



## Research paper

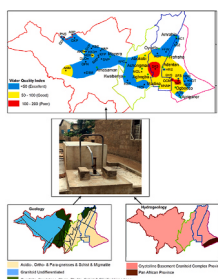
## Assessing groundwater quality in peri-urban Accra, Ghana: Implications for drinking and irrigation purposes

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## HIGHLIGHTS

- Groundwater quality available to >630,000 inhabitants in peri-urban Accra established.
- 92% of groundwater samples classified as good or excellent quality based on WQI.
- Groundwater from most boreholes categorised as suitable for irrigation.
- High influence of geology and hydrogeology on water quality.
- The dominant water type in the study area is NaCl.

## GRAPHICAL ABSTRACT



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## ABSTRACT

In many developing countries, cities are faced with rising water demand due to rapidly increasing population, inadequate municipal water supply and growing sanitation pressure. Consequently, groundwater resources are being heavily relied on to meet the demand. However, the long-term supply and quality of groundwater are threatened by multiple anthropogenic pressures. This study assessed the quality and suitability of groundwater available to more than 600,000 inhabitants in several peri-urban communities in Accra, the capital city of Ghana. Thirty-six (36) borehole samples were analysed for their suitability for domestic and irrigation purposes based on relevant physicochemical parameters. In addition, water quality index (WQI), sodium absorption ratio, and relevant statistical plots were employed to assess the groundwater's quality and suitability for domestic and irrigation purposes. The results indicate that almost all parameters measured were within the WHO recommended limits for drinking water for most samples. This is reflected in the classification of 92% of water samples as good or excellent quality for domestic purposes using WQI. The abundance of ions in groundwater followed the trend:  $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$  for cations, and  $\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^- > \text{F}^- > \text{NO}_3^-$  for anions. By using principal component and hierarchical cluster analyses, the study identified mineral dissolution and anthropogenic activities as the main factors influencing groundwater chemistry in the study area. These factors resulted in mixed water types, viz: Na–Ca–Mg–Cl and Na–Ca–Mg–SO<sub>4</sub>, and Na–Cl as the dominant water type. Classifications based on the Wilcox and USSS diagrams suggest that groundwater in the study area is generally suitable for irrigation. Given that these boreholes are new, the results from this study represent background levels and have

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important implications for groundwater development and management in the rapidly developing capital of Ghana.

### 1. Introduction

Globally, urbanisation is on the increase. The rate of increase is substantial in many sub-Saharan African countries and mostly outstrips the supply of resources, including pipe-borne water. In Ghana, an estimated 57% of the population live in urban areas, with an annual urban growth rate of about 3.34% compared to a rural growth rate of 0.69% (UNDESA, 2018). Additionally, the urban population of approximately 18 million is expected to more than double by 2050, placing tremendous pressure on urban resources.

In Accra, the capital city of Ghana, access to potable water is under massive pressure from rapid urbanisation. Based on provisional results of Ghana’s most recent population and housing census (2021), the Greater Accra Region, which is the location of Accra, is currently the most populous in the country (GSS, 2021). Many of the new inhabitants of Accra are based in peri-urban settlements where municipal water supply is lacking. As a result, groundwater resources are becoming the primary source of water for many urban/peri-urban communities in the country through the sinking of boreholes for domestic, industrial and irrigation purposes (Yidana et al., 2011).

However, the interplay of a rapidly growing urban population, increasing exploitation of water resources and escalating pollution from anthropogenic activities have combined to exacerbate the vulnerability and potential contamination of aquifers (Burri et al., 2019; Jia et al.,

2020; Rezaei et al., 2020; Saka et al., 2013). Anthropogenic activities such as physical changes to landscapes, application of synthetic chemicals, and massive exploitation of underground water resources threaten the sustainability of future water supply in urban areas and amplify the risks of water scarcity, particularly among poor urban dwellers. This situation is projected to worsen under climate change scenarios (Ahmad and Al-Ghouti, 2020; Bodrud-Doza et al., 2020; Saka et al., 2013). These developments have occasioned the need to investigate the state and fate of groundwater resources in many cities in the African sub-region (Cobbing and Hiller, 2019).

Groundwater quality and development has been highly researched in Ghana for decades and has played a pivotal role in the livelihoods of people in hundreds of communities (Anornu et al., 2017; Sunkari et al., 2020; Yidana et al., 2008, 2012). Nonetheless, groundwater development and use, mainly through the sinking of boreholes, have been primarily restricted to rural areas and the semi-arid Northern regions of the country (Akurugu et al., 2020; Chegbeleh et al., 2020; Loh et al., 2020; Lutz et al., 2007; Nsiah et al., 2018; Sunkari and Abu, 2019; Yidana et al., 2008; Zango et al., 2019). Until recent years, groundwater developments in southern Ghana and urban areas of the country have been low and restricted mainly to private boreholes (Kortatsi, 2006; Kortatsi and Jorgensen, 2001; Saka et al., 2013; Sunkari et al., 2019, 2020). However, given the growing population burden, which is not matched by development in surface water infrastructure, groundwater resources

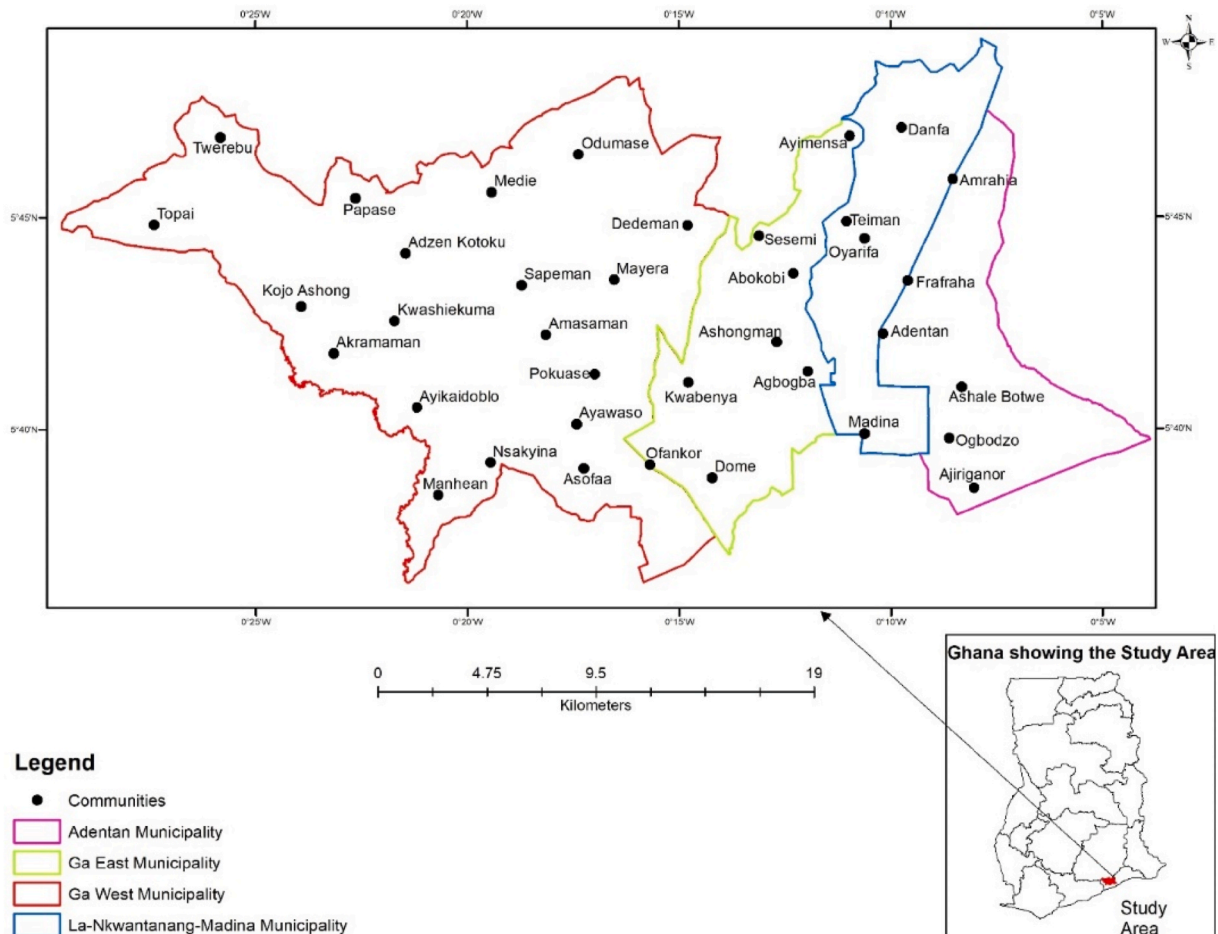
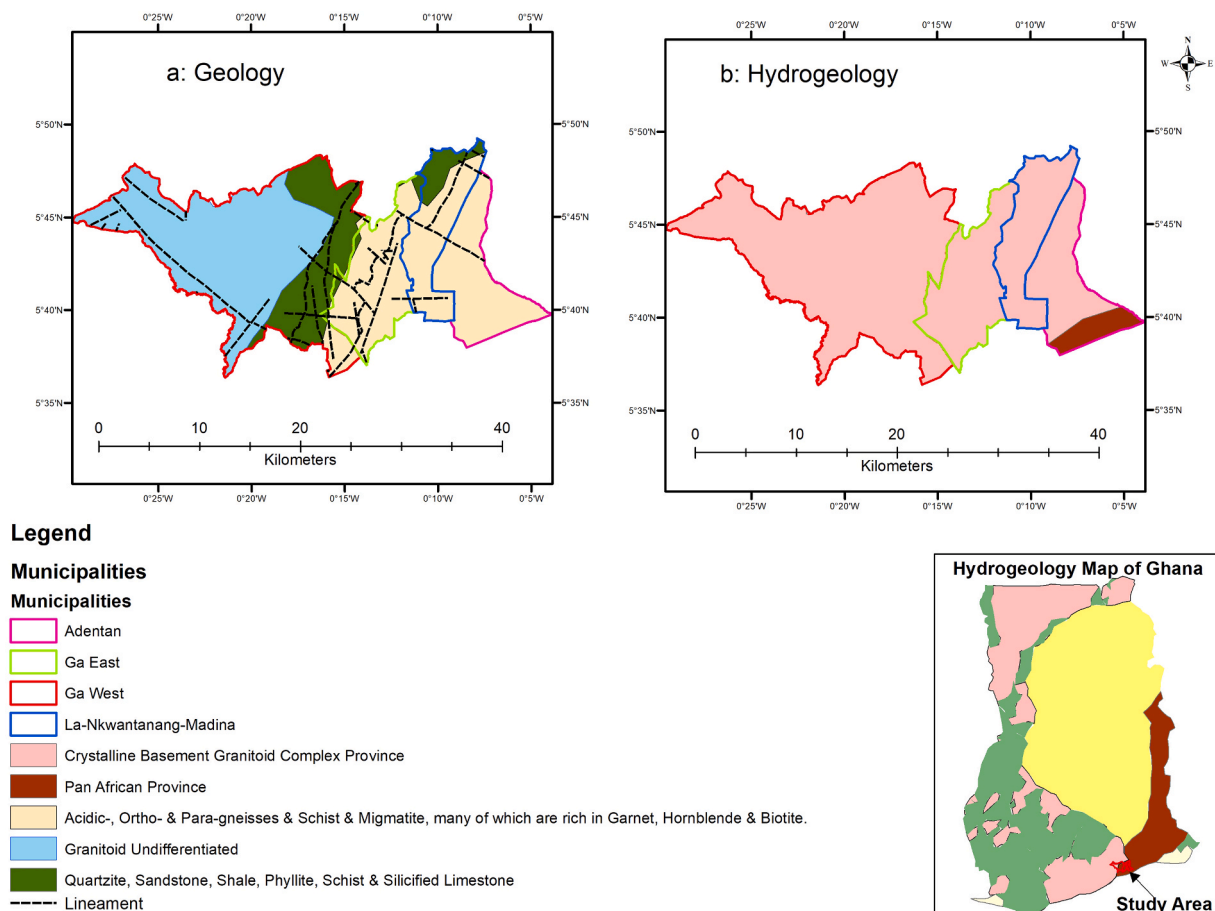


Fig. 1. Map of the study area showing major communities.



