Hydrochemistry and multivariate statistical analysis of the quality of water from Lake Bosomtwe for agricultural and human consumption

Gordon Amankwaa, Xifeng Yin, Liming Zhang, Weihong Huang, Yunfei Cao and Xiaoni Ni

ABSTRACT

One of the six major meteoric lakes in the world, Lake Bosomtwe, is of great ecological significance for Ghanaians and the scientific community, most importantly for agricultural and human consumption. Water samples ($n = 30$) were collected to analyze the hydrogeochemical characteristics and water quality of the lake. Statistical methods including correlation, principal component, cluster analysis, Gibbs ratio, and the Piper–Trilinear diagram were used to analyze parameters. The Water Quality Index revealed that the lake water is not suitable for human consumption because measured pH, temperature, total dissolved solids, color, and bicarbonate exceeded their respective thresholds on all occasions. The calculated sodium absorption ratio (13.7–14.8) and soluble sodium percentage (94.43–95.43%) showed that the lake is not appropriate for irrigation as they exceeded their respective limit of 2 and 60%. The Gibbs ratio revealed that rock–water interaction is the underlying mechanism for water evolution. The Piper–Trilinear diagram revealed that alkalies earth and weak acids dominate the water chemistry of the lake. The dominant cation is sodium (82.22%), while the dominant anion is bicarbonate (79.39%). Five monitoring stations were identified, and the water quality was influenced by diverse anthropogenic and natural sources. The findings will provide a reference for policymakers and decision-makers at Lake Bosomtwe.

Key words | Canadian Council of Ministers of Environment Water Quality Index (CCME-WQI), irrigation, Nemerow Pollution Index (NPI), sodium absorption ratio (SAR), soluble sodium percentage (SSP), surface water

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HIGHLIGHTS

- The water quality is not suitable for human consumption.
- Alkalies earth and weak acids dominate the water chemistry of the lake.
- The rock–water interaction is the underlying mechanism for water evolution.
- The dominant cation is Na^+ (82.22%), while the dominant anion is HCO_3^- (79.39%).
- The lake has high salinity hazard and high sodium (alkali) hazards, making it unsuitable for agricultural use.

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INTRODUCTION

Globally, clean and safe water is not adequately supplied to over a billion of the world's population (Patton et al. 2020). As a consequence of water diseases and disasters, about 6–8 million people die every year, thus making water availability a major concern for the world (Rahmanian et al. 2015). About 2.5% of the overall water resource is freshwater, of which 0.3% is available as lake water (Vasistha & Ganguly 2020). The utility of the available and accessible lake resource to man and aquatic organisms predicates on its quality even though this quality has been compromised as a consequence of uncontrolled human activity, hydrochemical behavior, and climate change (Tiyasha & Yaseen 2020). There are complexities in the unprecedented alterations in the baseline water quality because of the variations in inflows and outflows of water. The existing tool, technology, and method for identifying and monitoring the specific alterations in the baseline water quality are based on the analyses of physical and chemical parameters (Sasi et al. 2018; Carrasco et al. 2019). Therefore, the parametric values describe and characterize historical, current, and potential water conditions and modifications.

The Water Quality Index (WQI) is the tool used by policymakers, managers, and governments for the assessment of the water quality conditions or status. The WQI employs quantitative constructs, inculcates threshold limits (objectives), and communicates outcomes as a numerical rating that rates on an excellent to a bad scale (Paca et al. 2019; Kale et al. 2020). There are quite a few WQI indices all over the world: Fuzzy Logic-WQI (Oliveira et al. 2019), Chemical-WQI (Tsegaye et al. 2006), Modified-WQI (Singh et al. 2015), Oregon-WQI (Kafraway et al. 2017), Canadian Council of Ministers of Environment-WQI (Lumb et al. 2006), and Pollution Index (Goher et al. 2014). Globally, the CCME-WQI methodology is, according to the United Nations Environmental Program, very appropriate for drinking water quality evaluation (Rickwood & Carr 2009). In the overall water quality evaluation of an aquatic ecosystem, the CCME-WQI employs a more rigorous approach, compared with other approaches (Damodhar & Reddy 2013; Zhao et al. 2016). In fact, the CCME-WQI methodology is flexible and can accurately determine whether or not the general water quality status meets the desired objectives (threshold limits) (Zhao et al. 2016). It is accomplished by selecting desired objectives for water quality depending on the study area and purpose.

Another commonly applied tool to assess a lake's water quality status is the multivariate statistical tools, which simplify the results to be understood by the common public (Luo et al. 2017; Mitra 2017). Chounlamany et al. (2017) applied multivariate statistical techniques in the assessment of the water quality of the segment of river Marikina, taking into account 12 physicochemical parameters. Four significant clusters were established as monitoring stations, and January–May and June–September were identified as dry and wet seasons. The principal component analysis, which explained a total variance of 83%, identified anthropogenic impacts, rainfall, and soil erosion as sources of pollution. Soltani et al. (2017) used a multivariate statistical technique to assess the hydrochemistry of Kordkandi-Duzduzan plain, Iran. Calazans et al. (2018) applied cluster analysis and principal component analysis to optimize the surface water quality network monitoring in the Paraopeba river basin, Brazil. All the above studies utilized multivariate statistical tools to study hydrochemical processes, investigate plausible causes of pollutants, classify associations, and control factors for the monitoring of water quality.

Inclusive of Lake Bosomtwe, there is an unprecedented anthropopressure on natural lakes all over the world which is concerted by the ever-increasing population and industrialization (Ji et al. 2019). Lake Bosomtwe is a major meteoric lake and West Africa's largest natural lake. The lake has no outlet and the 22 farming communities within the shore of the catchment area bank on the lake for water supply. During the dry season (winter), residents in the catchment area of the lake rely on Lake Bosomtwe for drinking, bathing, irrigation, washing, and cooking (Otu 2010). The lack of proper sewage disposal and the unchecked use of fertilizers and agrochemicals also culminated in the lake's water quality and ecological state becoming depleted, which may be harmful to aquatic, agricultural, and human health. Hitherto, no research is undertaken to utilize WQI, Nemerow Pollution Index (NPI), multivariate statistics, and hydrochemical analysis to determine Bosomtwe Lake's water quality status.

