ORIGINAL ARTICLE

Assessment of seawater intrusion using ionic ratios: the case of coastal communities along the Central Region of Ghana

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Abstract

Seawater intrusion is a worldwide phenomenon resulting in groundwater quality challenges in coastal aquifers, which has prompted many investigations into its occurrence, sources, and age. To identify the origin of saline groundwater in the coastal communities of Central Region, Ghana, a combination of ten (10) different major ionic ratios—viz. Na/Cl, Mg/Cl, Ca/Mg, K/Cl, SO_4/Cl, Ca/ $(HCO_3 + SO_4)$, $(Ca + Mg)$/Cl, Cl/ $(SO_4 + HCO_3)$, Na/Ca and Ca/SO_4–and Base Exchange Index (BEX) computed from physico-chemical data on sixty-nine (69) boreholes in the communities have been analysed. The results show elevated levels of chloride concentrations in most of the groundwater in the study area, indicating salinization process by seawater intrusion. Also, the concentrations of the major ions (Na^+, Ca^{2+}, Mg^{2+}, and SO_4^{2-}) constituted more than 80% of the total dissolved solids and correlated well with Cl^-, indicating they are from a common source. The spatial variation of the combined effect of the different ionic ratios and BEX classifications showed that, most of the groundwater with high salinity may be due to seawater intrusion. Significantly, the study has delineated areas in the communities with poor groundwater quality arising from seawater intrusion; these areas need to be avoided in the development of the resource for water supply.

Keywords Seawater · Groundwater Quality · Ionic Ratios · Spatial Variation · Ghana

Introduction

Groundwater remains the most precious resource on earth as it serves as the only source of potable freshwater for over two (2) billion people worldwide (Giménez and Morell 1997; Todd and Mays 2005). Groundwater within coastal aquifers serves as an important source of potable water for the ever growing coastal populations (Jones et al. 1999). High salinity in most coastal aquifers has deteriorated their groundwater quality (Nadler et al. 1981; Jones et al. 1999; Moujabber El et al. 2006; Lee 2007; Nair 2016). Thus, groundwater in most coastal areas are becoming unsuitable for any use including domestic, industrial and irrigation purposes (Ganyaglo 2015). The high saline contents in some

of the coastal aquifers may be due to seawater intrusion, dissolution of rocks and other anthropogenic influences like irrigation returns (Martínez et al. 2009; Mtoni et al. 2013). Along the coastal regions, there often exist an interaction between groundwater and seawater. This interaction may intensify due to over-exploitation of the available freshwater in the coastal aquifers arising from the increasing populations and may lead to intrusion of seawater into the coastal aquifers.

Seawater intrusion process have been studied, monitored and mapped using different approaches like geochemical (Vengosh and Rosenthal 1994; Carol and Kruse 2012; Nair 2016) and geophysical (Kouzana et al. 2010) approaches. The characterization has focussed on the identification of the possible sources of the salinity in the coastal groundwater, the mode of transportation and the levels of contamination. The closeness to the coast may also have resulted in the associated elevated salinity observed in groundwater in most coastal areas.

According to Kazakis et al. (2016), seawater intrusion is a complex and geochemically interconnected phenomenon and, therefore, combinations of different indicators must be employed to verify its occurrences. However, seawater

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intrusion phenomenon has been investigated and/or studied, mapped, and monitored using different approaches including groundwater flow models, geochemistry, and geophysics. Isotopes and water chemistry can reveal seawater wedge theory, ages and transport pathways; this can indicate the sources of the saline water (Capenter 1978; Vengosh and Rosenthal 1994; Louvat et al. 1999; Ganyaglo et al. 2010, 2017). In coastal aquifers, reduction of groundwater table through over exploitation may cause seawater to flow in-land region degrading groundwater quality within the aquifer. Due to increasing demand for potable water for the growing population living in many coastal towns, and the desire to realize the United Nation's SDG number six (6) by accessing more groundwater to meet demands, it is imperative to study the movement of seawater in the coastal aquifers to predict their migration and possibly work out suitable preventive and remediation measures to minimize their effect.