**Fig. 2.** (a): Geological map of the study area illustrating the structures within the rock types. (b): Hydrogeological characteristics of the study area.

present a more affordable means of water access and are rapidly becoming an essential proportion of urban water supply (Saka et al., 2013). This has led to increasing research into groundwater resources in Ghana's urban areas, including Accra (Foppen et al., 2020; Hagan and Darko, 2020; Kortatsi, 2006; Saka et al., 2013; Sunkari et al., 2019).

As is occurring in other parts of the world, peri-urban Accra is faced with an increasing urban sprawl characterised by unplanned settlements and land-use change, promoting unsustainable developments and associated environmental concerns in the city (Yiran et al., 2020). Studies show that the study area, which includes Ga West, Ga East, La-Nkwantanang-Madina, and Adentan municipalities of Accra, is faced with significant changes in land use, increasing commercial activities, massive generation of waste, and improper waste management systems (Sunkari et al., 2019; Tibu et al., 2019). Moreover, evidence suggests that the rate of environmental degradation and pollution in Ghana's capital city is mirrored by the population growth rate (Owusu, 2002). These challenges have been associated with adverse health consequences, including one of the highest prevalence of Buruli ulcer cases in the country within some of the peri-urban communities under study (Kofie et al., 2008; Owusu and Adamba, 2012). In addition, rapid population growth, unplanned developments and other anthropogenic activities act as significant contributors to groundwater quality degradation (Antony et al., 2020). Previous studies by Sunkari et al. (2019) and Saka et al. (2013) have shown that groundwater chemistry in the Ga West Municipality of Accra is primarily controlled by seawater intrusion, leaching of chemicals from pit latrines and refuse dumps, interaction with minerals and agrochemicals.

While studies on groundwater quality in some of the municipalities in the study area exist, they have been restricted to fewer boreholes in few locations often for private use. Given the rising concern for water

quality and scarcity in peri-urban Accra, the government of Ghana through the Community Water and Sanitation Agency (CWSA) has prioritised the sinking of boreholes in several communities to address potable water needs of thousands of its residents. This study provides the most comprehensive groundwater quality assessment of carefully planned and engineered boreholes located in the Ga West, Ga East, La-Nkwantanang-Madina, and Adentan municipalities. By employing a combination of multivariate statistical methods and conventional hydrochemical techniques, the study examined the main factors controlling the hydrochemistry of groundwater in the study areas. The findings provide valuable information on the quality of groundwater resources within a large portion of peri-urban Accra that will help inform policy on the development, management, and sustainable use of groundwater resources within the Greater Accra Region of Ghana.

## 2. Study area

### 2.1. Location and climate

This study was carried out in four of the fastest-growing municipalities in Accra: Ga West, Ga East, La-Nkwantanang-Madina, and Adentan (Fig. 1). The study area lies within longitudes 5°35'0"N and 5°50'0"N and latitudes 0°30'0"W and 0°50'0"W. The area shares boundaries to the north with Upper West Akim, Nsawam Adoagyiri and Akwapim South districts, Ga South Municipal to the west, Kpone Kata-manso to the east, and Ga Central, Okaikwai North, Ayawaso West, Ledzokuku, Krowor, and Tema West municipalities to the south.

These municipalities were chosen because of a combination of factors, some of which are discussed herein, that affect the demand and supply/availability of groundwater. Until recent years, these

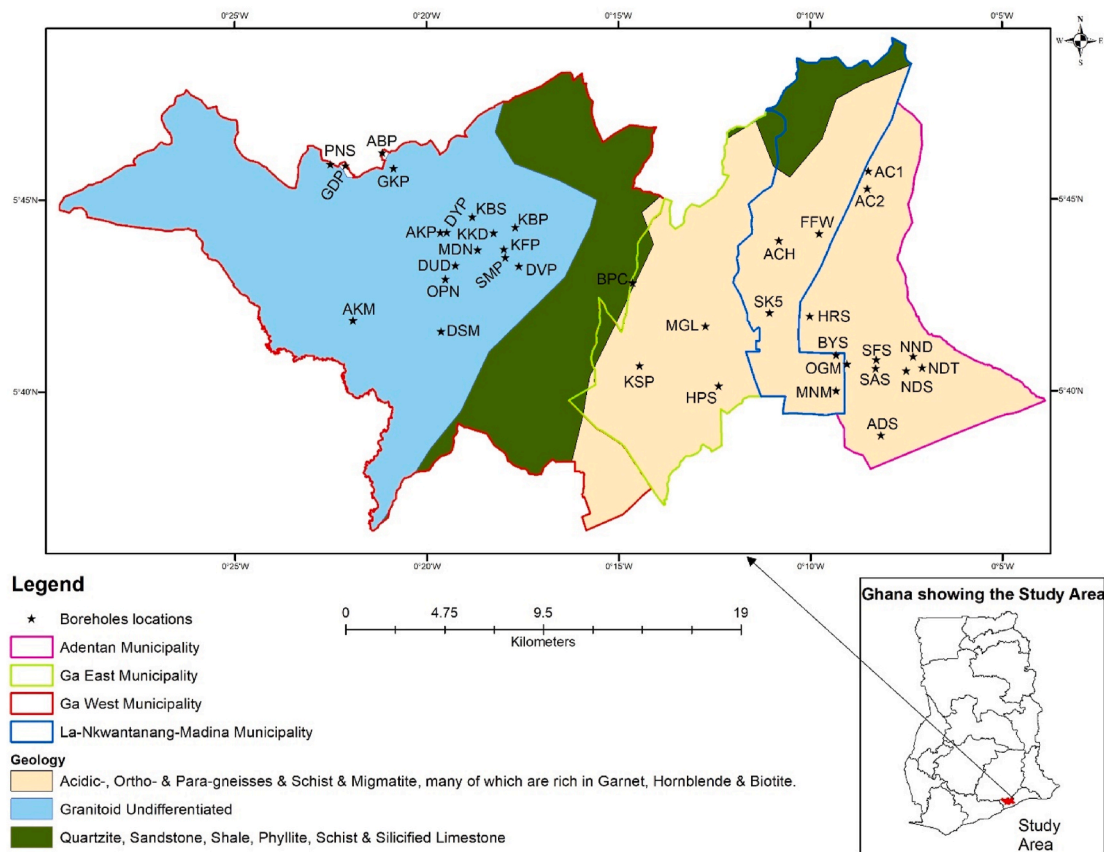


Fig. 3. Map of the study area illustrating the locations of boreholes over the geology.

municipalities were considered rural but are now urban areas due to the rapid urbanisation of Accra (Yiran et al., 2020). Studies have attributed the settlement or relocation of people to peri-urban areas such as the study areas to several factors related to cost and affordability, including lower rent, preferences, changing lifestyle and lower land prices (Baye et al., 2020; Opong and Yeboah, 2013). As more and more people move into these peri-urban areas, they begin to densify and the demand for services, including water for domestic and other purposes, increases. However, the provision of potable water in these peri-urban areas remains a major challenge due to cost.

Given that many of the communities in these municipalities are not connected to municipal water supply, there is a growing dependence on groundwater supply as a source of potable water for domestic use. In this regard, several boreholes have been drilled in these communities by the Community Water and Sanitation Agency (CWSA) of Ghana for water supply purposes. The purpose is not only to meet the growing domestic water needs but also the associated increases in industrial and agricultural water demand in the communities. At the same time, the rapid urbanisation and developments in the areas under study have been associated with poor planning and are largely characterised by the gross absence of appropriate sanitary facilities. According to the Ghana Statistical Service, nearly one-quarter of households in the study area are without conventional toilet facilities (GSS, 2012), posing considerable risks to the environment.

In addition, groundwater availability may be impacted by climate change and climate variability. The area is characterised by high temperatures ranging between 25.1 °C and 32.1 °C and low rainfall between 79 cm yr<sup>-1</sup> to 127 cm yr<sup>-1</sup> (GSS, 2012). The rainfall availability is projected to further decrease due to climate change (IPCC, 2014), with negative implications for groundwater recharge. The effect of low rainfall on groundwater recharge may be exacerbated by the continuous increase in human settlement and other activities, which make the land

surface impervious, resulting in more runoff and less infiltration (Hagan et al., 2018).

## 2.2. Geology and hydrogeology

The geology of the study area is predominantly Dahomeyan and Togo Structural rocks intruded by undifferentiated granitoid. The Dahomeyan comprises acidic-, ortho-, and para-gneisses, schist and migmatite, many of which are rich in garnet, hornblende, and biotite (Fig. 2a).

The Dahomeyan Structural Unit in Ghana generally consists of felsic and mafic gneisses that alternate (Grant, 1967). The main litho-tectonic units of the Dahomeyan are: (i) quartzo-feldspathic and augen-gneisses locally referred to as Ho gneisses, (ii) a suture zone of distinct mafic and ultramafic rocks, and (iii) a granitoid gneiss-migmatite assemblages. The Dahomeyan is distinct from other rocks in the country because of its composition of high-grade metamorphic rocks (Holm, 1973). The Togo Structural Unit within the study area comprises schist, quartzite, and phyllite, with rare occurrences of sandstone, shale, and silicified limestone (Fig. 2a). The main lithologies of the Togo Unit are schists, quartzites, phyllites and phyllonites. The phyllites and phyllonites are intensely deformed and usually occur along with thrust contact between Togo and Dahomeyan rocks or as thin intercalations with quartzite (Anani et al., 2019; Darko et al., 2019). Nude et al. (2015) have reclassified shale, sandstone, and silicified limestone to belong to the Buem Structural Unit. Structurally, regional lineament within the study area indicates two main orientations of NE-SW and NW-SW trends. These fractures tend to control the borehole yields within the study area.