For the purpose of this study and the physicochemical parameters analyzed, CCME-WQI, NPI, and multivariate statistics were adopted to explain and simplify the results from water quality analysis. The specific objectives are (i) to assess the lake's water quality using the CCME-WQI and the NPI, (ii) to assess the suitability of the lake's water for irrigation by calculating the sodium adsorption ratio (SAR) and percentage, (iii) to undertake multivariate statistical analysis of parameters using SPSS, and (iv) to analyze geochemical processes using Piper–Trilinear diagram, Gibbs ratio, and the US Salinity Laboratory (USSL) diagram.

METHODOLOGY

Study area

Lake Bosomtwe is situated in the Ashanti region, Ghana (6°30N and 1°25 W) within 35 km from Kumasi (the second-largest city in Ghana). The geology of the lake comprises of Precambrian-age Birimian and Tarkwaian rocks dominated by shale, schist, phyletic, and meta-sandstones (Junner & Hirst 1946). The lake is contained in a 1 million-year-old meteorite impact crater which is hydrologically closed due to its elongated height (210 m amsl), as shown in Figure 1. The rate of precipitation and evaporation, therefore, determines the lake's level in Ghana during the two main seasons (dry and rainy). Given the over-reliance on the lake's resources for drinking, irrigation, and domestic uses, the residents within the catchment area are primarily farmers who use fertilizers and agrochemicals in their operations. All farms and domestic runoffs can ultimately modify the quality of the water and ecological status (Parris 2011; Müller et al. 2020).

Water sampling

For February 2018, 30 georeferenced water samples were collected for laboratory analysis. A pre-cleaned 1-L plastic water bottle was rinsed three times with the lake water before samples were collected at an approximate depth of 10 cm. Onsite measurement of some physical parameters was carried out using a multipurpose HANNA Instrument (Model – HI 98130, RI, USA) to measure electrical conductivity (EC) and pH. Turbidity and temperature were also measured using a Turbidity meter (Model – 2100P, CO, USA) and a thermometer. The collected samples obtained were labeled and placed in ice coolers for onward transportation to the laboratory for further analysis.

Analysis of physicochemical parameters and quality assurance/quality control (QA/QC)

The physicochemical parameters analyzed were pH, EC, temperature, turbidity, total dissolved solids (TDS), total suspended solids (TSS), color, hardness, biological oxygen demand (BOD), chemical oxygen demand (COD), nitrate, sulfate, calcium, chloride, magnesium, sodium, potassium, carbonate, and bicarbonate. Some physical parameters (EC, TDS, temperature, and pH) were measured at the points of water sampling, whereas the other parameters were analyzed according to the methods reported by Chounlamany et al. (2018) and Asare–Donkor et al. (2018).

All reagents used to analyze samples in triplicates were of analytical grades. All international standard protocols for water physicochemical analysis were followed. The standard method for water quality analysis (APHA 2012) was used. Briefly, to accomplish quality assurance and quality control, duplicates, and blank samples for all parameters were carried out through the analytical processes (Pengra et al. 2019).

Data analysis

Descriptive statistics (mean, standard deviation, range, kurtosis, and coefficient of variation) of all parameters measured were calculated using the SPSS software version 20. Pearson correlation analysis was performed on the parameters to identify the existing relationships and their controlling effects on water quality. A cluster analysis technique was applied to classify sampling sites into simplified groups (clusters) designated as monitoring stations. The principal component analysis was carried out on the parameters analyzed to explore the plausible pollution sources and influencing (or motivating) factors. Finally, MS Excel and Aq.QA spreadsheet for water analysis were used for the geochemical analysis (Piper–Trilinear diagram,

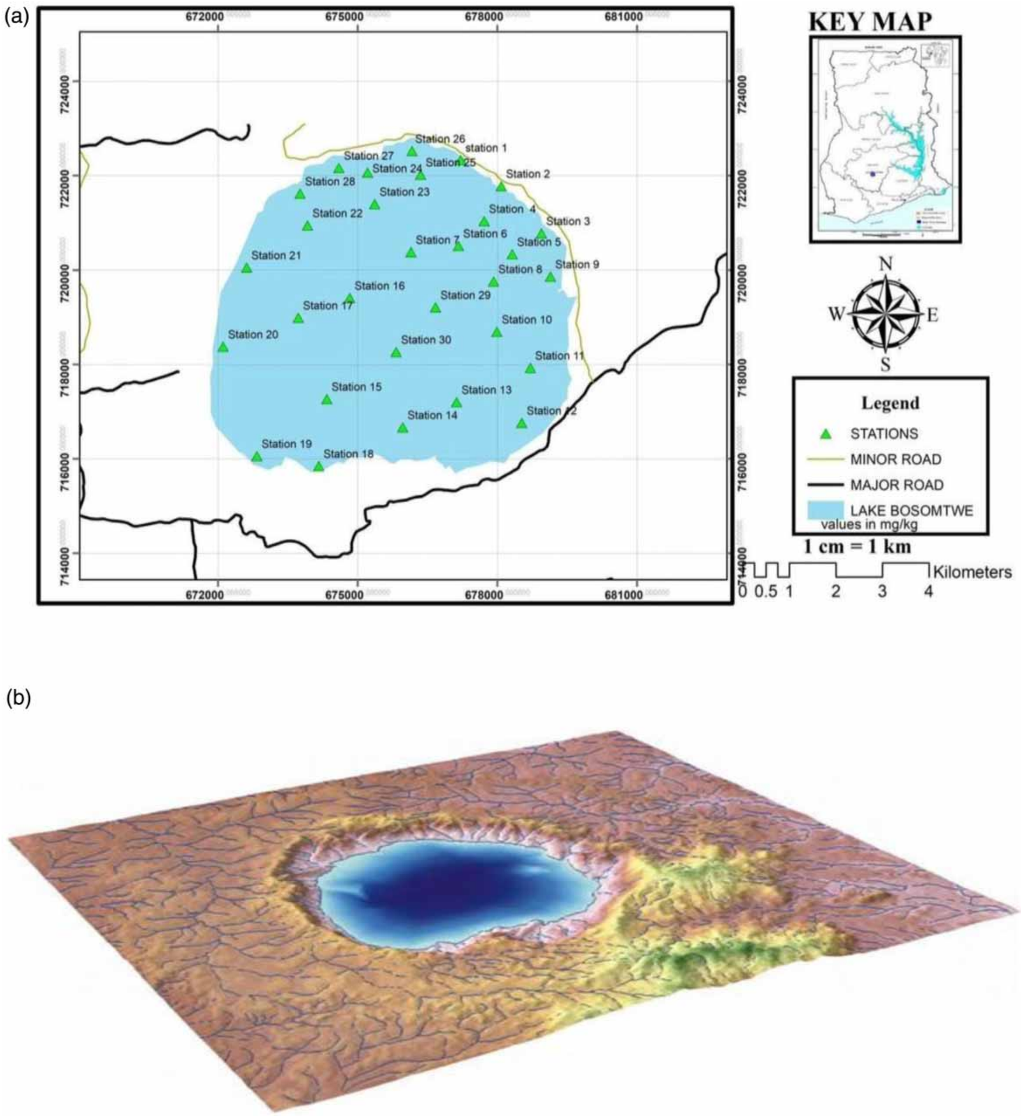

Figure 1 | (a) Study map of Bosomtwe Lake showing sampling points. (b) Shuttle radar topography mission (SRTM) data of Bosomtwe Lake showing the elongated crater rim and the drainage pattern. From Koeberl & Reimold (2005).