Origin and ages of saline groundwaters have been predicted using isotopic studies (Carol et al. 2009) although this method may be costly and its applicability in developing countries like Ghana may hinder salinity studies. On the other hand, ionic concentrations of the major ions have been used to delineate groundwater salinity (Moujabber El et al. 2006). Bear et al. (1999) stated that in continental fresh groundwater, the dominant anions are bicarbonate (HCO_3) and sulphate (SO_4) and, if not polluted through anthropogenic sources, the dominant cations are Ca^{2+} and Mg^{2+} and, to a larger extent, the alkali ions (Na + and K +) but Ca^{2+} predominates over Mg^{2+} in most cases. However, Chloride (Cl^-) and Sodium (Na^+) are the dominant ions in seawater.

Groundwater quality can be assessed based on the concentrations of major ions dissolved in it (Todd and Mays 2005). This is because, naturally, the chemical composition of groundwater changes as it moves from a recharge point to discharge areas; so, the concentrations of major ions in water may help identify whether the groundwater has been polluted as a result of seawater intrusion (Sudaryanto and Naily 2018). During seawater intrusion process, the ratio of the major ions in the fresh water is highly affected due to freshwater-saltwater interactions (oxidation–reduction and ion exchange) (Giménez and Morell 1997; Stoessell 1997; Marimuthu et al. 2005; Zarei et al. 2012; Sudaryanto and Naily 2018). As a result, several ionic ratios have been proposed and used for identifying salinization associated with seawater intrusion in coastal aquifers; some of these ratios are Na/Cl, Ca/Mg, Ca/Na, and Cl/ ($HCO_3 + SO_4$) (Giménez and Morell 1997; Vengosh and Pankratov 1998; Kim et al. 2003a, b; Scheidleder 2003; Marimuthu et al. 2005; Panno et al. 2006; Lee 2007; Carol and Kruse 2012). The shifts in these molar ionic ratios may be associated with seawater intrusion phenomenon. These different ionic ratios appear to give dissimilar results due to their underlining differences; therefore, it is important to integrate their effects to arrive at

a more consistent conclusion. Vengosh and Rosenthal (1994) and Klassen et al. (2014) have indicated that the identification of seawater intrusion into fresh coastal groundwater should not be limited to the use of a single chemical parameter since it can be problematic. Therefore, to effectively determine seawater intrusion, more chemical parameters must be considered in the analysis stage to ensure availability of a combination of different ionic ratios for the assessment. These ionic ratios are used simply because "composition of groundwater also reflects the composition of its recharge in part independently of the material it contacted" (Stuyfzand 1993).

In this study, different ionic ratios are employed to assess the levels of possible seawater intrusion into the groundwater in the coastal communities within the Central Region of Ghana. Geographical Information System (GIS) has been used extensively in such groundwater studies (Machiwal et al. 2011; Pradhan 2014; Rao et al. 2016; Chang et al. 2019; Douaoui et al. 2019; Serele et al. 2019); thus, the Inverse Distance Weighted (IDW) interpolation method was used as an aid in spatial mapping of the ionic ratios over the study area. Monitoring and early detection of the origin of salinity are important for water management and successful remediation (Jones et al. 1999). Thus, the study is envisaged to help delineate areas that are heavily affected by the seawater intrusion to guide exploration and exploitation of groundwater resources within the study area.

Methodology

Description of study area

The study area is the coastal line of the Central Region of Ghana (Fig. 1), covering an area of approximately 230 km^2, and bounded by latitudes 5º 0′ and 5º 50′ N and longitudes 0º 20′ and 1º 40′ W. The region shares boundaries with the Ashanti and Eastern Regions to the north, Greater Accra Region to the east, Western Region to the west, and the Atlantic Ocean (Gulf of Guinea) to the south. The vegetation cover of the study area is predominantly coastal savannah, comprising grassland and few trees with semi-deciduous forest going inlands from the coast. The study area lies within the dry equatorial and moist semi-equatorial zones, and has a bimodal rainfall pattern; the annual rainfall ranges from 1000 mm along the coast to about 2000 mm in the interior. The wettest months are May–July and September–October, with the driest period occurring from December to February and a brief period in August. Mean monthly temperatures range from 24 °C in the coolest month (August) to about 30 °C in the hottest months (March–April) (Ghana Statistical Service 2013). Ground elevation ranges from sea level to about 379 m and rises with distance away from the sea with

