca) ratio. Any other factor influencing the hydrochemistry in an aquifer apart from these three factors mentioned above cannot be distinguished from the Gibbs diagram. Researchers (e.g., Obiefuna and Orazulike 2011; Yidana et al. 2012a; Sakyi et al. 2016; Koffi et al. 2017) have used the Gibbs diagram simultaneously with other diagrams to identify the major sources of variation in hydrochemical data. For instance, Yidana et al. (2012b) used the diagram together with hierarchical cluster analysis to distinguish anthropogenic sources from the natural sources in the variation of hydrochemistry in the aquifer underlying the Ankobra Basin.

It is evident from Fig. 7 that most of the samples in the present study plot within the rock dominance portion of the boomerang. This shows that the main mechanism influencing the hydrochemistry of the water is the interaction between the recharge water, rocks and their weathered products. These water samples are characterised by moderate TDS and Na/(Na + Ca) ratio. It is also obvious that the lake water has the fingerprint of evaporative enrichment of the major parameters due to the exposure of the lake to high ambient

temperatures and low humidity, which encourage surface evaporation. However, the dilution effects of inflowing rainwater (and possibly groundwater) tend to mask the effects of evaporation such that the total dissolved contents are not so high. It is also apparent that due to the high residence time of much of the water in the lake, silicate mineral weathering processes have contributed significantly to the hydrochemistry of the lake. Banoeng-Yakubo (2000) asserts that weathering of the Birimian rocks has resulted in forming a thick regolith that constitutes the most common type of aquifer in the area. Studies on the geochemistry of soils around the crater (Boamah and Koeberl 2002) have indicated that rocks have reached the highest degree of weathering due to intense chemical weathering. They further stated that the soils and their parent rocks are depleted in the major ions. This suggests that the major ions in the groundwater may have been derived from the leaching of minerals and weathering of rocks underlying the area. A few of the samples that have low to moderate TDS and high Na/(Na + Ca) ratio plot along the rainfall–rock dominance side of the diagram implying Groundwater that is influenced by precipitation where the recharge process appears to be rapid and does not provide for long residence time in order for active water–rock interaction to occur. Finally, the chemistry of samples that plot outside the envelope could be influenced by evaporation of surface water and moisture in the unsaturated zone, which is influential in the development of the chemical composition of surface water bodies and shallow groundwater (Garrels and Mackenzie 1967; Balugani et al. 2017). A bivariate plot of (Ca²⁺ + Mg²⁺) and (SO₄²⁻ + HCO₃⁻) (Fig. 8) shows that both silicate and carbonate mineral weathering contribute

Fig. 7 Gibbs diagram showing the positions of the water samples in the study area