Gibbs ratio, and the US Salinity Laboratory (USSL) diagram).

Water Quality Index

In this study, CCME-WQI and NPI approaches were used to compute the water quality indices for the various parameters analyzed. These two indices compare measured concentration values of parameters to WHO and CCME-WQI permissible limits.

Canadian Council Ministers of the Environment Water Quality Index

The CCME-WQI approach as detailed in Lumb *et al.* (2006) was used to calculate the overall water quality at Bosomtwe Lake. In its evaluation, the method integrates scope (F_1), frequency (F_2), and amplitude (F_3). To understand the water quality, the calculated CCME-WQI value is ranked on the scale of 95–100 (excellent), 80–94 (good), 65–79 (fair), 45–64 (marginal), and 0–44 (poor).

Scope (F_1): It measures the number of variables (physicochemical parameters) that surpass their threshold values (objectives). F_1 represented in mathematical terms as:

$$F_1 = \left(\frac{\text{Number of failed variables}}{\text{Total number of variables}}\right) \times 100 \tag{1}$$

Frequency (F_2): It measures the number of occasions that the threshold values (objectives) were exceeded (unmet). F_2 is described mathematically as:

$$F_2 = \left(\frac{\text{Number of failed tests}}{\text{Total number of variables}}\right) \times 100 \tag{2}$$

Amplitude (F_3): It measures the extent to which the threshold values (objectives) were exceeded (unmet). F_3 is estimated using a three-step approach:

1. First of all, the excursion is measured which represents the number of times that an individual concentration is below or above the threshold value (objective). When the test value must not exceed the threshold value (objective), the excursion is mathematically expressed as:

$$excursion = \left(\frac{\text{Failed Test Value}_\text{i}}{Objective_j}\right) - 1 \tag{3}$$

For the cases in which the test value must not fall below the threshold value (objective), the mathematical equation is expressed as:

$$\text{Excursion} = \left(\frac{\text{Objective}\,j}{\text{Failed test value}}\right) - 1 \tag{4}$$

2. Secondly, a normalized sum of excursion (nse) measuring the collective amount by which individual tests exceed threshold limit (objective) is determined by dividing the total sum of individual excursions by the total number of tests. The normalized sum of excursion (nse) is described in mathematical terms as:

$$\text{nse} = \frac{\sum_{i=1}^{n} \text{Objective}\,j}{\text{Total number of tests}} \tag{5}$$

3. F_3 is then estimated by using an asymptotic function that scales nse to yield a value between 0 and 100. F_3 is estimated through the equation below:

$$F_3 = \frac{\text{nse}}{0.01\text{nse} + 0.01} \tag{6}$$

Finally, the CCME-WQI index is estimated using the equation below:

$$\text{CCME-WQI} = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right) \tag{7}$$

Nemerow Pollution Index

The NPI measures the relative contribution of contaminants of individual parameters by comparing the measured concentration value of individual parameters at a sampling point to its permissible water quality limit. It integrates the effects of individual parameters (Yan et al. 2015). The NPI was adopted by the current study to identify the pollution causing physicochemical parameters, so that the extent of pollution would be ascertained. The NPI is mathematically expressed as:

$$\text{NPI} = \frac{C_i}{C_o} \tag{8}$$

where C_i represents the measured concentration value of parameter I and C_o represent the permissible water quality limit of parameter i. The NPI value of <1 implies no pollution, while the NPI value of >1 suggests the presence of pollution.

Irrigation water quality

Calculating for the sodium absorption ratio (SAR) and soluble sodium percentage (SSP) was done to determine the suitability of water from Bosomtwe Lake for irrigation purposes. We calculated the SSP and SAR using the following equations:

$$\text{SSP} = \frac{N^+ + K^+}{Ca^{2+} + Mg^{2+} + N^+ + K^+} \times 100 \tag{9}$$

$$\text{SAR} = \frac{Na^{2+}}{\sqrt{Ca^{2+} + Mg^{2+}}} \tag{10}$$

RESULTS AND DISCUSSION

Table 1 provides descriptive statistics of the values of the physicochemical parameters of all the 30 samples analyzed from Bosomtwe Lake water.

Physical parameter (pH, electric conductivity, temperature, turbidity, TDS, TSS, and color)

pH and temperature

The pH measures the acidity and alkalinity of water. The water pH affects biotic activities and a high pH also results from the process of photosynthesis (Singh *et al.* 2017). This suggests high vitality activities in Bosomtwe Lake. The observed pH varied from 8.8 to 9.3, with a reported mean and standard deviation of 8.9 ± 0.17. The water from Bosomtwe Lake is alkaline, and the reported pH value exceeded the potability value recommended by the WHO (2011). Temperature specifies the level of thermal input in water (Christine *et al.* 2018), and the measurements reported from the study ranged from 29 to 30 °C. While the WHO does not have a threshold level for temperature, pH is reported to fall as thermal input rises (Jagaba *et al.* 2020). Rising and falling in temperatures can have an impact on biological activities, in particular on ecological biodiversity and also chemical reactions in water. The increase in water temperatures reduces the hydrogen–oxygen reaction caused by the release of hydrogen ions, which raises the water acidity level. Whereas a drop in temperature strengthens hydrogen–oxygen bond and raises the dissolved oxygen (DO) level in water (Akiya & Savage 2002).