In Ghana, the hydrogeological terranes follow the geological terranes to a large extent (Dapaah-Siakwan and Gyau-Boakye, 2000). Banoeng-Yakubo et al. (2010) have identified five hydrogeological provinces following the work of Gyau-Boakye and Tumbulto (2000). These

**Table 1**  
Water quality index (WQI) classification.

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

delineations are based on the knowledge and understanding of the rock types on current knowledge of the rock types, well depths, well yields, groundwater quality, among others. The hydrogeology of the study area falls under the Basement Complex Province (aquifers of all granitoids) and the Pan African Province (aquifers of the Buem and Togo Structural Units) (Fig. 2b).

The Dahomeyan System is characterised by low yields of groundwater from hand-dug wells and boreholes (Dapaah-Siakwan and Gyau-Boakye, 2000). The low yield is due to the rock types (gneisses) made of colossal crystalline structure and the impervious nature of their weathered material (clay). The Togo Structural Unit, which is highly fractured and jointed with folded layers of rocks, build a fracture flow aquifer system. Recharge to groundwater within this basement complex type is high, with highly variable depth to groundwater table (Yidana et al., 2014). Thus, within the Togo Structural Unit, the degree and extent of fracturing control borehole yields. The geological formations characterising the study area, therefore, suggest that the hydrogeological conditions would be controlled by secondary permeabilities arising from structures (fractures and joint systems) due to deformation.

Locally, a single aquifer unit within the weathered zone (made up of quartzite-schist formations) has been identified for the Ga East and Adentan municipalities based on available data and current understanding of the hydrogeology. The aquifer thickness ranges from 6.5 m to 31.5 m, and the borehole depths range from 50 m to 90 m (Hagan and Darko, 2020). Preliminary studies into the aquifer system within the Ga West municipality similarly reveals a single aquifer unit within the weathered zone (granite formation) with aquifer thickness ranging from 10 m to 36 m and borehole depths of 32 m–78 m.

### 3. Materials and methods

#### 3.1. Sample collection and hydrochemical analysis

Groundwater samples from thirty-six (36) newly constructed boreholes within the study area were used in this study (Fig. 3). Water samples were collected into pre-washed high-density polyethylene bottles of 500 mL capacity. All samples were stored at < 4 °C using ice in an ice-chest prior to laboratory analysis.

To assess the water quality, samples were analysed for the following physicochemical parameters: hydrogen ion concentration (pH), electrical conductivity (EC), total dissolved solids (TDS), total hardness (TH), and the ions chloride (Cl<sup>-</sup>), fluoride (F<sup>-</sup>), sulphate (SO<sub>4</sub><sup>2-</sup>), nitrate (NO<sub>3</sub><sup>-</sup>), bicarbonate (HCO<sub>3</sub><sup>-</sup>), calcium (Ca<sup>2+</sup>), magnesium (Mg<sup>2+</sup>), sodium (Na<sup>+</sup>) and potassium (K<sup>+</sup>).

The analysis of samples was conducted at the Water Research Laboratory of the Centre for Scientific and Industrial Research (CSIR) in Accra and the Water Quality Laboratory of the Ghana Water Company Limited in Ho, Ghana. Samples were analysed based on standard procedures for water analysis as outlined by the American Public Health Association (APHA). The pH was measured at room temperature using a pH meter (Suntex, Model No. SP-2100). Electrical conductivity and TDS were measured using a Lovibond ConsoDirect con 200 instruments. Total Hardness (HD), calcium and magnesium were measured using the EDTA titrimetric method. Potassium and sodium were determined using a digital flame photometer (GallenKamp, FGA-350-1). The analysis of nitrates and sulphates were performed by employing an

ultraviolet-visible (UV-Vis) spectrophotometer, using the hydrazine reduction and barium chloride reduction, respectively. Chloride was estimated by the argentometric titration method, while fluoride was determined using an ion-selective electrode method (Orion, Thermo Scientific).

#### 3.2. Data processing, multivariate statistical analysis and water quality assessment

The results obtained from the physicochemical analysis was used to characterise the quality of groundwater, first, by comparing values of the physicochemical parameters with their respective WHO standards. In addition, other methods for quality assessment of groundwater, including the water quality index, were employed. The Water Quality Index (WQI) method was used to evaluate the suitability of water for drinking/domestic purposes. The computation of the WQI is a four-step approach:

The first step involves assigning weight ( $w_i$ ) to each of the twelve-parameter considered (pH, TH, TDS, Ca<sup>2+</sup>, Mg<sup>2+</sup>, Na<sup>+</sup>, K<sup>+</sup>, HCO<sub>3</sub><sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, Cl<sup>-</sup>, NO<sub>3</sub><sup>-</sup>, F<sup>-</sup>) for the computation of WQI based on their relative importance to the overall quality of groundwater. Parameters such as pH, NO<sub>3</sub><sup>-</sup>, and F<sup>-</sup> were assigned a maximum weight of 5 due to their significant role in the water quality assessment, while weights ranging from 2 to 4 were assigned to the remaining parameters based on their relative roles in the water quality assessment.

The second step involves the computation of relative weight of each parameter:

$$W_i = \frac{w_i}{\sum_{i=1}^n w_i}$$

where  $W_i$  is the relative weight,  $w_i$  is the weight of each parameter and  $n$  is the number of parameters.

The third step is based on a computation of the quality rating scale ( $q_i$ ) for each parameter:

$$q_i = \frac{C_i}{S_i} \times 100$$

where  $q_i$  is the quality rating,  $C_i$  is the concentration of each parameter in mg L<sup>-1</sup> and  $S_i$  is the WHO standard for each parameter in mg L<sup>-1</sup>.

The fourth step is the determination of the sub-index (SI) for each parameter. This is then used to calculate the WQI:

$$SI = W_i \times q_i$$

The overall WQI was then computed by summing all the sub-index values for each sample:

$$WQI = \sum_{i=1}^n SI$$

The computed WQIs were then classified using the classification model proposed by Sahu and Sikdar (Table 1).

#### 3.3. Irrigation water quality assessment

The quality of groundwater for irrigation purposes was determined using several indices, including the United States Salinity Laboratory (USSL) diagram, the Wilcox diagram, and values of EC, TH, KI, MH, PI, SAR and %Na. These indices are considered effective approaches to assessing the suitability of water for irrigation purposes and are described below:

##### 3.3.1. Kelly's Index (KI)

Kelly's index (KI) expresses the ratio between sodium ions versus calcium and magnesium ions present in groundwater as follows:

**Table 2**  
Basic statistics on major physicochemical parameters.

Parameter	Minimum value	Mean	Maximum value	Std. deviation	Co-eff.of variation	Total number within WHO limit	Total number outside WHO limit	WHO Limits
pH	5.90	7.27	9.90	0.82	11.3	30	6	6.5–8.5
EC	260.00	1389.55	6628.00	1315.84	94.70	29	7	2000
TDS	130.0	727.7	3314.0	680.2	93.5	28	8	1000
TH	30.0	247.7	1067.0	244.2	98.6	23	13	200
Ca <sup>2+</sup>	6.40	61.73	283.00	65.33	105.88	34	2	200
Mg <sup>2+</sup>	2.4	22.7	87.4	20.4	89.9	36	0	150
Na <sup>+</sup>	11.50	123.70	703.40	136.77	110.47	32	6	200
K <sup>+</sup>	1.00	2.11	5.30	0.98	46.487	36	0	30
HCO <sub>3</sub> <sup>-</sup>	11.1	84.4	353.8	68.4	81.1	35	1	250
SO <sub>4</sub> <sup>2-</sup>	10.0	99.5	714.0	138.4	139.0	34	2	250
Cl <sup>-</sup>	18.0	207.6	1099.0	243.3	117.2	28	8	250
NO <sub>3</sub> <sup>-</sup>	<0.001	0.110	0.463	0.137	124.1	36	0	50
F <sup>-</sup>	<0.001	0.124	0.472	0.124	100.533	36	0	1.5

$$KI = \left[ \frac{Na^+}{(Ca^{2+} + Mg^{2+})} \right]$$

KI thus indicates the amount of sodium in water compared to calcium and magnesium.

### 3.3.2. Magnesium Hazard (MH)

The magnesium hazard (MH) index helps to measure the relative amount of magnesium in water and hence its possible impact on soil and crops when used for irrigation. MH is computed as follows:

$$MH = \left[ \frac{Mg^{2+}}{(Ca^{2+} + Mg^{2+})} \right] \times 100$$

### 3.3.3. Permeability Index (PI)

The permeability index (PI) measures the relative concentrations of HCO<sub>3</sub><sup>-</sup> and Na<sup>+</sup> to those of sodium, magnesium and calcium, based on the equation below (Doneen, 1964):

$$PI = \left[ \frac{(Na^+ + \sqrt{HCO_3^-})}{(Na^+ + Ca^{2+} + Mg^{2+})} \right] \times 100$$

### 3.3.4. Sodium absorption ratio (SAR)

The sodium absorption ratio (SAR) indicates the degree to which other cations may be replaced by sodium. The value of SAR is calculated based on the formula proposed by (Richards, 1954):

$$SAR = \frac{Na^+}{\sqrt{\frac{1}{2}(Ca^{2+} + Mg^{2+})}}$$

### 3.3.5. Percentage sodium (%Na)

The percentage sodium (%Na) is another vital factor in characterising the suitability of groundwater for irrigation purposes. The Na<sup>+</sup> content is expressed as a soluble sodium percentage, and is computed as follows:

$$\%Na = \left[ \frac{(Na^+ + K^+)}{(Na^+ + K^+ + Ca^{2+} + Mg^{2+})} \right] \times 100$$

## 3.4. Quality assurance

Several quality assurance measures were undertaken, from sampling and sample pretreatment to analysis and data treatment aimed at ensuring the quality of the data produced. These include the use of analytical grade reagents and chemicals, as well as sample and reagent blanks. All samples were analysed in duplicates, and where necessary, in triplicates.

The assurance of the quality and validity of data obtained in work

was measured by calculating the charge balance error (CBE) for each sample. A CBE of  $\pm 5\%$  was obtained in almost all samples, suggesting a perfect quality of analysis. A few samples showed a CBE of 10%, which was assumed to be of good quality (APHA, 2012).

## 4. Results and discussions

### 4.1. Hydrochemistry

The descriptive statistics of the results obtained from the chemical analysis of all parameters studied are presented in Table 2, together with their applicable WHO guideline values for drinking water. The pH of samples showed little variability with few outliers. The values ranged from 5.90 to 9.90, with a mean value of  $7.27 \pm 0.14$ , suggesting the groundwater under study may be considered largely neutral to slightly basic. However, approximately 17% of the water samples fell outside of the WHO recommended standard of 6.50–8.50 for drinking water. Nonetheless, the pH value of water in itself is not known to have a significant effect on human consumption. Rather, the pH effect is largely based on its source and influence on the dissolution of other elements, some of which may be harmful. In this study, the pH values reported are generally within optimal levels and do not favour the excessive dissolution of ions and heavy metals. However, a low pH of 5.90 was obtained from a borehole at New Nmai Djor (NND), raising concern for the dissolution of heavy metals, some of which may be toxic upon consumption (Yidana, 2010). The low pH may be due to the dissolution of granites, phyllites and schist in the Togo formation (Ganyaglo et al., 2019; Saka et al., 2013).