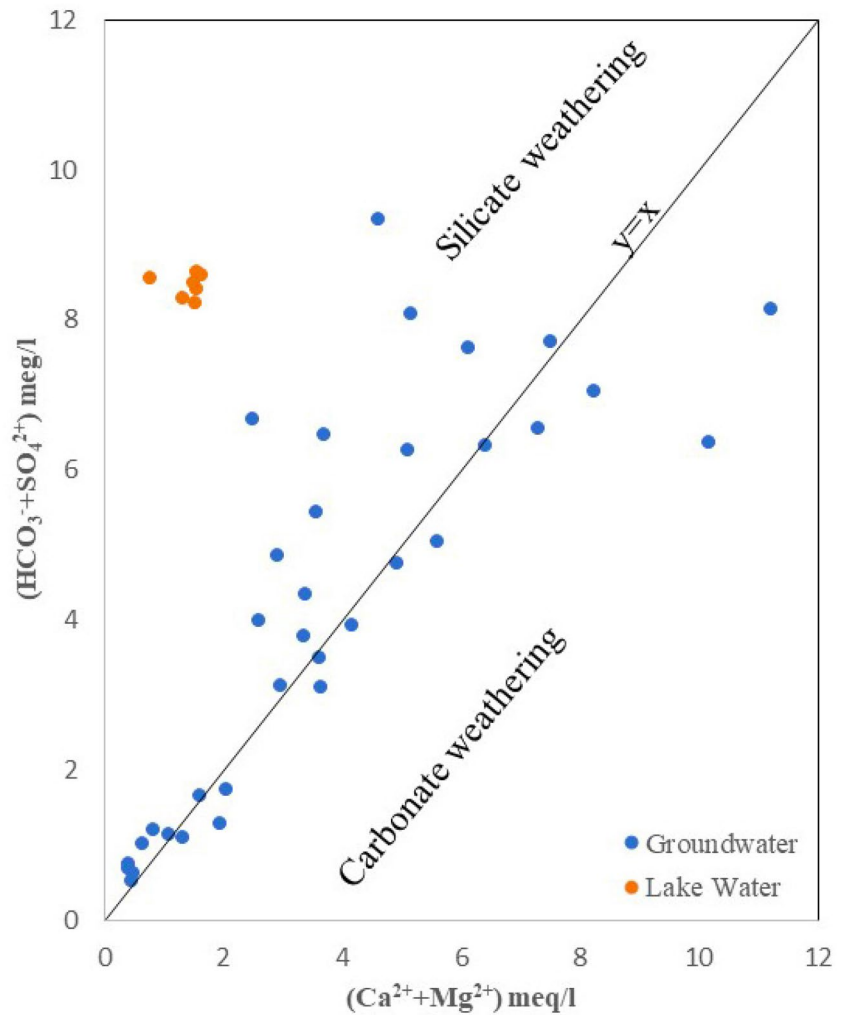
to the chemistry of Groundwater. Majority of the samples plot above the 1:1 equiline, suggesting that silicate mineral weathering is the principal hydrochemical process in the groundwater system (Boateng et al. 2016; Nematollahi et al. 2016).

Groundwater quality assessment for domestic use

An evaluation of groundwater quality based on the water quality index (WQI) has been made. The distribution of the trace elements used in calculating WQI for the groundwater from aquifers underlying the BIC and its surrounding areas is shown in the Box plot (Figs. 9 and 10). The WQI provides a single value used to express the overall groundwater quality at a specific location and time based on certain vital water quality parameters. This method has been employed by many researchers to turn a complex water quality data into information that is understandable by the general public and policymakers.

The computed WQI values are usually classified into five categories (Table 2) (Sahu and Sikdar 2008) and provide a much more global picture of the suitability of groundwater for domestic uses. The results based on this classification scheme for each sample presented in Table 3 classify groundwater samples as good to excellent for human consumption. All the major ions and some of the trace elements used in calculating the WQI have concentrations within the WHO (2017) guideline values for domestic use. However, six samples representing about 18% of the total samples show elevated Mn above 100 µg/l, the WHO's guideline value. Two of the boreholes, GW055 and GW056 located at Adaito have manganese concentration of 492 µg/l and 267 µg/l respectively. The others include GW057 (186 µg/l), GW048 (119 µg/l), GW062 (367 µg/l) and GW069 (158 µg/l) and are, respectively, located at Yapesa, Dunkura, Brodekwno No. 2 and Adumasa. The borehole located at Brodekwno No. 2 is the only borehole with nickel concentration above the WHO guideline

Fig. 8 Scatter plot of $(\text{SO}_4^{2-} + \text{HCO}_3^-)$ versus $(\text{Ca}^{2+} + \text{Mg}^{2+})$ for the samples