EC, turbidity, and color

EC quantitatively measures the water's ability to carry electric currents in it. EC measurements ranged from 1,241 to 1,301 μS/cm, with a mean and standard deviation of

Table 1 | Descriptive statistics of the physicochemical parameters of water samples collected from Bosomtwe Lake ($n = 30$)

Parameters	Unit	Range	Mean ± SD	CV (%)	Kurtosis	WHO	CCME (drinking)	CCME (Aquatic)
pH	pH unit	8.8–9.3	8.9 ± 0.17	1.91	−0.55	7.0–8.5	6.5–8.5	5–9
EC	(μS/cm)	1,241–1,301	1,262.8 ± 25.01	1.98	−1.34	1,000	*N/A	*N/A
Temperature	(°C)	29–30	29.50 ± 0.51	1.73	−1.15	Ambient	15	15
Turbidity	(NTU)	0.90–1.32	1.02 ± 0.22	21.57	0.36	5	5	5
TDS	(mg/L)	855–880	864.47 ± 10.16	1.18	−1.33	1,000	500	500
TSS	(mg/L)	7–18	12.77 ± 2.47	19.34	−0.358	1,000	*N/A	*N/A
Color	(TCU)	71–100	85.47 ± 9.54	11.16	−1.31	15	15	15
Hardness	(mg/L)	18–33	24.93 ± 5.25	21.06	−1.60	150	*N/A	*N/A
BOD	(mg/L)	2.0–4.1	2.96 ± 0.72	24.32	−1.12	6	*N/A	*N/A
COD	(mg/L)	20.0–21.4	20.69 ± 0.54	2.61	−0.791	10	*N/A	*N/A
NO_3^-	(mg/L)	0.52–1.1	0.81 ± 0.30	37.04	−0.877	45	48.2	*N/A
SO_4^-	(mg/L)	2.3–9.23	5.72 ± 0.44	7.69	1.920	200	500	500
Ca^{2+}	(mg/L)	2.1–3.4	3.09 ± 0.20	6.47	0.04	75	*N/A	*N/A
Cl^-	(mg/L)	91.1–100.1	94.85 ± 2.78	2.93	0.704	250	250	250
Mg^{2+}	(mg/L)	13.50–14.73	14.01 ± 0.33	2.36	0.11	50	*N/A	*N/A
Na^+	(mg/L)	253–263	257.03 ± 0.62	0.24	0.6	200	*N/A	*N/A
K^+	(mg/L)	43.9–45.82	44.14 ± 0.21	0.48	0.046	12	*N/A	*N/A
HCO_3^-	(mg/L)	622.3–660.81	649.83 ± 7.28	1.12	−1.04	300	*N/A	*N/A
CO_3^{2-}	(mg/L)	302.3–313.5	308.16 ± 4.01	1.3	−1.23	*N/A	*N/A	*N/A

*N/A values were not available.

1,262.8 ± 25.01 μS/cm. Measurements for drinking water in all samples exceeded the WHO limit (WHO 2011). While there are no known public safety consequences for a high level of EC measurement, it may impact water mineralization and treatment cost (Rahmanian *et al.* 2015). Therefore, high EC measurements recorded in the study suggest the likelihood of high contamination of dissolved ions originating from domestic and agricultural wastes within the lake's catchment area. Dissolved ions including chloride, calcium, and magnesium facilitate the transmission of electric current. Chemical and domestic runoffs from farms and various households (Jagaba *et al.* 2020) may be linked to the possible cause for elevated water conductivity due to the high concentration of dissolved ions released into the lake. Turbidity is the cloudiness of water that microorganisms, and suspended particles and organic matter can induce (Jagaba *et al.* 2020). The observed turbidity values ranged from 0.90 to 1.32 NTU, and the reported values were below the recommended WHO limit (WHO 2011). Bosomtwe Lake's color ranged from 71 to 100 Pt-Co which exceeds the 15 Pt-Co WHO limit (WHO 2011). The excesses could be attributed to the high water content of iron in Bosomtwe Lake (Jagaba *et al.* 2020).

Total dissolved solids and total suspended solids

TDS and TSS may express the level of contamination in water. A growing increase in their levels may affect turbidity and water conductivity (Vasistha & Ganguly 2020). They comprise organic matter, phytoplankton, silt, clay, and dissolved salts such as Ca, Na, Mg, and Cl^- which are dissolved and undissolved in water. It could have health implications for the vulnerable population (Jagaba *et al.* 2020) when exposed at high levels. Variations in the TDS values ranged from 855 to 880 mg/L in all water samples collected. The recorded mean and standard deviation reported for TDS was 864.47 ± 10.16 mg/L. The TSS values varied from 6 to 15 mg/L with a mean and standard deviation of 12.77 ± 2.47 mg/L. The TDS and TSS recorded in the study were within their respective WHO drinking water limit of 1,000 mg/L (WHO 2011). The relatively low levels of recorded TDS and TSS indicate that Bosomtwe Lake is less polluted and therefore receives relatively low inorganic and organic inputs.

Chemical parameters (BOD, COD, hardness, nitrate, sulfate, calcium, potassium, sodium, magnesium, and chloride)

Biological oxygen demand and chemical oxygen demand

BOD reflects the level of waste in the water that can be degraded biologically. High BOD levels in water may destroy aquatic life due to competition for DO. DO is utilized by microbes during the biodegradation process that may alter oxygen levels in water (Vasistha & Ganguly 2020). The BOD values in the current study varied between 2.0 and 4.1 mg/L, with an average of 2.96 mg/L. The BOD levels of all samples recorded were below the WHO recommended potability limit of 6 mg/L (WHO 2011). This may mean minimal organic debris, and the aquatic life is supported by Bosomtwe Lake's ecosystem (Mitra 2017). However, the observed COD levels of all samples ranged from 20.0 to 21.4 mg/L, which significantly exceeded the recommended WHO 10 mg/L threshold. These results may indicate the likelihood of organic contaminants being exacerbated by the rates of biological activity and higher temperatures in Bosomtwe Lake (Mutlu 2019).