The EC of groundwater samples ranged from 260.0 to 6628.0  $\mu S cm^{-1}$  with a mean value of  $1389.5 \pm 219.3 \mu S cm^{-1}$ . The large standard deviation in the mean value reflects the wide variation in the measured values from the various wells. Approximately 19% of EC values were above the recommended standard of 2000.0  $\mu S cm^{-1}$ . Similar to the EC data, the values of TDS showed a wide variability ranging from 130.0 mg L<sup>-1</sup> to 3314.0 mg L<sup>-1</sup> with a mean value of  $727.7 \pm 113.36 mg L^{-1}$ . Given the WHO guideline of 1000.0 mg L<sup>-1</sup>, 22% of the samples analysed reported values higher than the recommended limit. The values of total hardness (TH) also displayed a high variation with a minimum of 30.0 mg L<sup>-1</sup> and a maximum of 1067.0 mg L<sup>-1</sup> and a mean of  $247.70 \pm 40.70 mg L^{-1}$ . Approximately 36% of the samples were above the WHO limit of 200.0 mg L<sup>-1</sup>.

Based on the mean values of parameters, the abundance of ions analysed in this study increased as follows:  $K^+ < Mg^{2+} < Ca^{2+} < Na^+$  for cations and  $NO_3^- < F^- < HCO_3^- < SO_4^{2-} < Cl^-$  for anions. The levels of K<sup>+</sup> and Mg<sup>2+</sup> for all 36 sampled boreholes were within their respective WHO acceptable limits for drinking water. However, approximately 6% and 11% of water samples showed levels of Ca<sup>2+</sup> and Na<sup>+</sup> respectively, above the WHO recommended limits. For anions, all 36 sampled boreholes had levels of NO<sub>3</sub><sup>-</sup> and F<sup>-</sup> well within their respective WHO

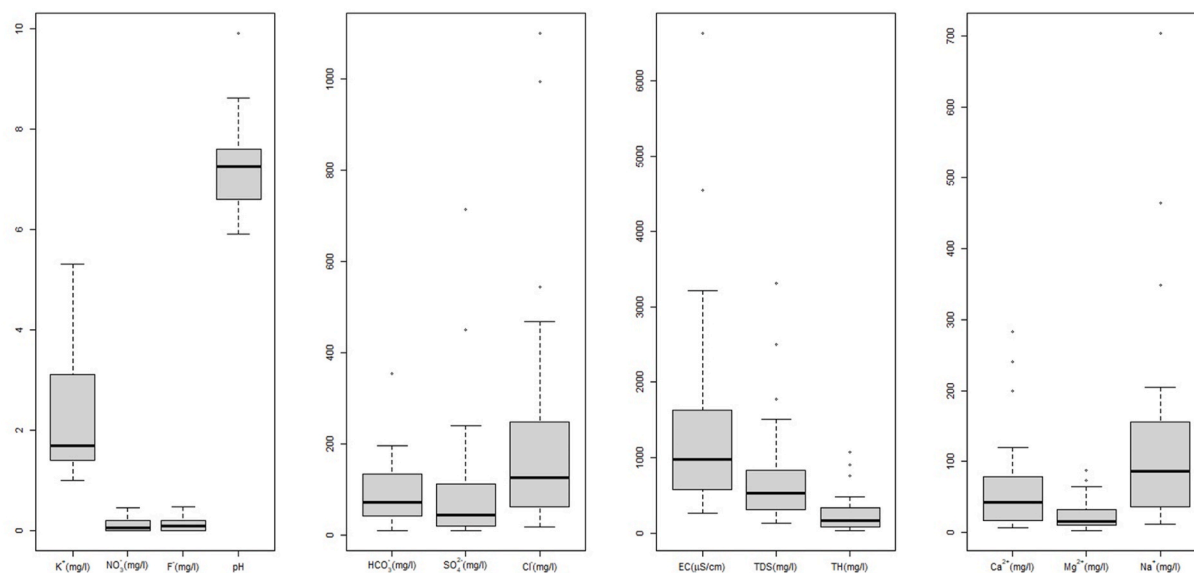


Fig. 4. Boxplot of physicochemical parameters.

Table 3

Correlation matrix between water quality parameters.

	pH	EC	TDS	TH	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Na <sup>+</sup>	K <sup>+</sup>	HCO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	Cl <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	F <sup>-</sup>
pH	1.00												
EC	-0.09	1.00											
TDS	-0.11	<b>1.00</b>	1.00										
TH	-0.15	<b>0.93</b>	<b>0.94</b>	1.00									
Ca <sup>2+</sup>	-0.14	<b>0.94</b>	<b>0.95</b>	<b>0.99</b>	1.00								
Mg <sup>2+</sup>	-0.21	<b>0.89</b>	<b>0.91</b>	<b>0.97</b>	<b>0.95</b>	1.00							
Na <sup>+</sup>	-0.08	<b>0.94</b>	<b>0.93</b>	<b>0.80</b>	<b>0.82</b>	<b>0.76</b>	1.00						
K <sup>+</sup>	-0.10	0.13	0.19	0.35	0.29	0.44	0.07	1.00					
HCO <sub>3</sub> <sup>-</sup>	0.21	0.44	0.41	0.32	0.37	0.24	0.37	-0.46	1.00				
SO <sub>4</sub> <sup>2-</sup>	-0.18	<b>0.76</b>	<b>0.79</b>	<b>0.79</b>	<b>0.78</b>	<b>0.80</b>	<b>0.78</b>	0.47	0.03	1.00			
Cl <sup>-</sup>	-0.14	<b>0.97</b>	<b>0.98</b>	<b>0.93</b>	<b>0.94</b>	<b>0.89</b>	<b>0.95</b>	0.24	0.31	<b>0.82</b>	1.00		
NO <sub>3</sub> <sup>-</sup>	-0.41	0.18	0.22	0.33	0.30	0.38	0.13	<b>0.56</b>	-0.40	0.48	0.25	1.00	
F <sup>-</sup>	-0.47	-0.16	-0.13	-0.09	-0.12	-0.04	-0.14	0.20	-0.45	-0.03	-0.11	<b>0.60</b>	1.00

recommended limits for drinking water. However, approximately 6% of boreholes had SO<sub>4</sub><sup>2-</sup> concentrations above the WHO recommended limit for drinking water, while 3% of samples showed concentrations of HCO<sub>3</sub><sup>-</sup> exceeding the WHO acceptable limit. The concentration of Cl<sup>-</sup> was highest among all ions considered, with levels exceeding the recommended maximum concentration in more than 22% of samples studied.

#### 4.2. Multivariate statistical analysis

A visual assessment of the distribution of data was performed using boxplots and are shown in Fig. 4. The boxplots show two or more large values that are distinct from the bulk of the data for Mg<sup>2+</sup>, Ca<sup>2+</sup>, and Na<sup>+</sup>. These observations can be considered as outliers. The distribution of all the cations is skewed to the right. These observations are similar to the boxplots for EC, TDS, and TH. The borehole with a pH value of 9.90 is quite distinct from the other wells and thus, can be considered an outlier. This renders the distribution right-skewed. The anions Cl<sup>-</sup>, HCO<sub>3</sub><sup>-</sup>, and SO<sub>4</sub><sup>2-</sup> show one or more outliers. The boxplot for each of these anions indicates right-skewness. However, NO<sub>3</sub><sup>-</sup> is slightly positively skewed while F<sup>-</sup> is approximately symmetric. Most parameters including Na<sup>+</sup>, K<sup>+</sup>, Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, pH, EC, and TDS showed the presence of at least one outlier contributing to the skewness of the distributions.

Pearson's correlation was computed to identify trends and correlation between the water quality parameters analysed (Table 3). In this regard, parameters that have a correlation coefficient ( $r$ ) of at least  $|0.5|$

are considered to be significantly correlated. The correlation matrix revealed significant correlations between several parameters, most of which are strong and positive. For instance, very strong positive correlations ( $\geq 0.89$ ) were recorded between EC and the following parameters, TDS, TH, Ca<sup>2+</sup>, Mg<sup>2+</sup>, and Cl<sup>-</sup>, due to the interdependence of EC on these parameters. This assertion is evident in the significant loadings of Ca<sup>2+</sup>, Mg<sup>2+</sup>, Na<sup>+</sup>, SO<sub>4</sub><sup>2-</sup> and Cl<sup>-</sup> with TDS and EC, also reported in other similar studies in the study area (Saka et al., 2013; Sunkari et al., 2019). On the other hand, pH showed a weak positive correlation with most parameters. Based on these relationships, a mixed water type system comprising Na-Ca-Mg-Cl and Na-Ca-Mg-SO<sub>4</sub> dominate the groundwater system in the area. These correlations were further visualised using scatter plot matrices (Fig. 5). The strong correlation between any two parameters is depicted by the linearity of the plot generated as observed for parameters such as EC and TDS (row 3 – column 2), and TDS and Ca<sup>2+</sup> (row 5 – column 3). Similarly, column 1 depicts a weak correlation that exists between pH and the other parameters.

In addition, Principal Component Analysis (PCA) was performed using the R statistical package to illustrate relationships between the physicochemical parameters (Badeenezhad et al., 2020; Khawla and Mohamed, 2020). The PCA of the 12 physicochemical parameters showed that over 80% of the total variation in the groundwater system in the study area is explained by the first two components (Table 4a). Component 1 (PCA-1) showed significant positive loadings with TDS, Cl<sup>-</sup>, TH, Mg<sup>2+</sup>, Na<sup>+</sup>, and SO<sub>4</sub><sup>2-</sup> (Table 4b), which may be attributable to mineral dissolution as a result of rock water interaction (Loh et al., 2020;



Fig. 5. Scatter diagram matrix for the physiochemical parameters.

Table 4a  
Total variance explained by components.

Component	Initial eigenvalues			Total			Cummulative %		
	Total	% of variance	Cummulative %	Total	% of variance	Cummulative %	Total	% of variance	Cummulative %
1	6.530	59.367	59.367	6.530	59.367	59.367	6.527	59.332	59.332
2	2.360	21.456	80.823	2.360	21.456	80.823	2.364	21.491	80.823
3	0.767	6.973	87.796						
4	0.503	4.573	92.369						
5	0.382	3.472	95.841						
6	0.276	2.509	98.350						
7	0.113	1.028	99.377						
8	0.043	0.387	99.765						
9	0.013	0.115	99.880						
10	0.008	0.076	99.956						

Table 4b  
Principal components.