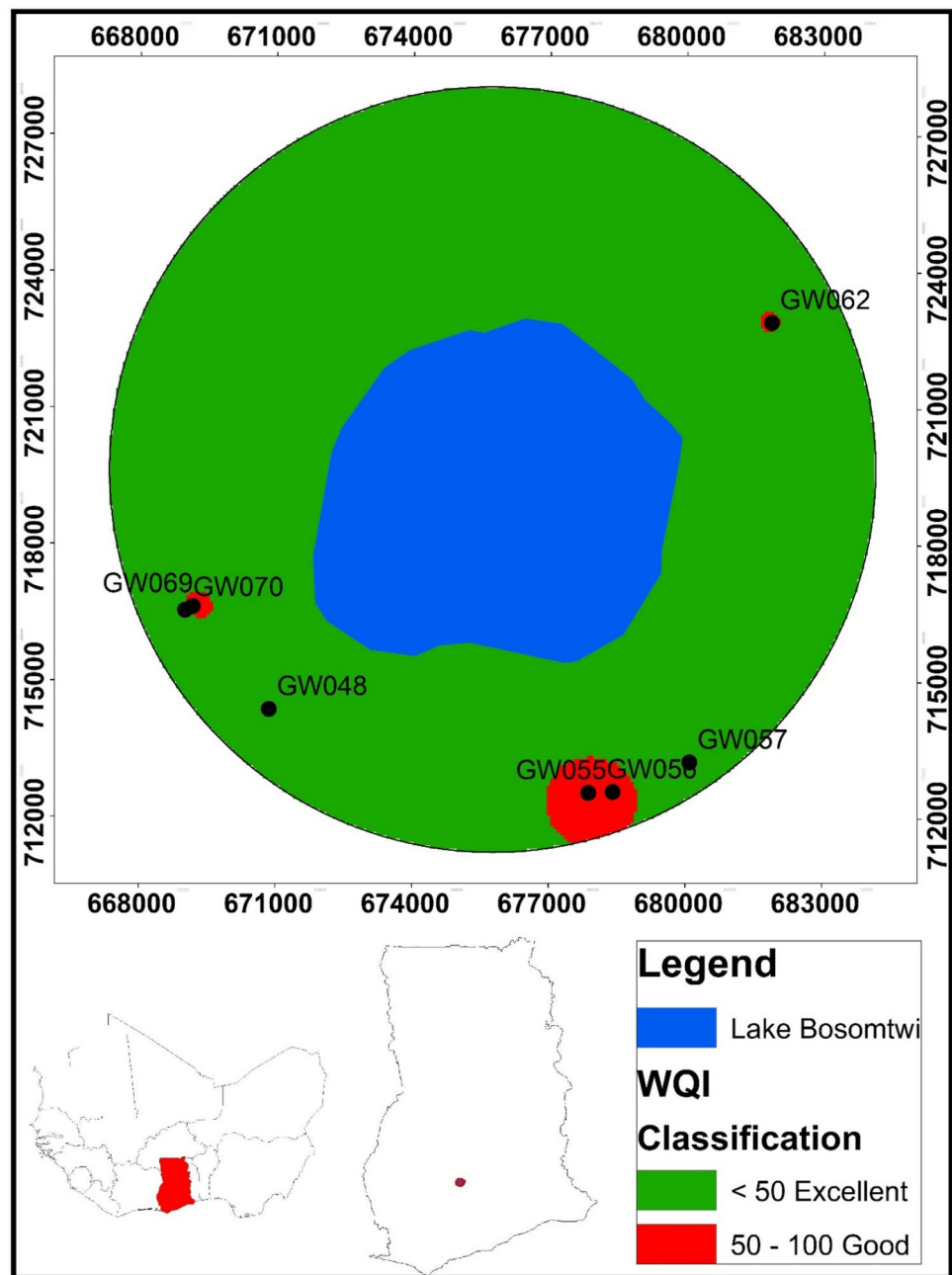


value. On the other hand, Fe concentration in 5 boreholes exceeded the WHO recommended value of $300 \mu\text{g/l}$. These include GW042 ($350 \mu\text{g/l}$), GW048 ($510 \mu\text{g/l}$), GW056 ($1020 \mu\text{g/l}$), GW070 ($730 \mu\text{g/l}$) and GW069 ($2490 \mu\text{g/l}$). While GW070 and GW069, both located at Adumasa, visibly show sediment loads in the groundwater, the others were noted as dirty during sample filtration. Even though the guideline value for both iron and manganese are for aesthetic reasons, their presence in groundwater can indicate deteriorating groundwater quality which may cause adverse health effects (Chapman, 1996; Bjørklund et al. 2017; Chen et al. 2019). Complaints of food discolouration has been reported by consumers in these communities. Spatially, the water quality index grouped the groundwater samples into excellent (green colour) and good (red) as shown in Figs. 9 and 10. Those areas that exhibited the good index are characterized by the boreholes that showed elevated iron, nickel and manganese.

Irrigation water quality

The United States Salinity Laboratory (USSL 1954) combined the SAR with the EC to classify irrigation water. In line with the USSL (1954) scheme, a plot of SAR against EC on a semi-log axis (Fig. 11) was made to assess water quality from the study area for irrigation purposes. The diagram classifies the water into five (5) categories of low salinity/sodium hazard (C1S1), medium salinity/low sodium (C2S1), high salinity/low sodium hazard (C3S1), high salinity/medium sodium hazard (C3S2) and high-salinity/high-sodium hazard (C3S3) irrigation waters (Fig. 11). About 21% of groundwater samples that plotted within the C1S1 region of the USSL diagram are acceptable for irrigation of most