Nitrate, sulfate, sodium, potassium, and chloride

Sodium ions (Na^+) are derivatives of silicate weathered rocks. Sodium ion concentrations ranged between 253 and 263 mg/L, which surpassed the WHO recommended limit of 200 mg/L (WHO 2011). Sources of chlorine are from minerals that contain chloride salts and rainfall (Jagaba *et al.* 2020). The presence of excess chlorides in water renders the water salty and has severe health implications such as cardiac and kidney problems. Concentrations of chloride were below the WHO threshold limit of 250 mg/L (WHO 2011). It ranged from 91.1 to 100.1 mg/L, with a mean and standard deviation of 94.85 ± 2.78 mg/L. The plausible sources of nitrate in the lake are oxidation of nitrogen-based fertilizers, humans and animal excreta through the processes of microbial nitrification and activities of phytoplankton (Asare–Donkor *et al.* 2018). The nitrate concentration level was lower than 45 mg/L WHO standard, as the reported concentrations varied between 0.52 and

1.1 mg/L with a mean and standard deviation of 0.81 ± 0.30 mg/L. Sulfate concentration ranged from 2.3 to 9.23 mg/L with a standard mean concentration of 5.72 ± 0.44 mg/L which is lower than 200 mg/L set by the WHO (WHO 2011). The potassium concentration in all of the investigated water samples varied from 43.9 to 45.82 mg/L, with a mean and standard deviation of 44.14 ± 0.21 mg/L. All the potassium concentration in the 30 samples was found to be above the WHO maximum limit of 12 mg/L. Runoff from agricultural farmlands contaminated with fertilizers may be traced to the possible source of potassium in water (Vasistha & Ganguly 2020).

Calcium, magnesium, carbonates, bicarbonates, and hardness

When present in the correct amount, magnesium and calcium are essential elements in the water. They often control the hardness of water, and their overdose may render humans with scaling and abdominal ailments. Calcium, therefore, is an essential body nutrient when ingested at the right level, as it promotes growth, helps develop healthy teeth and bones, and prevents blood clotting, scaling, and rickets. Calcium concentrations in all samples ranged from 2.1 to 3.4 mg/L, with a mean and standard deviation of 3.09 ± 0.20 mg/L. All the calcium values recorded fell below the recommended WHO limit of 75 mg/L (WHO 2011). Magnesium concentrations varied from 13.50 to 14.73 mg/L, with a mean and standard deviation of 14.01 ± 0.33, which falls within the WHO potability limit of 50 mg/L. Carbonates and total hardness ranged between 302.3–313.5 and 18–33 mg/L, respectively, with mean and standard deviations of 308.16 ± 4.01 and 24.93 ± 5.25 mg/L, respectively. Bicarbonates varied from 622.3 to 660.81 mg/L, with a mean and standard deviation of 649.83 ± 7.28 mg/L. However, all the values recorded for bicarbonates exceeded the WHO drinking water limit of 300 mg/L (WHO 2011). It is worth noting that calcium and magnesium precipitate as carbonates in water with elevated levels of carbonate and bicarbonate, which then augment the sodium levels (Taloor *et al.* 2020). The high level of sodium in Bosomtwe Lake in this case may also be attributed to the reasons given above.

Multivariate statistical analysis of parameters

Correlation analysis, cluster analysis, and principal component analysis were performed on the parameters to further explore the relationships, sources, association, and factors affecting Bosomtwe Lake's water quality and ecological status.

Correlation analysis

Pearson's correlation analysis was performed among physicochemical parameters which were investigated as shown in Table 2. A strong correlation between EC and TDS ($r = 0.950$) was observed. This could be attributed to the electric current holding ions in the TDS. Total hardness strongly correlated with calcium ($r = 0.893$), magnesium ($r = 0.764$), bicarbonate ($r = 0.886$), and carbonate ($r = 0.897$). The calcium and magnesium inputs demonstrate the tremendous release of dolomite into the lake water. The strong correlation between calcium and magnesium ($r = 0.897$) also suggests that they are the major contributors to total hardness. The lake water pH was strongly correlated with EC ($r = 0.958$) and TDS ($r = 0.883$). The plausible reason for the strong correlation between pH and EC could be ascribed to hydroxyl ions conducting electric currents. This condition has augmented the level of carbonate and bicarbonate in the lake. The strong correlation between carbonate and bicarbonate ($r = 0.973$) can be attributed to homogeneity in enrichment and geochemical processes. There were significant correlations also observed between TSS and color ($r = 0.747$), TSS and chloride ($r = 0.713$), and color and chloride ($r = 0.585$). However, the negative correlation between potassium, bicarbonate, and carbonate could suggest that potassium did not influence or control the total hardness of Bosomtwe Lake. The BOD and COD ($r = 0.922$) were also negatively correlated, as eutrophication of Bosomtwe Lake can result in competition for DO (Li & Liao 2003).

Clustering according to the inter-relationship and effect of parameters on water quality

Using the ward method (Luo *et al.* 2017), hierarchical cluster analysis was performed on data to group the 30 sampling

Table 2 | Correlation analysis of physicochemical parameters of water from Bosomtwe Lake ($N = 30$)

	pH	EC	Temperature	Turbidity	TDS	TSS	Color	Hardness	BOD	COD	NO_3^-	SO_4^-	Ca^{2+}	Cl^-	Mg^{2+}	Na^+	K^+	HCO_3^-	CO_3^{2-}
pH	1																		
EC	0.958**	1																	
Temperature	−0.081	−0.169	1																
Turbidity	−0.163	−0.106	0.131	1															
TDS	0.883**	0.950**	−0.133	−0.072	1														
TSS	−0.217	−0.260	0.096	0.104	−0.362**	1													
Color	−0.045	−0.088	0.156	0.177	−0.183	0.747**	1												
Hardness	−0.233	−0.231	−0.220	−0.168	−0.177	−0.171	−0.266	1											
BOD	−0.317	−0.355	−0.118	0.003	−0.356	0.072	0.026	0.335	1										
COD	0.349	0.341	0.137	−0.037	0.343	−0.091	0.017	−0.265	−0.922**	1									
NO_3^-	0.061	0.148	−0.234	0.142	0.143	−0.421*	−0.363*	0.204	0.203	−0.132	1								
SO_4^-	−0.349	−0.256	−0.084	0.235	−0.184	0.096	−0.011	−0.144	0.143	−0.309	−0.049	1							
Ca^{2+}	−0.141	−0.099	−0.267	−0.120	−0.020	−0.247	−0.312	0.893**	0.266	−0.241	0.215	−0.095	1						
Cl^-	−0.252	−0.334	0.081	0.028	−436*	0.713**	0.585**	−018	0.098	−023	−325	0.157	−0.178	1					
Mg^{2+}	−136	−114	−.206	−197	−033	−349	−356	0.764**	0.178	−146	0.205	−0.086	0.897**	−0.281	1				
Na^+	−0.050	−0.008	0.050	0.231	0.048	−0.036	0.104	−137	0.122	−0.130	0.223	0.166	−0.124	0.136	−0.056	1			
K^-	0.479**	0.399*	0.000	−305	0.257	0.268	0.251	−0.400*	−0.210	0.227	0.032	−0.271	−0.425*	0.213	−0.338	0.254	1		
HCO_3^-	−0.057	−0.048	−0.240	−0.184	0.032	−0.240	−0.242	0.886**	0.302	−0.188	0.171	−0.174	0.936**	−0.180	0.852**	−0.205	−0.438*	1	
CO_3^{2-}	−0.060	−0.026	−0.283	−0.162	0.063	−0.249	−0.294	0.897**	0.282	−0.212	0.194	−0.115	0.960**	−0.200	0.850**	−0.107	−0.430*	0.973**	1