Fig. 1 Study area with sampling points
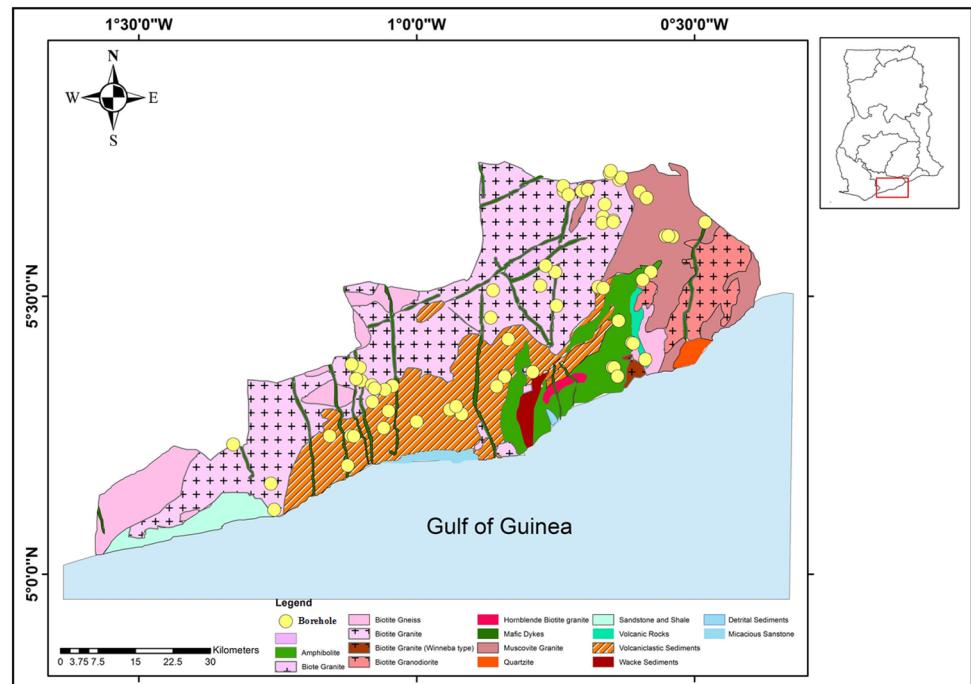
approximately 70% of the land area below 30 m (Adams et al. 2017).

The study area is underlain by the Birimian Supergroup, which is intruded by the basin granitoids and, to some extent, the sandstones and shales of Sekondian origin at the tail end of Elmina (Asiedu 2005), which lies unconformably on the Ajua shales (Fig. 1). There is also a biotite gneiss formation within the western part of the study area.

The granitoids exhibit some foliations, and all the rocks are crisscrossed by mafic dykes of predominantly doleritic composition (Grenholm 2011). Some of the rock types in the area include quartz diorite, tonalite, trondhjemite, granodiorite, adamellite, and granites. The main ferromagnesian mineral found in the basin type granitoids is biotite, which is commonly accompanied by muscovite. The basin granitoids occur as synorogenic foliated batholiths, chiefly in the central portions of the Birimian sedimentary basins; they are peraluminous and generally granodioritic in composition (Leube et al. 1990a, b). Primary porosity and permeability are absent in the rocks due to their mode of formations. Thus, groundwater accumulation and movement are mainly controlled by secondary porosity due to chemical weathering and development of secondary structures such as fissures and fractures.

Available drilling logs from the study area suggest that there are approximately three hydrostratigraphic units, viz. topsoil, completely weathered to slightly weathered rock and the fresh bedrock. The drilling logs also show an average overburden thickness (weathered zone) of 15 m, ranging between 3 and 32 m. Groundwater occurrence is controlled

mainly by secondary porosity in the weathered overburden (forming shallow unconfined aquifer) and fractures and/or fissures within the fresh basement rocks.

Data and methods

Sixty-nine (69) water quality datasets from different boreholes were collated from the reports for the study area (Fig. 1). These boreholes were all within distances of 2–40 km from the seashore. The boreholes were drilled for domestic water supply purposes and depths ranged from 31 to 80 m, with an average depth of 60 m. Also, depth from the ground level to water levels in the boreholes ranged from 1.8 to 20 m with an average of 9.33 m whereas the borehole yields, determined from available pumping test data, ranged between 6 and 60 L/min with a mean of 22 L/min.