	Components	
	1	2
TDS	0.983	-0.074
Cl <sup>-</sup>	0.980	-0.017
Ca <sup>2+</sup>	0.973	-0.011
TH	0.972	0.028
Mg <sup>2+</sup>	0.945	0.108
Na <sup>+</sup>	0.908	-0.111
SO <sub>4</sub> <sup>2-</sup>	0.856	0.216
F <sup>-</sup>	-0.118	0.841
NO <sub>3</sub> <sup>-</sup>	0.31	0.824
HCO <sub>3</sub> <sup>-</sup>	0.353	-0.685
pH	-0.150	-0.656

Saka et al., 2013; Yidana, 2010). Component 2 (PCA-2), on the other hand, showed significant positive loadings with F<sup>-</sup> and NO<sub>3</sub><sup>-</sup> and significant negative loadings with HCO<sub>3</sub><sup>-</sup> and pH. The significant positive loadings of NO<sub>3</sub><sup>-</sup> and F<sup>-</sup> with PCA-2 suggest the influence of

anthropogenic activities in the area (Yidana, 2010; Yidana et al., 2010). NO<sub>3</sub><sup>-</sup> and F<sup>-</sup> in groundwater could result from phosphate fertilisers from agricultural farms or the burning of coal or disposal of fly ash on the land surface. These are common activities that characterise the study area, and therefore, could contribute to significant amounts of these ions in groundwater in the study area.

Furthermore, using the “hclust” function in the statistical package R, a hierarchical cluster analysis (HCA) was performed for the parameters based on a hierarchical tree (dendrogram) using Ward’s method to project the similarities/correlations amongst them (Fig. 6) (Ibe et al., 2020; Loh et al., 2020). Results from HCA suggest two distinct clusters with a phenon line drawn at a linkage distance of 22 (Fig. 6). Cluster 1 comprises TH, Ca<sup>2+</sup>, Mg<sup>2+</sup>, TDS, Cl<sup>-</sup>, Na<sup>+</sup>, SO<sub>4</sub><sup>2-</sup>, pH, and HCO<sub>3</sub><sup>-</sup>, whereas Cluster 2 consists of NO<sub>3</sub><sup>-</sup>, F<sup>-</sup>, and K<sup>+</sup>. Cluster 1 suggests the influence of ion dissolution as a result of rock-water interactions and is in agreement with results from PCA-1 (Table 4b). The sub-clustering of Ca<sup>2+</sup>, Mg<sup>2+</sup>, and TH is clearly seen in the HCA, which corroborates the contribution of carbonate hardness. Similarly, the relation between Na<sup>+</sup> and Cl<sup>-</sup> as well as their contribution to TDS (Tables 3 and 4b) is clearly evident in the HCA, where they are linked at the closest linkage distance.

Rescaled Distance Cluster Combine

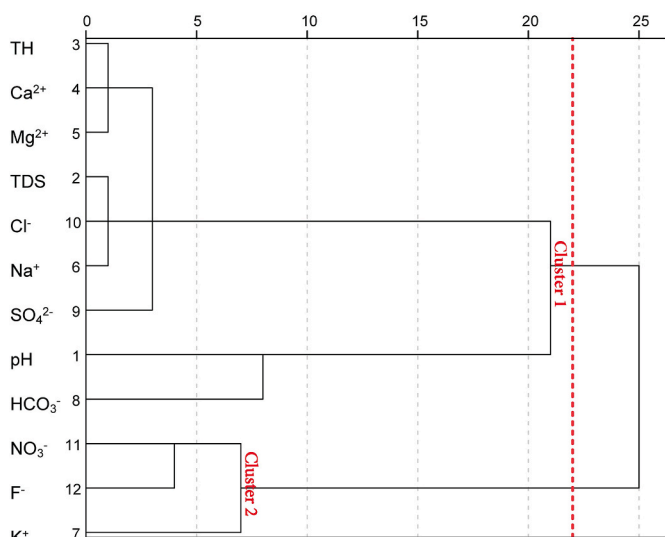


Fig. 6. Dendrogram for R-mode HCA

Table 5  
Parameters used to compute WQI.

Parameter	WHO (2017) Standard ( $S_i$ ) ( $\text{mg L}^{-1}$ )	Weight ( $w_i$ )	Relative Weight ( $W_i$ )
pH	8.5	5	0.1282
TDS	1000	4	0.1026
TH	200	4	0.1026
Ca <sup>2+</sup>	200	2	0.0513
Mg <sup>2+</sup>	150	2	0.0513
Na <sup>+</sup>	200	2	0.0513
K <sup>+</sup>	30	2	0.0513
HCO <sub>3</sub> <sup>-</sup>	250	2	0.0513
SO <sub>4</sub> <sup>2-</sup>	250	3	0.0769
Cl <sup>-</sup>	250	3	0.0769
NO <sub>3</sub> <sup>-</sup>	50	5	0.1282
F <sup>-</sup>	1.5	5	0.1282
		$\sum w_i = 39$	$\sum W_i = 1$

Table 6  
Computed WQIs for the various borehole samples.

Borehole Location	WQI	Borehole Location	WQI
SK5	170.03	SFS	38.26
FFW	42.67	SMP	24.48
KSP	40.15	DVP	48.37
BPC	16.94	KBP	25.74
MNM	54.30	MDN	71.80
BYS	84.87	GKP	33.18
ACH	44.52	KKD	19.42
MGL	76.98	ABP	19.85
HPS	39.02	DUD	29.51
ADS	39.02	AKP	69.45
NDS	51.89	KBS	28.95
AC2	42.22	KFP	35.67
HRS	52.07	GDP	27.51
AC1	23.24	OPN	19.60
NMD	28.22	PNS	21.12
NDT	25.28	AKM	71.64
OGM	101.66	DSM	54.15
SAS	168.47	DYP	33.98

Table 7  
Groundwater classification based on WQI.

WQI	Water Type	Number of Samples	Percentage of Samples
<50	Excellent water	24	67
50–100	Good water	9	25
100–200	Poor water	3	8

This shows their close relation, suggesting Na–Cl as the dominant water type. Lastly, similar to the PCA-2, cluster 2 represents the influence of anthropogenic activities, as evident by the clustering of K<sup>+</sup>, F<sup>-</sup>, and NO<sub>3</sub><sup>-</sup>, which are constituents of agrochemicals that may be runoff from farmlands.

4.3. Groundwater quality and suitability for domestic/drinking purposes

The predominant use of borehole water in the study locations is for domestic purposes, including cooking, drinking, and washing. Given the use and heavy reliance on this source of water, the quality of borehole water is critical due to its possible health implications. Of the parameters measured, EC and TDS had about 19% and 22% of samples reporting values outside of the WHO recommended limits, respectively. The value of EC is primarily an indication of the total dissolved ions present in water which is expressed as TDS. TDS is an essential parameter in water quality and represents the variety of solids dissolved in a solution, including chlorides, carbonates, bicarbonates, sulphates, calcium, magnesium, sodium and potassium (Adimalla and Taloor, 2020). The measured TDS values in this study are low compared to a similar study in the Accra plains, where about 75% of the borehole samples showed TDS ranging from 1000 to 10,000 with Na<sup>+</sup> and Cl<sup>-</sup> as the dominant ions (Kortatsi, 2006). However, similar results 148.1–4020.0 have been reported for TDS in groundwater samples from Ga West municipality (Saka et al., 2013). In this study, TDS ranged from 130.0 to 3314.0 mg L<sup>-1</sup>.

The values of TH were generally high, with about 36% of samples having values above 200 mg L<sup>-1</sup>, the recommended limit set by the WHO. The high levels of TH is a reflection of the generally high values of Ca<sup>2+</sup> ions. TH represents the total concentration of dissolved Ca<sup>2+</sup> and Mg<sup>2+</sup> ion concentrations in groundwater and may influence the taste of drinking water and reduce the effectiveness of detergents. Although there is a low association with health, water with TH values above 200 mg L<sup>-1</sup> has a high probability of causing scales deposition in pipes, water systems, and excessive use of soap and formation of scum (WHO, 2017). In about 11% of boreholes, pH values were lower than 6.5, the lower limit recommended by the WHO. Low pH values have no direct health effects. Nonetheless, the cause of the low pH and the increased dissolution of ions may introduce adverse health impacts for groundwater (WHO, 2017). Generally, acidity in groundwater is associated with granite-based minerals. In the current study, only about 6% of the groundwater samples reported a pH above 8.5. With nearly 97% of the boreholes occurring in the Dahomeyan and Granitoid, the observed pH levels may be attributable to the quartzo-feldspathic (acidic) and the mafic (basic) compositions of the gneiss in the Dahomeyan and the granites.

Overall, the concentration of ions in the groundwater samples were low and within acceptable limits. However, Cl<sup>-</sup> and Na<sup>+</sup> concentrations were above the recommended limits in 22%, and 11% of borehole samples studied, respectively. The ions with concentrations above their respective WHO guideline values have been shown in Fig. 8. Chloride was the most abundant anion present in the samples studied. This could be linked to the metamorphic nature of the terrain. The gneissic rocks of the Dahomeyan comprise minerals of quartz, feldspars, and variable proportions of micas (chlorite, muscovite, and biotite), and their alteration releases Cl, Mg, Fe etc in solution. The findings from this study show that about 22% of samples had high chloride concentrations above a recommended value of 250.0 mg L<sup>-1</sup>, with values ranging from 18.00

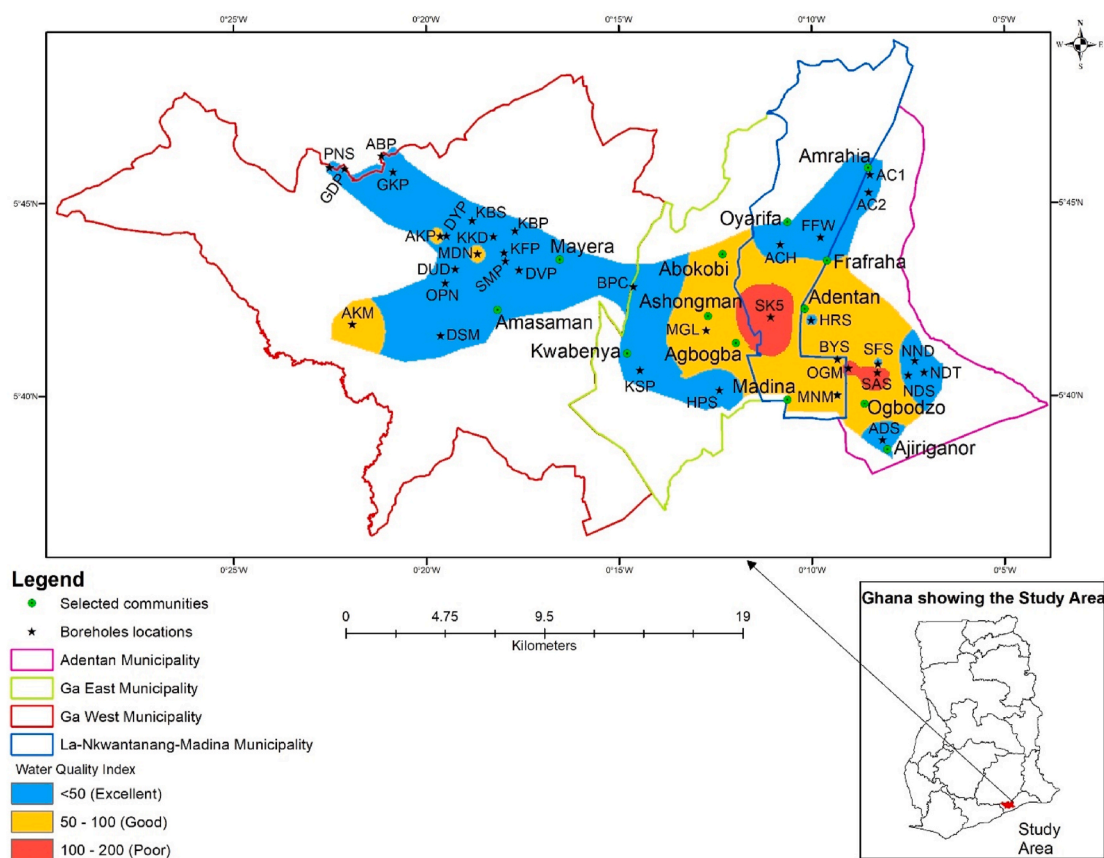


Fig. 7. Spatial distribution of water quality indices.