**Correlation is significant at the 0.01 level (two-tailed).

*Correlation is significant at the 0.05 level (two-tailed).

sites into clusters according to heterogeneity. Using the Z-score, the parameters were transformed, and the Euclidean pattern was applied as the interval. With the use of hierarchical clustering analysis, five statistically significant clusters were identified, and the results are displayed in a dendrogram (Figure 2). Cluster 1 consists of four samples representing 13.33% of the total samples; cluster 2 consists of eight samples representing 26.67%; cluster 3 (seven samples) represents 23.33%; cluster 4 (six samples) represents 20% and cluster 5 (five samples) represents 16.67% of the total samples. Finally, results from the cluster analysis indicate that the historical, current, and potential water quality conditions and modifications of Bosomtwe Lake can be monitored using the simplified monitoring stations. According to the cluster analysis, five established monitoring stations listed in clusters 1–5 can be used as representative sampling sites to assess the water quality of Bosomtwe Lake. As a consequence, effective water quality monitoring strategies for Bosomtwe Lake can be formulated using the findings of the current study.

Sources of pollutants and their associations

The principal component analysis was performed on the Kaiser normalized parameters. At Eigenvalue >1, six principal components were extracted which explained 82.12% of total variance as shown in Table 3 and Figure 3. Components 1, 2, 3, 4, 5, and 6 explained percentage variance of 29.37, 21.23, 10.97, 8.76, 6.10, and 5.68, respectively. Component 1 is strongly loaded with pH, EC, TDS, and moderately with temperature (negative). The negative correlation between temperature and the other parameters proves that seasonal variability affects the lake water quality as the rise and fall in temperature (influenced by changes in season) affects the pH of water. Also, pH can subsequently affect the flow of electric current. Principal component 2 is strongly loaded with hardness, bicarbonate, carbonate, calcium, and magnesium. The possible source may be traced to geogenic processes comprising dissolved carbonates that can arise from underlying rock weathering and surface runoff. Principal component 3 was strongly loaded with TSS, color, chloride, and moderately with nitrate. It depicts leachate from agricultural and domestic sources of pollutants. COD, BOD, and temperature were strongly loaded in component 4 that depicts inorganic and organic contaminants from household wastewater and leachate as pollution sources. Finally, components 5 and 6 have strong to moderate loading of turbidity, sulfate, potassium (negative), nitrate, and sodium. The two components might be influenced by uncontrolled agricultural practices that entail the use of agrochemicals and fertilizers within the lake's catchment area.

Assessment of water quality for drinking and aquatic life

Using Equations (1)–(8), the suitability of the water for drinking was assessed. The CCME-WQI was used to determine the

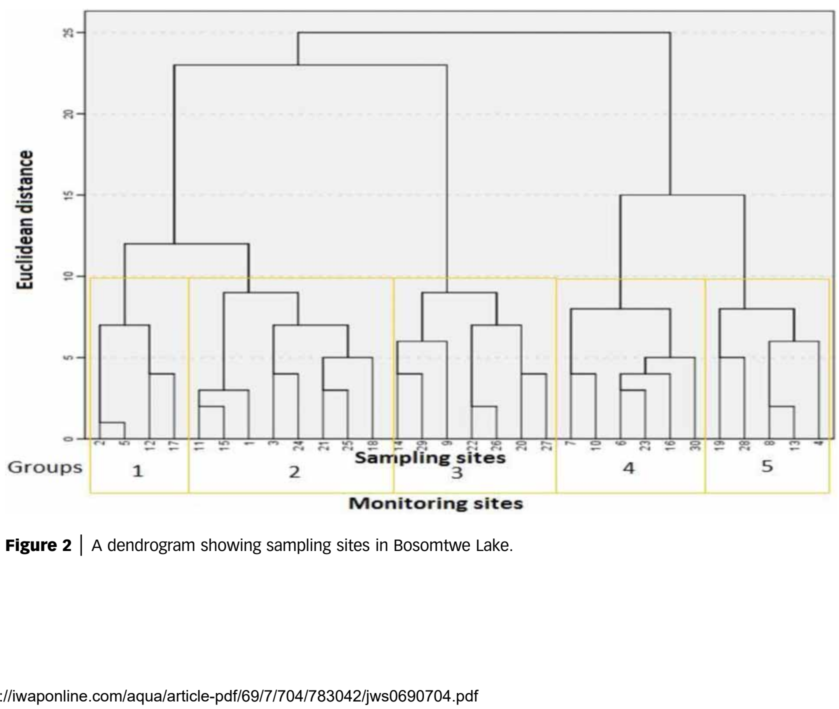

Figure 2 | A dendrogram showing sampling sites in Bosomtwe Lake.

Table 3 | Factor loadings of Bosomtwe Lake physicochemical parameters

	Principal component					
	1	2	3	4	5	6
pH	0.893	−0.129	−0.078	0.171	−0.251	0.014
EC	0.945	−0.103	−0.138	0.157	−118	0.042
Temperature	−0.422	−0.278	0.022	0.437	−0.137	0.172
Turbidity	−0.072	−0.067	0.109	0.179	0.752	0.427
TDS	0.899	−0.047	−0.251	0.190	−0.021	0.056
TSS	−0.149	−0.151	0.903	−0.059	0.016	−0.056
Color	−0.014	−0.179	0.862	0.051	0.000	0.109
Hardness	−0.146	0.915	−0.061	−0.165	−0.079	−0.042
BOD	−0.259	0.177	0.043	−0.853	−0.028	0.171
COD	0.244	−0.104	−0.004	0.888	−0.092	−0.113
Nitrate	0.153	0.202	−0.413	−0.217	0.002	0.541
Sulfate	−0.135	−0.210	0.018	−0.351	0.677	−0.088
Ca^{2+}	−0.007	0.957	−0.141	−0.131	0.021	−0.034
Cl^{-}	−222	−0.067	0.820	−0.063	−0.009	−0.156
Mg^{2+}	−0.057	0.878	−0.251	−0.051	−0.067	0.002
Na^{+}	−0.011	−0.136	0.007	−0.095	0.053	0.836
K^{+}	0.376	−0.385	0.310	0.023	−0.600	0.271
HCO_3^{-}	0.196	0.914	−0.091	0.100	−0.031	−0.081
CO_3^{2-}	0.212	0.934	−0.115	0.128	0.013	−0.029
Eigenvalue	5.58	4.03	2.09	1.67	1.16	1.08
% Variance	29.37	21.23	10.97	8.76	6.10	5.68
Cumulative % variance	29.37	50.60	61.58	70.34	76.44	82.12

Factor loadings are statistically different.