Groundwater samples for laboratory water quality analyses were taken during the pumping test for each borehole (i.e., close to the end of the pumping phase). The sampling, storage and transportation of the groundwater samples and analytical protocols in the laboratory for this study followed the standards described in APHA (1995) and Appelo and Postma (2005) to ensure consistency in approach and data quality. The physico-chemical parameters of interest for this study were the pH, EC, and the concentrations of the major cations and anions –i.e., Ca^{2+}, Na^+, Mg^{2+}, K^+, HCO_3^-, NO_3^-, Cl^-, and SO_4^{2-}. The electrical conductivity (EC) and pH were measured in-situ using the portable HQ40d18 series meter. On the other hand, at the laboratory, concentrations of Na^+ and K^+ ions were determined using the Flame

Photometer, Ca^{2+} and Mg^{2+} were measured using Atomic Absorption Spectrometry (AAS), Cl^- and HCO_3^- concentrations were determined by titrimetry, SO_4^{2-} was analysed using Ultraviolet Spectrometer, and NO_3^- was determined with the Brucine reagent.

Data analyses

Prior to analyses of the data, the accuracy of the water quality data was assessed using the anion-cation balance approach, which assumes that water should be neutral, through computation of the charge balance error (CBE) (Domenico and Schwartz 1997) expressed as:

$$CBE = \frac{\sum |C| - \sum |A|}{\sum |C| + \sum |A|} \times 100 \qquad (1)$$

The CBE values showed majority of the water quality data were within the acceptable CBE value range of $\pm 5\%$, with just 7% of the data outside the range. Thus, the accuracy of the water quality data was assumed to be good for the subsequent analyses in the study.

The major ion concentrations were converted from mg/L to meq/L, which is a normalization procedure to take out the effect of the charges, prior to their analyses in the study. Ten (10) different ionic ratios used in delineating saline contaminated coastal groundwater (Nadler et al. 1981; Rosenthal 1988; Bear et al. 1999; Moujabber El et al. 2006; Lee 2007; Klassen et al. 2014; Klassen and Allen 2017) were determined. These groundwater chemical ionic ratios are Na/Cl, Mg/Cl, Ca/Mg, K/Cl, SO_4/Cl, Ca/($HCO_3 + SO_4$), (Ca + Mg)/Cl, Cl/($SO_4 + HCO_3$), Na/Ca and Cl/HCO_3. Descriptive statistical analyses were performed on the data using Statistical Package for the Social Sciences (SPSS) software to check first the normality of the data. Analysis of EC and chloride (Cl) were also done to check the possible correlation existing between them. These two parameters (EC and Chloride concentration) have been universally accepted as indicators for salinization of groundwater along many coastal aquifers; therefore, was appropriate to find their influence on the ionic ratios.

Base Exchange Indices (BEX) developed by Stuyfzand (1989) can also be used to distinguish if an aquifer is undergoing salinization or freshening. According to Klassen et al. (2014), the best index for a dolomite free aquifer system (Stuyfzand 1989) is BEX, given as:

$$BEX = Na + K + Mg - 1.0716Cl \text{ (meq/L)} \qquad (2)$$

Thus, BEX values were calculated for all the samples. A negative BEX value represents salinization and a positive BEX represents freshening whereas a BEX with a value of zero represents no base exchange.

Spatial maps of the ionic ratios were generated with the ArcGIS 10.4.1 software employing the Inverse Distance Weighted (IDW) interpolation technique. Since there are different spatial modelling techniques available for application in GIS, data exploratory analyses, involving checking the normality and trend of selection, were all done before the IDW interpolation method was selected. This method utilizes a defined or selected set of sample points for estimating output grid cell value and interpolates the values of a random field (e.g., concentrations of chemical constituents, ionic ratios, etc.) as a function of the geographic location from observation of neighbouring values (Ketata-rokbani et al. 2011). Individual spatial maps were generated for all the ten (10) ionic ratios to check the trend of salinity with respect to the ratios; subsequently, these maps were integrated using the overlay technique in ArcGIS environment.

Results and discussion

Evaluation of water quality parameters

Table 1 is a summary of the measured water quality parameters used in this study. The EC varies between 182 and 10,910 µS/cm with an average of 2010 µS/cm and about 50% of the total sampled water show EC value > 1000 µS/cm. Most of the sampled groundwater (90%) within 5–20 km (close to the sea) had EC between 1000 and 10,910 µS/cm. EC value of 1000 µS/cm and above is an indication of seawater intrusion (Giménez and Morell 1997; Kim et al. 2003a, b; Kim et al. 2019) and therefore most of the groundwater close to coastline are classified as saline water while the in-land groundwater (> 20 km) are considered fresh water.