crops and almost all soil types, and the potential of this class of irrigation water to cause infiltration problem is improbable. The C2S1 category contains about 38% of groundwater samples. This irrigation water type can be used to irrigate most crops but can be detrimental to

Fig. 9 Spatial distribution of water quality index(WQI)



salt-sensitive crops that include but not limited to beans and peanuts. Forty-one percent (41%) of the studied groundwater samples plot in the high salinity/low sodium hazard (C3S1) field. This type of irrigation water can have an undesirable effect on moderately sensitive crops such as grains, forage and vegetables, and therefore, should not be applied on soils with restricted drainage (Kumar et al. 2007; Daliakopoulos et al. 2016; Sayyad-Amin et al. 2016). The lake water plot within the C3S2 and C3S3 field and are not suitable for irrigation. However, where it becomes necessary to use the lake water for irrigation, it should be used in generous amounts on salt-tolerant crops and soils with very high permeability

like sands. The use of this category of water for irrigation requires special soil and water management (Kumar et al. 2007; Daliakopoulos et al. 2016).

Like the USSSL diagram, the Wilcox diagram also classifies irrigation water quality based on sodium content. This diagram was used in this study to substantiate the findings based on the USSSL classification system. The Wilcox diagram (Fig. 12) shows that all but one groundwater sample fall within the 'Excellent to good' (representing 68% of total Groundwater from the area) and 'good to permissible' (29% of total groundwater samples) irrigation water categories, thus classifying the groundwater as

Fig. 10 Boxplot of trace element distribution in the ground-water samples of the study area