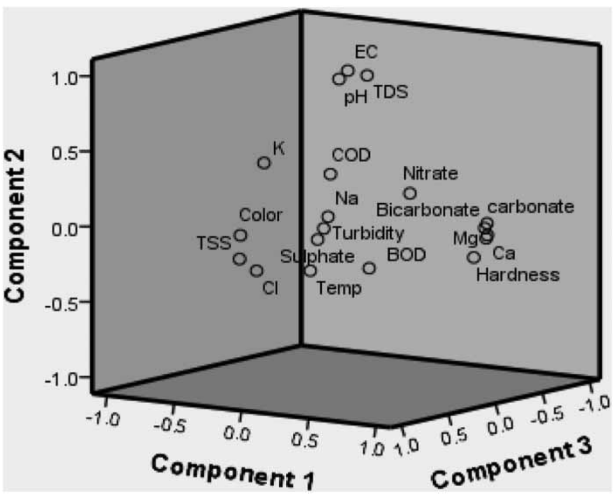

Figure 3 | Factor loadings of Lake Bosomtwe's physicochemical parameters.

overall quality of Bosomtwe Lake water for drinking purposes, whereas the NPI was performed on the parameters to estimate the extent of pollution contribution of individual parameters per sample relative to its permissible limit.

The water quality status for drinking is ranked on the scale of 95–100 (excellent), 80–94 (good), 65–79 (fair), 45–64 (marginal), and 0–44 (poor) (Lumb *et al.* 2006). The CCME-WQI value obtained was 56.79, indicating that Bosomtwe Lake's water condition in 2018 was rated as *marginal*. This suggests that the water quality of Lake Bosomtwe is threatened and conditions usually exceed permissible levels which require further treatment before drinking. Measured pH, temperature, TDS, and color exceeded their respective thresholds on all occasions which may affect human and aquatic life because a section of the locals depends on the lake's water for drinking and other domestic purposes.

Next, the NPI approach (Equation (8)) was utilized to identify pollution causing parameters by estimating the relative contribution of each parameter. The values recorded were compared to their respective WHO permissible levels. The calculated NPI value for all parameters measured for turbidity, TDS, TSS, hardness, BOD, nitrate, sulfate, calcium, chloride, and magnesium were less than one, suggesting the absence of pollution. However, in all 30 samples measured, the pH, EC, color COD, bicarbonate, sodium, and potassium recorded the NPI value exceeding one. The results suggest the presence of pollution and further express their threat to Bosomtwe Lake water quality.

Assessment of water quality for irrigation purposes

As a result of the elevated sodium and potassium levels, it was important to estimate the suitability of lake water for irrigation purposes because residents within the lake's catchment area bank on the lake during the dry season to irrigate their vegetable farmland. The EC, TDS, calcium, magnesium, and sodium ions determine the appropriateness of surface water to irrigate. In this light, SSP and SAR were calculated using Equations (9) and (10). According to Alam (2014), SSP and SAR measure the sodium hazard that may result from irrigation water polluted with sodium ions. Sodium ions polluted irrigation water may retard plant growth by affecting the soil's texture, alkalinity, permeability, and aeration (Bob *et al.* 2016).

Using Equation (9), SSP was estimated to measure the extent to which sodium ions in the water will react with chloride ions in soil to create an alkaline or saline condition in the soil. The threshold limit for a calculated SSP is 60%. However, the calculated SAP value in this study ranged between 94.43 and 95.43%, indicating unsuitability of the water system for irrigating farmlands within the catchment area

Next, the degree of adsorption of sodium ions in water by the soil was measured by calculating the SAR using Equation (10). According to Ayuba *et al.* (2013), the calculated SAR value ≤2 indicate that the water system is suitable for irrigation, while the SAR value >2 implies that the water system is not suitable for irrigation. The calculated SAR varied between 13.7 and 14.8, indicating the unsuitability of the water system for irrigating the farmland.

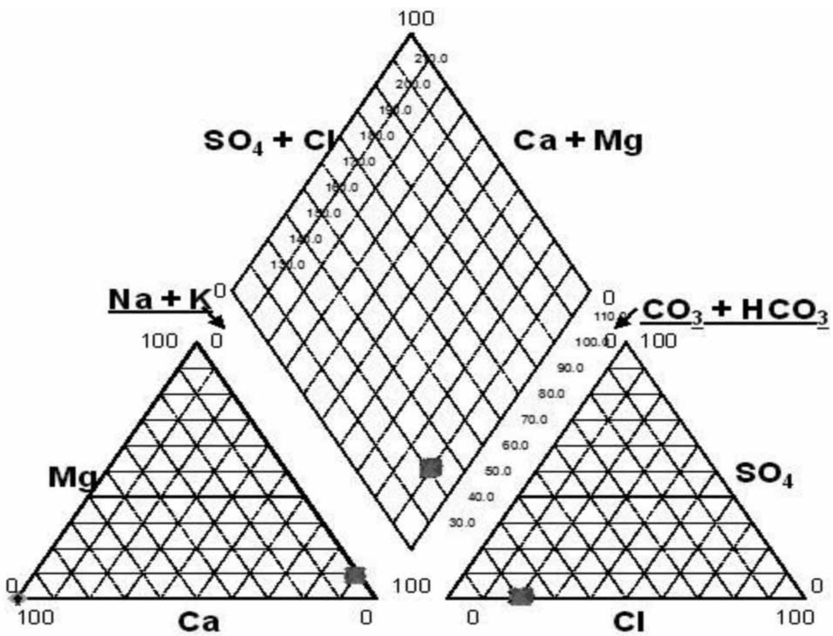

Figure 4 | A Piper–Trilinear diagram showing the geochemical classification of surface water.