$\text{mg L}^{-1}$  to  $1099.0 \text{ mg L}^{-1}$ . While the level of chloride is generally low, the concentration of chloride in groundwater samples from SK5 and SAS were considerably high, with values of  $1099.0 \text{ mg L}^{-1}$  and  $993.0 \text{ mg L}^{-1}$ , respectively.

The excessive chloride content in groundwater, particularly near coastal areas, is generally found to be a result of seawater intrusion (Saka et al., 2013; Sunkari et al., 2019; Yidana et al., 2010). Nonetheless, domestic wastes, agricultural activities, municipal effluents and leaching from septic tanks have been suggested as possible sources of elevated levels of chloride in groundwater (Adimalla and Taloor, 2020). In a study of 164 boreholes, Kortatsi (2006) showed that the majority of the samples studied were moderately saline to brackish, with relatively high concentrations of chloride ranging from  $58 \text{ mg L}^{-1}$  to  $8511 \text{ mg L}^{-1}$ . These high levels may not only be considered a health hazard but also make the water corrosive and taste salty. As such, chloride in water is considered a vital contamination index.

Compared to  $\text{Cl}^-$ , other anions showed generally low levels and were well within acceptable limits for drinking water. For instance, in all samples, the maximum nitrate and fluoride concentrations measured were each  $<0.150 \text{ mg L}^{-1}$ . The low concentration of nitrates in the groundwater reflects the low impact of anthropogenic activities on the underground water systems, particularly from chemical fertiliser usage, sewage and wastewater (Barakat, 2020). In a review of over 80,000 research publications spanning 40 years from 1978 to 2017, Jia et al. (2020) have identified nitrates as the most frequently encountered pollutant in groundwater. Nitrates in groundwater are of particular concern as they have been linked to harmful health effects, including methemoglobinemia (blue-baby syndrome) in infants and the risk of stomach cancer (Adimalla et al., 2021; Shukla and Saxena, 2020). The major sources of nitrates in groundwater are agriculture and sewage waste (Burri et al., 2019). Sewage/manure has been estimated as the significant source (80%) of nitrates contamination in groundwater in the

lower volta river basin in Ghana (Egbi et al., 2020). In locations with inappropriately planned sanitation, pit latrines have been observed to contribute to high levels of nitrates in groundwater through underground discharges from latrines located nearby boreholes (Egbi et al., 2020). Nevertheless, high nitrate levels tend to be more prevalent in surface water and shallow groundwater. The results from this study suggest that nitrates are not a major challenge to groundwater quality, perhaps due to the lack of major agricultural activities and other major industrial activities in the location. At the same time, research shows that contaminant levels in groundwater may steadily build up to significantly high levels as groundwater undergoes contamination. For instance, Anornu et al. (2017) have shown that, after three decades, about 95% of groundwater in the Upper East Region of Ghana had nitrate levels above baseline concentrations. Given that the boreholes in this study are relatively new, the impact of anthropogenic pollutants such as nitrates is expected to be minimal. Nonetheless, the rapidly increasing human settlements and their attendant implications for anthropogenic activities are projected to have a more significant impact in the future.

Fluoride contamination of groundwater is known to be a major concern in Northern Ghana. Several studies have reported high fluoride concentrations in Northern Ghana and many other locations, particularly in coastal towns (Dongzagla et al., 2019; Ganyaglo et al., 2019; Loh et al., 2020; Rossiter et al., 2010; Sunkari et al., 2018; Sunkari and Abu, 2019; Zango et al., 2021). The high fluoride content is attributed to the underlying geology characterised by fluoride-bearing minerals such as fluorite and apatite in crystalline basement rocks of granite and Birimian (Alfredo et al., 2014). In this study, fluoride concentrations were low and ranged between  $<0.001 \text{ mg L}^{-1}$  and  $0.472 \text{ mg L}^{-1}$  with a mean value of  $0.124 \text{ mg L}^{-1}$ . The observed low levels may be due to the presence of variable proportions of micas in the study area. Higher values of fluoride ranging from  $0.21 \text{ mg L}^{-1}$  to  $1.88 \text{ mg L}^{-1}$  have been

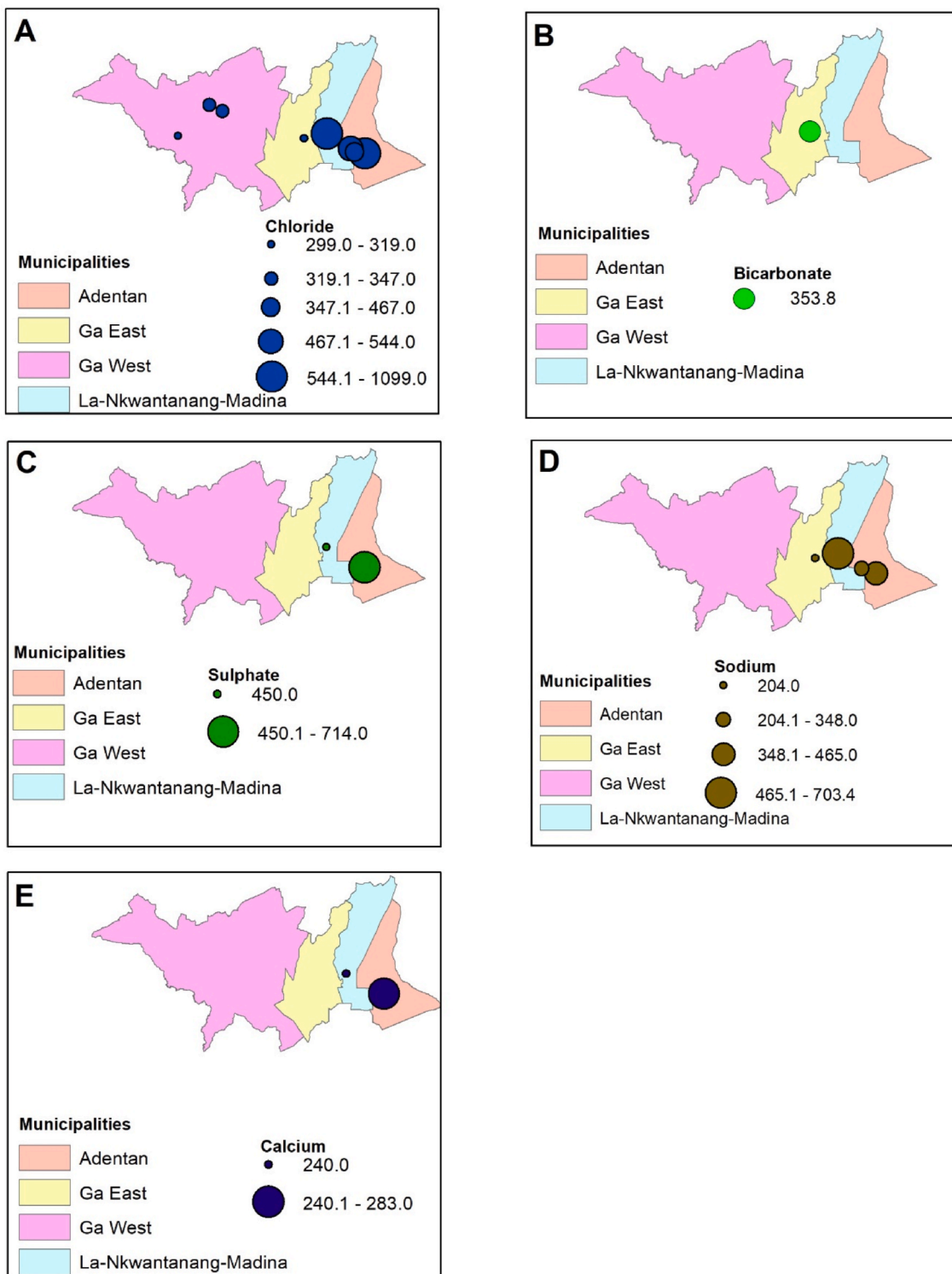


Fig. 8. Spatial distribution map of ions above their respective WHO Guideline values.

reported in the Ga West municipality of Ghana (Sunkari et al., 2019). The higher levels were suggested to be due to the possible dissolution of mica minerals. While fluoride is an essential element for human health, excess of it in the human body poses health risks. In moderate concentrations (0.7 mg L<sup>-1</sup> – 1.2 mg L<sup>-1</sup>), fluoride is believed to promote good teeth and bone development (Freeze and Lehr, 2009). However, higher intake (≥1.5 mg L<sup>-1</sup>) may result in dental fluorosis, particularly among children (Ganyaglo et al., 2019).