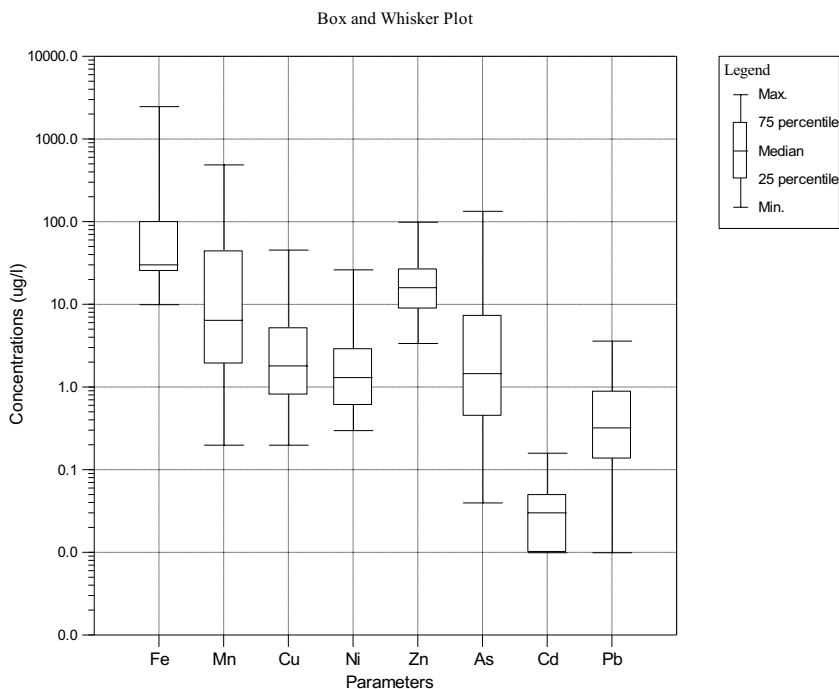


Table 2 Classification categories of WQI

WQI	Category
< 50	Excellent water
50–100	Good water
100–200	Poor water
200–300	Very poor water
> 300	Water unsuitable for drinking

suitability for irrigation. However, the lake samples plot within the 'doubtful to unsuitable' category suggesting that the lake water contains excessive sodium. Continued lake water application for irrigation over time may accumulate sodium onto soil particles and cause swelling/dispersion of soil clays, surface crusting and pore-clogging. The soil eventually becomes hard and compact when dry, thereby obstructing infiltration and increasing surface runoff (Bauder et al. 2011). Consequently, the lake water cannot be used for irrigation, or it should be used on salt-tolerant crops and on soil types that are highly permeable and not particularly susceptible to developing sodicity related problems.

The residual sodium carbonate (RSC) expressed in meq/l (Eq. 2.8) is an important index used to determine the HCO_3^- hazard and the suitability of water used in agriculture. The calculated RSC varied from -5.10 to 3.65 meq/l averaging -0.02 meq/l in the groundwater, while the lake water has a mean value of 7.01 meq/l.

According to RSC, the water quality classification for irrigation indicates that 85% of the total groundwater samples fall below RSC value of 1.25 and are therefore suitable for irrigation. Three other groundwater samples, representing 8% of the total number, are in the marginal range of 1.25–2.5, while the remaining 7% and all the lake samples have values greater than 2.5, suggesting that they are not suitable for irrigation. High levels of carbonates and bicarbonates in irrigation water can lead to calcite precipitation leaving Na as the dominant ion in solution, thus decreasing soil permeability, lowering infiltration capacity and increasing erosion, causing stunted plant growth (McClean and Jankowski 2000; Singh et al. 2015). Excessive bicarbonates in the lake water can also be problematic for micro-spray irrigation systems where scale build-up can clog orifices and reduce flow rates. On the whole, the groundwater in the area is suitable for irrigation. However, further groundwater resource quantification and sustainability studies should be conducted to determine how much groundwater can be abstracted for irrigation sustainably. The lake water is not generally suitable for irrigation but can be used where necessary under careful soil and water management practices.

Soil permeability is mainly affected by the long-term use of irrigation water containing excess sodium, calcium, magnesium and bicarbonate. In the wake of this, Doneen (1964) developed a standard for evaluating groundwater suitability for irrigation, premised on permeability index (PI). The permeability index of groundwater and lake water within Lake Bosomtwi ranged between 39.98 and 139.82% and 110.15 and 149.7%. Out of the 34 groundwater samples, 27 samples