The extreme values obtained for SSP and SAR express the likelihood that plant growth may be retarded by sodium ion pollution. Sodium ion pollution in soil may affect the texture by dispersing soil particles which may impede soil permeability and aeration (Taloor et al. 2020).

Hydrochemical analysis

The Bosomtwe Lake hydrochemical study revealed three hydrochemical faces as seen in Figure 4. The three faces comprise sodium and potassium type, bicarbonate type, and sodium bicarbonate type. The faces suggest that alkalies earth and weak acids dominate the water chemistry of the lake. The dominant cations are Na^+ (82.22%) followed by K^+ (8.36%), Mg^{2+} (8.25%), and Ca^+ (1.17%), respectively. The dominant anions are HCO_3^- (79.39%) followed by Cl^- (20.17%), SO_4^- (0.38), and NO_3^- (0.06), respectively. TDS shifts toward rock domination from the Gibbs plot (Figures 5 and 6), which indicates that water–rock interaction is the underlying process behind water evolution. Hence, the dissolution of carbonates through acidic precipitation and accumulation of ions control the chemistry of the surface water. The US Salinity Laboratory (USSL) diagram (Figure 7) revealed that all the water samples fell under high salinity hazard (C3–S3) and high sodium (alkali) hazards that indicate water unsuitability for farming purposes.

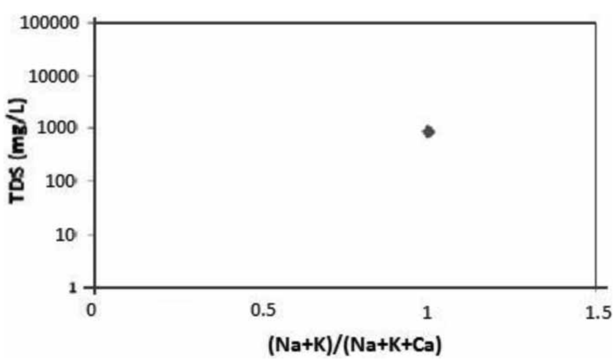

Figure 5 | Gibbs ratio of cations with relative TDS.

CONCLUSION

Thirty samples of water were collected for hydrochemical and water quality analyses. The parametric values for pH, EC, color, COD, sodium, and potassium exceeded the WHO and CCME permissible limit. The WQI assessment showed that the lake water is not suitable for human consumption. The Piper–Trilinear diagram showed three faces that indicate the lake's chemistry which is dominated by alkalies earth and weak acids. The Gibbs ratio revealed that the exchanges between rock and water control Lake Bosomtwe's water chemistry. From the USSL diagram, all the 30 water samples fell under high salinity hazard and high sodium (alkali) hazards rendering them unsuitable for irrigation purposes. Principal component analysis revealed that the main contributors of pollution were geogenic, domestic and agricultural runoffs, seasonal variation, unchecked application of fertilizers, and agrochemicals.

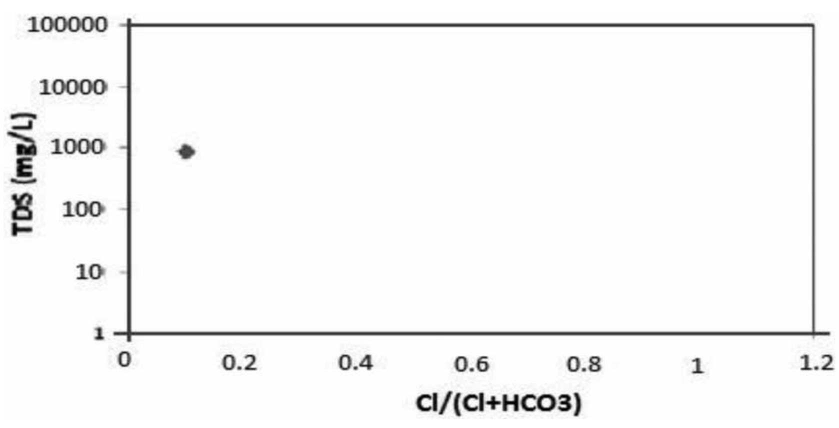

Figure 6 | Gibbs ratio of anions with relative TDS.

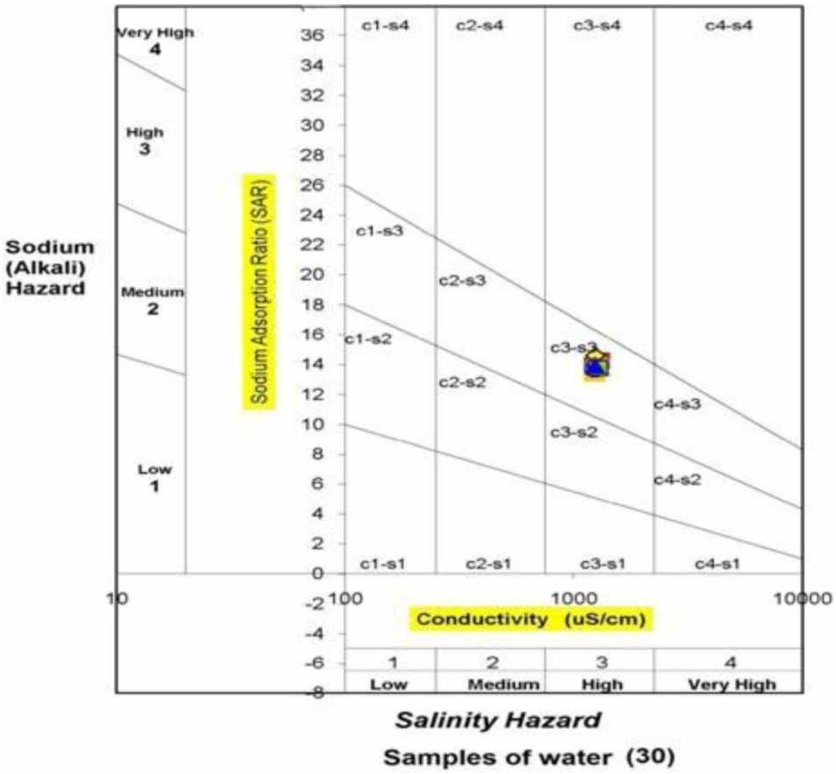

Figure 7 | Salinity hazard classification based on the USSL 1954.

Five statistically significant clusters were identified as monitoring sites. The findings will provide a reference for policymakers and decision-makers at Lake Bosomtwe.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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