The samples from this study revealed sulphate concentrations

ranging from 10.0 mg L<sup>-1</sup> to 714.0 mg L<sup>-1</sup>. Based on the WHO guideline value of 250.0 mg L<sup>-1</sup>, two samples reported values beyond the recommended limit. The two samples, FFW and SAS showed sulphate concentrations of 450.0 mg L<sup>-1</sup> and 714.0 mg L<sup>-1</sup>, respectively. The concentrations of sulphates obtained in this study are higher than that obtained in a similar study of boreholes in Ga West Municipality by Sunkari et al. (2019), who reported a maximum sulphate concentration of 312.2 mg L<sup>-1</sup> and a mean value of < 60.0 mg L<sup>-1</sup>. In previous studies in Ghana, low levels of sulphates have been observed, with occasional

**Table 8**  
Statistical summary on the assessment of groundwater suitability for irrigation.

Parameter	Range	Water Status	Number of Samples	Percentage of Samples	Min	Max	Mean
EC	<250	Excellent	0	0	260	6628	1389.49
	250–750	Good	14	38.9			
	750–2250	Permissible	15	41.7			
	2250–5000	Doubtful	6	16.7			
	>5000	Unsuitable	1	2.8			
TH	<75	Soft	7	19.4	29.84	1065.94	247.42
	75–150	Moderately Hard	7	19.4			
	150–300	Hard	12	33.3			
	>300	Very Hard	10	27.8			
KI	<1	Safe	16	44	0.22	3.39	1.23
	>1	Unsuitable	20	56			
MH	<50	Suitable	30	83	28.77	80.57	40.73
	>50	Unsuitable	6	17			
PI	<25	Safe	0	0	28.32	106.56	70.50
	25–75	Moderate	23	64			
	>75	Unsafe	13	26			
SAR	<10	Excellent	35	97	0.60	10.21	3.29
	10–18	Good	1	3			
	18–26	Fair	0	0			
	>26	Poor	0	0			
%Na	<20	Excellent	1	3	18.70	77.37	51.35
	20–40	Good	7	19			
	40–60	Permissible	15	42			
	60–80	Doubtful	13	36			
	>80	Unsuitable	0	0			

high values in some borehole samples across the country (Anim-Gyampo et al., 2019; Bhattacharya et al., 2012; Ganyaglo et al., 2019; Gyamfi et al., 2019; Kulinkina et al., 2017; Loh et al., 2020; Rossiter et al., 2010; Yidana, 2010). Generally, high levels of sulphates in groundwater result from the presence of mudstone geology and the oxidation of sulphide and sulphate minerals, including pyrites (Chegbeleh et al., 2020). The oxidation process also leads to the formation of other ions, acids, and sometimes the release of heavy metals such as nickel and arsenic (Gejl et al., 2020). While the use of inorganic fertilisers may contribute to sulphate concentrations in groundwater, the absence of significant farming activities in the study area suggests that the influence of fertiliser, if any, may be minimal. Similar findings have been obtained for several boreholes in locations close to the sampling area (Sunkari et al., 2019). However, some significantly high values have been recorded in some locations in Ghana as a result of the dissolution of minerals or saline water intrusion (Rossiter et al., 2010; Yidana et al., 2010, 2012). In general, elevated concentrations of sulphate may affect the taste of water as well as cause gastrointestinal disorders.

The content of bicarbonate ions in the borehole water in this study ranged from 11.1 mg L<sup>-1</sup> to 353.8 mg L<sup>-1</sup>. Similar, albeit slightly, higher findings have been reported for groundwater in the Kwahu-Bombouaka group of the Voltaian basin. The level of HCO<sub>3</sub><sup>-</sup> concentration was attributed to their precipitation through soils and rocks (Sunkari et al., 2020). This process may be catalysed by the atmospheric reaction of carbon dioxide to form carbonic acid, which dissolves such minerals releasing HCO<sub>3</sub><sup>-</sup> and associated ions in the process (Loh et al., 2020). HCO<sub>3</sub><sup>-</sup> is normally one of the most abundant anions in groundwater and is largely formed from the dissolution of silicate minerals and atmospheric infusion of CO<sub>2</sub>, and decomposition of organic compounds. Fresh groundwater in coastal areas is predominantly Ca–HCO<sub>3</sub>, often resulting from the dissolution of carbonate minerals. However, Sunkari et al. (2019) have reported HCO<sub>3</sub><sup>-</sup> as the dominant anion in boreholes with values ranging from 350 mg L<sup>-1</sup> to 2000 mg L<sup>-1</sup> with an average of 674 mg L<sup>-1</sup> in boreholes from Ga West municipality. The high concentrations of HCO<sub>3</sub><sup>-</sup> is believed to arise from the weathering of and dissolution of magmatic and metamorphic rocks, including granites, phyllites and schists, given their fractured aquifer characteristics (Sunkari et al., 2019). The concentration of HCO<sub>3</sub><sup>-</sup> in the study is significantly lower.

The presence and concentrations of ions in the groundwater samples studied were primarily influenced by dissolution from underground

rocks belonging to the Togo Series, which forms part of the Dahomeyan Formation (Sunkari et al., 2019). The major minerals present include calcite, quartz, feldspars, dolomite, and muscovite. These rock-water interactions result in high concentrations of inorganic ions often found in groundwater in the study locations and in various parts of the country, exceeding WHO guideline values in some cases (Rossiter et al., 2010; Sunkari et al., 2020, 2022).

#### 4.4. Groundwater quality based on WQI

In recent years, WQI has become increasingly important in assessing the overall quality of groundwater by providing the composite influence of physical and chemical parameters in terms of a single value, the index number (Lumb et al., 2011). This weighted arithmetic index approach assigns weights ( $w_i$ ) to water quality parameters based on their perceived significance relative to health implications and groundwater potability. WQI has been applied in almost all major studies assessing water quality for drinking purposes (Adimalla et al., 2020; Asadi et al., 2020; Bhadra et al., 2020; Lumb et al., 2011; Shukla and Saxena, 2021; Tian et al., 2019). The WQI for each of the considered parameters were computed based on parameters and weights (Table 5), and the overall results for the various samples are presented in Table 6. Classification of the computed WQIs based on the model proposed by Sahu and Sikdar (2008) is presented in Table 7.

Based on Table 7, about two-thirds (67%) of groundwater samples are considered as “excellent”, 25% as “good” and 8% as “poor” in quality. Thus, 92% of groundwater from the boreholes studied are deemed potable and generally suitable for domestic purposes. However, samples from SK5, SAS, and OGM were found to be of poor quality. The poor quality is primarily due to the relatively high concentrations of ions including Na<sup>+</sup>, Ca<sup>2+</sup>, K<sup>+</sup>, Mg<sup>2+</sup>, Cl<sup>-</sup>, and SO<sub>4</sub><sup>2-</sup>, thus influencing values of EC, TDS, and TH. These high values are in agreement with similar studies in the greater Accra region (Kortatsi, 2006; Sunkari et al., 2019, 2022). The alteration of the common minerals in the quartzo-feldspathic rocks in the Dahomeyan and schist present in Togo Structural Unit in the study area could account for the observed levels of the ions. These ions are released through water interaction and the metamorphism of rocks. In addition, groundwater samples from SAS and OGM showed the highest levels of nitrates in all samples studied. While the reported nitrate concentrations were low and well within the WHO recommended

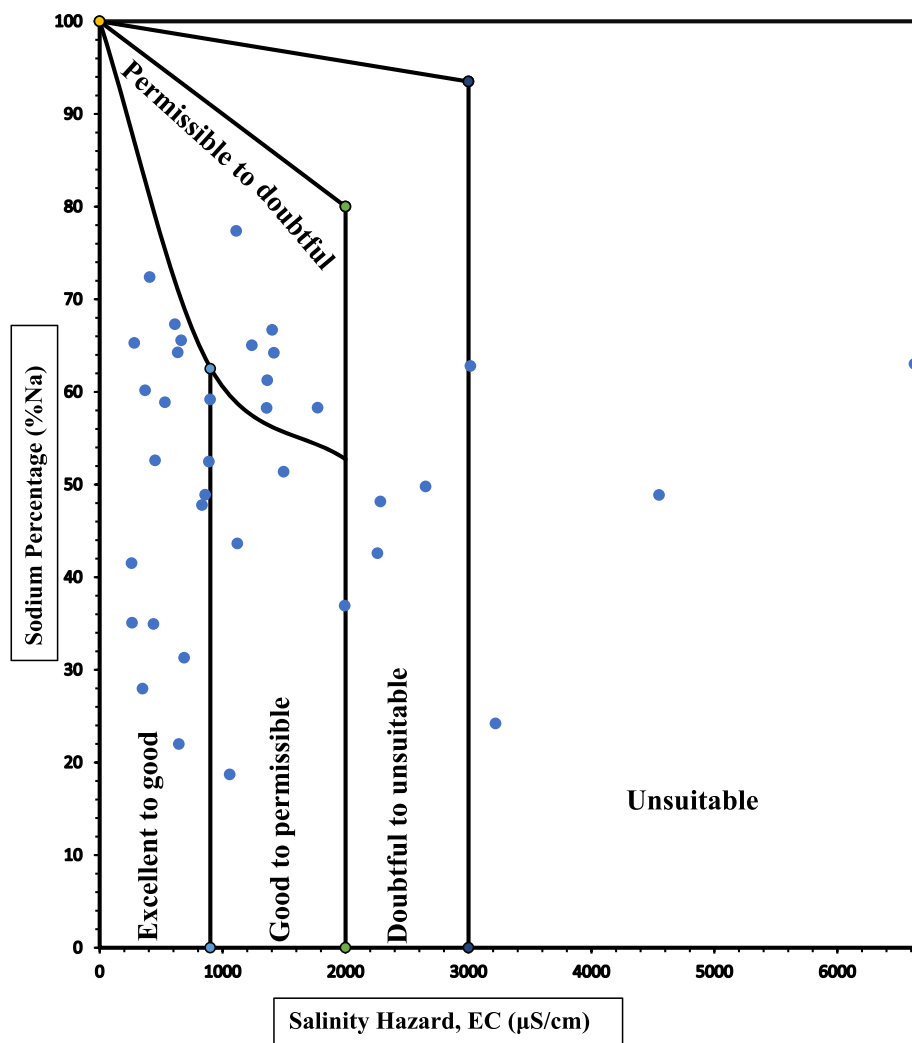


Fig. 9. Wilcox plot for groundwater categorisation for irrigation.

limits, the higher levels in these locations may be associated with localised contamination. Fig. 7 illustrates the spatial distribution of the computed WQIs interpolated based on an inverse distance weighting technique which produced the least root mean square error of 38.91.

#### 4.5. Groundwater suitability for irrigation

The quality of water for irrigation purposes largely depends on its mineral composition as this influences soil composition, structure and functions and has a resultant effect on plant health. As a result, several indices have been developed to estimate the suitability of groundwater resources for irrigation. In this study, several of these indices were utilised, and a statistical summary of the results of the assessment are presented in Table 8. Diagrammatic representations of these indices, including the use of Wilcox and USSS diagrams, are shown in Figs. 8 and 9.

##### 4.5.1. Kelly's Index (KI)

Kelly's index (KI) expresses the ratio between sodium ions versus calcium and magnesium ions present in groundwater and thus indicates the amount of sodium in water compared to calcium and magnesium. According to the index,  $KI > 1$  connotes an excess sodium ratio which is

unsuitable for irrigation, whereas  $KI < 1$  signifies a good sodium ratio suitable for irrigation purposes (Sundaray et al., 2009). Based on the results from this study, KI ranged from a minimum of 0.22 to a maximum of 3.39, with an average value of 1.23 (Table 8). The results suggest that groundwater from 44% of the boreholes studied are suitable for irrigation while 56% are unsuitable based on the Kelly index.