Table 3 WQI and classification of groundwater from the study area

Station ID	Sample ID	WQI	Classification	Station ID	Sample ID	WQI	Classification
Esaase	GW007	23.09	Excellent	Konkoma	GW045	29.83	Excellent
Adwafo	GW012	26.76	Excellent	Brodekwano2	GW046	20.58	Excellent
Obo	GW015	17.94	Excellent	Dunkura	GW048	38.53	Excellent
Obo	GW016	15.61	Excellent	Abosoma Jyide	GW054	12.57	Excellent
Pipie Kese	GW020	27.23	Excellent	Adaïto	GW055	65.20	Good
Brodekwano	GW021	45.68	Excellent	Adaïto	GW056	53.27	Good
Apewu/Banso	SW001	25.94	Excellent	Yapesa	GW057	28.93	Excellent
Timeabu	HW001	20.82	Excellent	Nyameani	GW058	11.58	Excellent
Dompa	GW024	20.70	Excellent	Sarpong Nkwanta	GW059	14.49	Excellent
Dompa	GW025	25.05	Excellent	Nkowinkwata	GW060	22.88	Excellent
Duase	GW028	26.46	Excellent	Pipie	GW061	39.52	Excellent
Ankaase	GW032	24.39	Excellent	Brodekwano2	GW062	54.18	Good
Ankaase	GW034	24.42	Excellent	Apewu/Banso	SW002	19.19	Excellent
Amakom	GW037	27.00	Excellent	Adumasa2	GW069	67.09	Good
Adjmamam	GW039	29.32	Excellent	Adumasa2	GW070	28.43	Excellent
Beposo	GW041	24.33	Excellent	Gyapoadu	GW072	10.51	Excellent
Pemenase	GW042	34.53	Excellent	Deduako	GW074	33.15	Excellent
Konkoma	GW044	41.08	Excellent	Dwumakro	GW078	8.71	Excellent

Fig. 11 USSL diagram of sodium hazard (SAR) versus salinity hazard (EC) for the samples

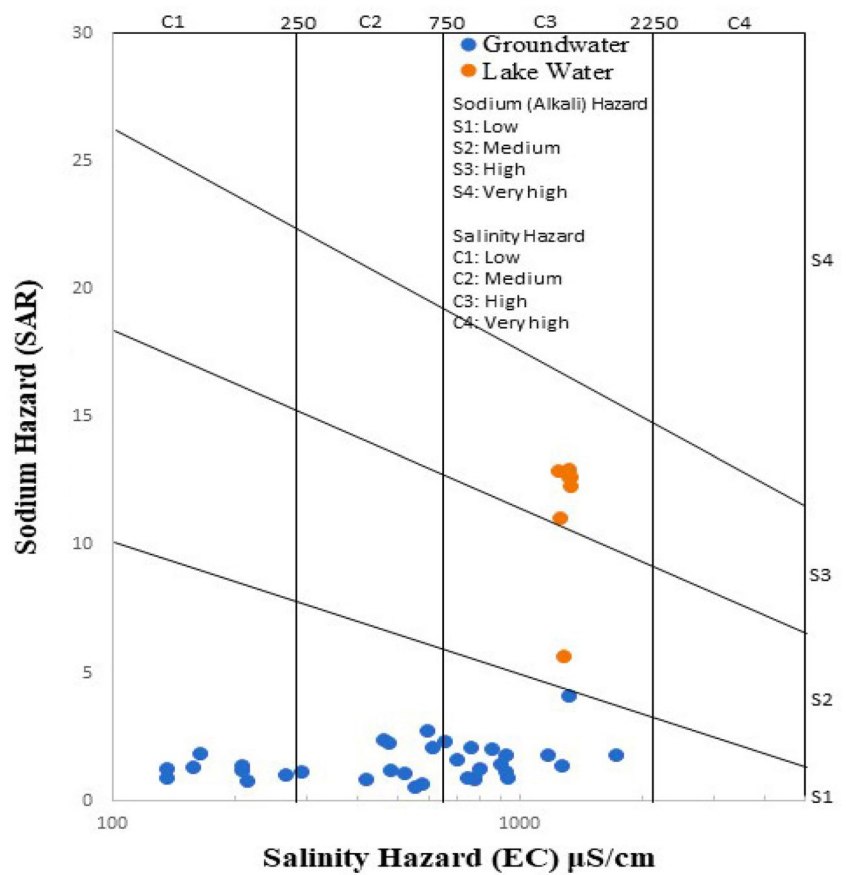
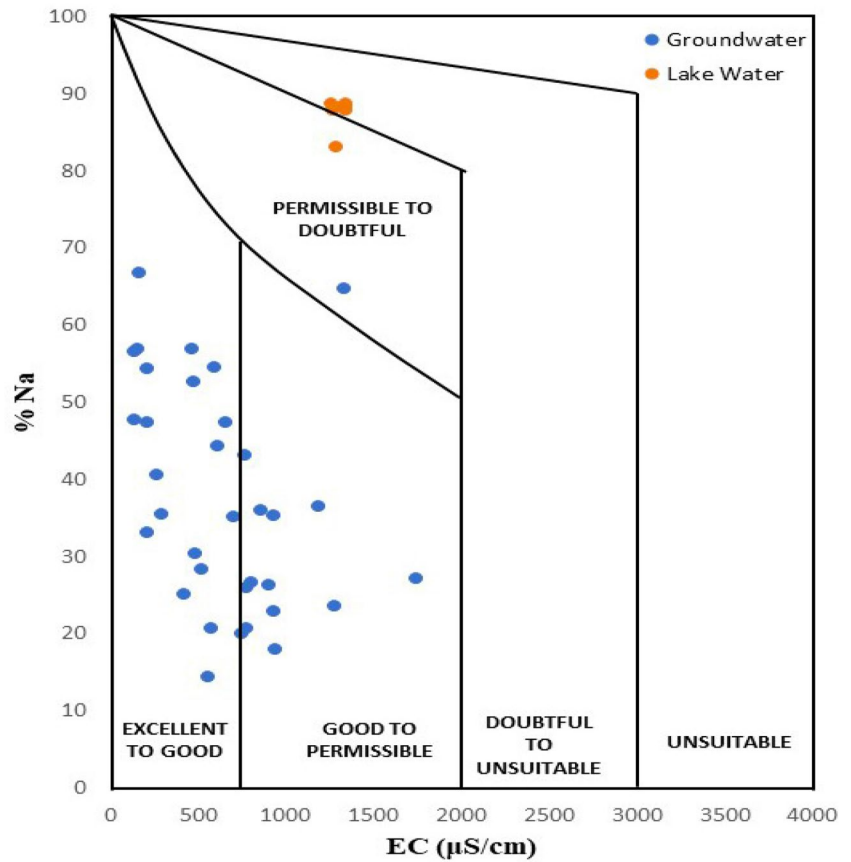


Fig. 12 A Wilcox diagram showing classification of irrigation water in the study area



representing 79.41% fell in Class I and Class II waters. The remaining seven samples representing 20.59% were Class III waters. Based on Doneen's (1964) criterion, 79.41% of the groundwater samples are suitable for irrigation and 20.59% unsuitable (Fig. 13).

Conclusions

The hydrochemical studies of aquifers around Lake Bosumtwi classify the Groundwater as slightly acidic, moderately hard to very hard with alkaline earths (Ca + Mg) exceeding alkali (Na + K) metals. On the other hand, the lake water is alkaline, showing an excess of alkali metals over the alkaline earth metals. Ca–Mg–HCO₃ hydrochemical

facies dominate the Groundwater whiles the lake water is Na–HCO₃ water type. These suggest no apparent incipient relationship, which benefits the main aquifer system in terms of recharge. The study also suggests rock weathering processes as the major sources of variation in the aquifers' hydrochemistry. WQI classify all the groundwater samples as good to excellent for human consumption. An evaluation of groundwater and lake water suitability for irrigation purposes based on salinity, sodicity, and bicarbonate hazard reveals that the groundwater in the area is generally suitable for irrigation. The study finds the lake water unsuitable for irrigation. However, where necessary, it can be used in generous amounts on highly permeable soils and salt-tolerant crops under special soil and water management practices.

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