##### 4.5.2. Magnesium Hazard (MH)

The impact of magnesium on crop yield is significant, particularly when its concentration far exceeds that of calcium (Paliwal, 1972). As a result, a magnesium hazard (MH) index helps to measure the relative amount of magnesium in water and hence its possible impact on soil and crops when used for irrigation. In general, the concentrations of calcium and magnesium ions present in groundwater are in a state that maintains an equilibrium (Hem, 1985). A shift in equilibrium as a result of excess magnesium has a damaging effect on soil structure and crop yield (Sundaray et al., 2009). Based on the results obtained for groundwater in the present study (Table 8), MH values range between 29% and 81%, with an average of 41%. Overall, 83% of samples are considered suitable ( $MH < 50\%$ ) for irrigation while 17% are considered unsuitable ( $MH > 50\%$ ) based on magnesium hazard.

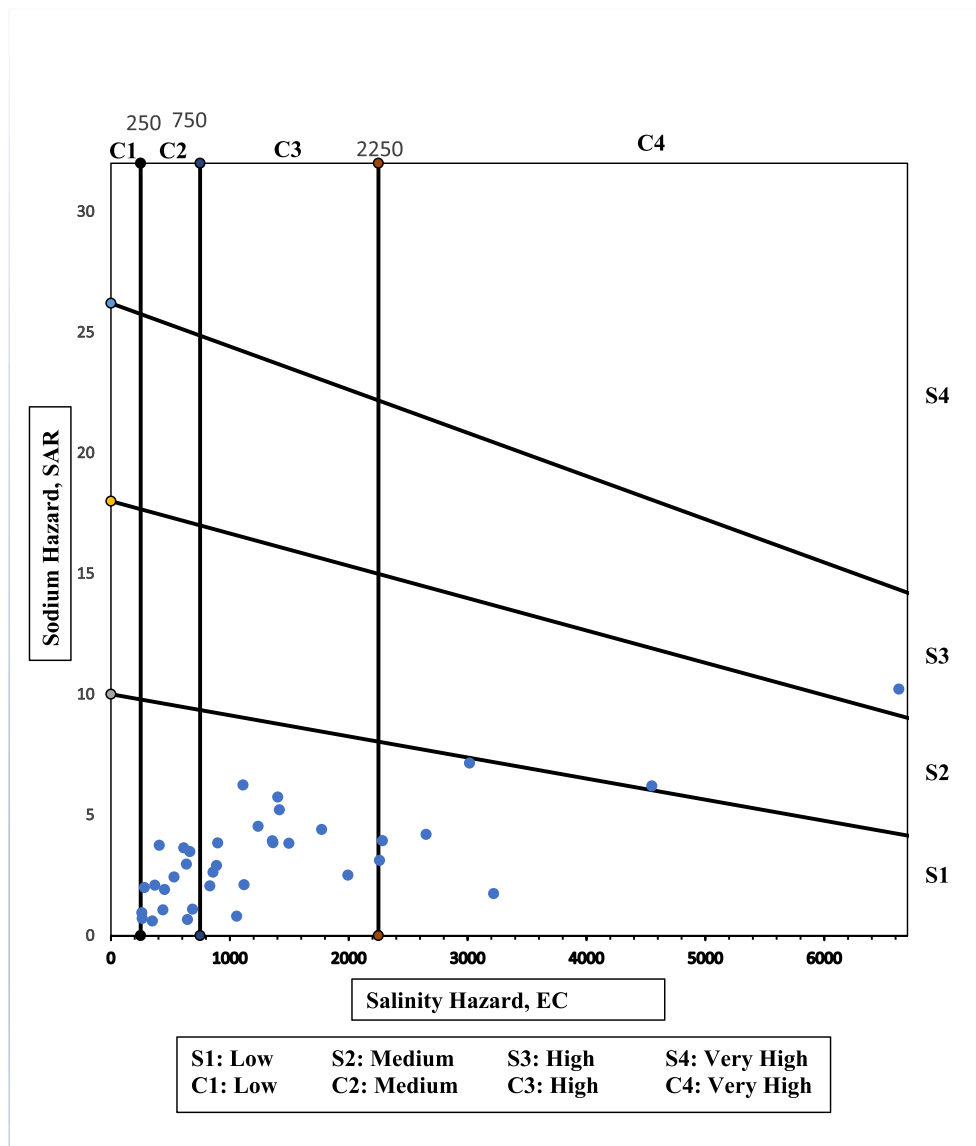


Fig. 10. USSSL diagram for groundwater classification for irrigation.

#### 4.5.3. Permeability Index (PI)

The permeability index (PI) measures the relative concentrations of  $\text{HCO}_3^-$  and  $\text{Na}^+$  to those of sodium, magnesium and calcium (Doneen, 1964). The poor quality of groundwater does not only have negative implications for crops but also soils. Such impact on soil is largely a result of the concentrations of dissolved ions particularly,  $\text{HCO}_3^-$ ,  $\text{Na}^+$ ,  $\text{Ca}^{2+}$ , and  $\text{Mg}^{2+}$ . These ions influence the permeability of soils, a vital parameter for the migration of dissolved minerals through soils and into plant roots. From Table 8, the PI values of the groundwater samples studied ranged from 28.32 to 106.56, with a mean of 70.50. These values suggest that 64% of groundwater in the study area are considered moderately safe (class II) for irrigation, while 36% of boreholes are deemed unsafe (class III) for irrigation based on Doneen classification (Doneen, 1964).

#### 4.5.4. Sodium absorption ratio (SAR)

Groundwater with relatively high  $\text{Na}^+$  concentration is associated with high SAR values, which result in the replacement of calcium and magnesium ions by sodium ions, becoming saturated with  $\text{Na}^+$  and thereby destroying soil structure. This makes the estimation of SAR of groundwater crucial in assessing their suitability for irrigation

(Richards, 1954). In the current study, all groundwater samples were deemed excellent (97%) or good (3%) for irrigation based on SAR values obtained (Table 8). Notwithstanding the generally high concentrations of sodium ions recorded in several groundwater samples, the optimal values of SAR reflect the equally high levels of calcium and magnesium ions in the samples studied. This resulted in SAR values of  $<10$  for almost all samples indicating their suitability for irrigation.

The USSSL diagram (Richards, 1954) further provides an important criterion for visualising and evaluating the quality of groundwater for irrigation based on SAR (sodium hazard) and EC (salinity hazard). This approach categorises each of SAR and EC into four groups: low; medium; high; and very high. The USSSL diagram of samples from the 36 boreholes studied are shown in Fig. 10. From this figure, the values of SAR were generally low, with about 94% of boreholes classified as low sodium hazard. On the other hand, the values of salinity were relatively high, with about 61% of boreholes categorised as high or very high. Based on Fig. 10, about 39% of boreholes were categorised in C2-S1 (medium salinity and low sodium hazard); another 39% of boreholes fell in the field of C3-S1 (high salinity and low sodium hazard); while about 14% of boreholes were categorised as C4-S1 (very high salinity and low sodium hazard). The remaining boreholes showed very high salinity with

either medium or high sodium hazards.

When used for irrigation, groundwater with high values of EC has the potential to accumulate salts in the soil, thereby promoting soil salinisation (Ghazaryan et al., 2020). This may impair the growth of crops by restricting water supply to the roots while also degrading the physical structure of soils. Based on data from the USSL diagram of the 36 boreholes analysed in this study, salinity may represent a concern for the potential use of the groundwater for irrigation purposes in about 19% of samples, despite the low values of SAR.

#### 4.5.5. Percentage sodium (%Na)

An excess amount of sodium ions ( $\text{Na}^+$ ) in irrigation water tends to replace calcium ( $\text{Ca}^{2+}$ ) and magnesium ( $\text{Mg}^{2+}$ ) ions within soil. This leads to reduced soil permeability and restricts the circulation of air and water resulting in the formation of dry and compact soils that are unsuitable for crop production (Collins and Jenkins, 1996). In the literature, %Na < 60% is considered suitable for irrigation (Wilcox, 1955; Yidana, 2010; Yidana et al., 2012). From Tables 8 and 3% of boreholes were categorised as “excellent” (%Na < 20%); 19% as “good” (20% < %Na < 40%); 42% as “permissible” (40% < %Na < 60%); and 36% as “doubtful” (60% < %Na < 80%) for irrigation purposes.

A graphical representation that gives a better understanding of the influence of %Na on irrigation is provided by the Wilcox classification, which plots values of %Na versus EC (Wilcox, 1955). Fig. 9 presents the computed %Na versus EC values on the Wilcox plot for sampled groundwater in this study. From the diagram, 50% of the borehole samples were classified as being “excellent to good” for irrigation, while 11% of samples were categorised as “unsuitable”. In general, the Wilcox diagram suggests that about 61% of the boreholes studied may be classified as suitable for irrigation purposes, whereas 19% are classified as unsuitable, with the remaining 20% falling in between these two classifications.

## 5. Conclusion

As groundwater resources become increasingly important in urban and peri-urban communities, the need for water quality assurance and management is imperative. By assessing the groundwater quality of 36 boreholes distributed in peri-urban communities in Accra, Ghana, this study has established the quality of water available to an estimated 630,000 inhabitants who rely on this source of water for domestic and irrigation purposes. The results of this study provide crucial information for groundwater development and management in Ghana’s capital city with a rapidly growing population.

The use of a variety of water quality indicators did not only help to provide sufficient information on the quality and suitability of the groundwater for varied purposes but also to increase the reliability of conclusions made in the study. The results from the WQI showed that 92% of the groundwater samples are of acceptable quality for domestic use, while the remaining 8% were classified as being of poor quality. Although the high percentage of groundwater of “good” quality portends well for groundwater development, the low quality of groundwater from some (8% of) boreholes suggests the need for caution in developing and sustaining the quality of groundwater resources in the communities.

In assessing the suitability of groundwater for irrigation, a diversity of indices that reflects varying emphasis and impacts of different ions, either separately or in combination with other ions, were applied. The findings from these assessments suggest that groundwater from the majority of boreholes studied is considered suitable for irrigation of crops. Nonetheless, several boreholes may require some level of treatment prior to their use for the irrigation of crops due to high levels of some ions. These findings are crucial considering the growing use of peri-urban landscapes for irrigated crop production.

The quality of water observed from the boreholes studied were mainly influenced by the presence and concentrations of dissolved ions

present, with  $\text{Na}^+$  and  $\text{Cl}^-$  being the dominant cation and anion, respectively. The observed levels of ions may be attributed to the mineral weathering of the rocks that underlain the terrain. The low levels of pollutants such as  $\text{NO}_3^-$  may reflect the lower impact of anthropogenic activities, new state of the boreholes, dept of wells and less developed residential settlements in the localities studied. Given the low impact of anthropogenic effects, the need for better management of these water resources is even more important, considering the potential harm to lives and the high cost of treatment of polluted water. As such, limiting groundwater pollution in the study area is crucial through appropriate land use, limiting runoff and discharge from agriculture and industries, respectively, and the education of inhabitants.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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