Chloride (Cl^-) concentrations varies between 15 and 3673 mg/l with the highest concentrations recorded in groundwater sampled within 20 km radius from the coastline. Chloride ion is one of the single parameters used to show the occurrence of seawater intrusion due to its conservative native. High concentrations of chloride constitute

Table 1 Statistical analysis of the measured parameters

Parameter	Mean	Median	Min	Max	SD
EC (µS/cm)	2010.19	1033	182.0	10,910	2224.71
Cl (mg/l)	530.40	169	15.0	3673	742.68
SO_4 (mg/l)	152.50	54	0.3	1080	221.76
HCO_3 (mg/l)	147.81	120	0.1	508	99.58
NO_3 (mg/l)	0.17	0.06	0	1.91	0.31
Na (mg/l)	183.77	79.20	5.2	920	203.80
K (mg/l)	9.19	5.10	0.6	126	17.44
Ca (mg/l)	127.87	56.20	4.0	889	177.80
Mg (mg/l)	71.92	25.60	4.6	531	111.42

a major indicator of seawater intrusion; chloride constitute more than 55% of the total dissolve solids in seawater (Nadler et al. 1980; Jones et al. 1999; Panno et al. 2006). This makes chloride ion a very sensitive indicator of salinization of coastal groundwaters (Moujabber El et al. 2006). Coastal groundwater showing Cl concentrations above 1000 mg/l may have been contaminated with seawater intrusion. However, there may be other sources of higher chloride concentrations in groundwater such as septic system or animal manure sources and sea spray. There is a strong correlation ($r = 0.97$) between chloride concentrations and corresponding EC values (Fig. 2d) indicating chloride ions are controlling the electrical conductance of the coastal groundwater.

The concentrations of the major ions (Na^+, Ca^{2+}, Mg^{2+}, K^+, SO_4^{2-}, NO_3, HCO_3^-) and EC plotted against chloride are shown in Fig. 2a–h with their corresponding coefficient of determination (r^2) for the least squares' linear regression line listed on each plot. The r^2 ranges from 0.000013 to 0.97 in Fig. 2. The good linear coefficient of determination between the Cl and the other major ions (Na^+, Ca^{2+}, Mg^{2+}, and SO_4^2) may be explained as freshwater mixing with a single-brine chemistry (Stoessell 1997). Thus, the linear correlations on Fig. 2 imply that the saline pollution is from a single brine solution (seawater). When seawater intrudes fresh coastal aquifers, ion exchange reaction occur from the interaction between seawater and the aquifer matrix (Carol and Kruse 2012); the cation exchange reactions are Ca–Na and Ca–Mg reactions. During the exchange reaction, there is depletion of Na and Mg while the Ca is enriched; this enrichment may have caused the good correlation of determination between the calcium concentrations with the chloride ions. However, there were very poor coefficient of determination for potassium, nitrate, and bicarbonate ion concentrations; thus, their sources of origins may be different from that of chloride.

Ionic ratios analyses

Ten (10) ionic ratios determined from the measured concentrations from the samples in the study area are summarized in Table 2; the minimum (min), maximum (max), mean and standard deviations (SD) are presented. The maximum ratio (1820.33) was obtained in Cl/HCO_3 while, the minimum ratio was seen in K/Cl (0.002).

The major cause of high saline water in many coastal aquifers is from seawater intrusion. Vengosh and Rosenthal (1994) found out that saline water associated with seawater intrusion is characterized by low Na/Cl ratio relative to that of freshwater and seawater. Since Na and Cl ions are the dominant elements in the chemical composition of saline groundwaters, the Na/Cl ratio of saltwater intrusion are usually lower than the marine values (< 0.86, molar ratio) (Schoeller 1956). The Na/Cl ratio for the study area varies between 0.11 and 3.58 with approximately 64% of the sampled groundwater showing lower Na/Cl (< 0.86), which indicates seawater intrusion in the study area. Figure 3a shows the spatial variation of the Na/Cl ratio in the study area and indicates about 80% of the contaminated area are within 20 km distance (in-land) from the shoreline. The area with high Na/Cl ratio (> 1) may have been contaminated by anthropogenic activities as suggested by Vengosh and Rosenthal (1994). When seawater intrudes into the fresh coastal aquifer, there is a chemical exchange process between the seawater and coastal aquifer rocks (Mercado 1986; Nadler et al. 1980). Calcium (Ca^{2+}) replaces Na^+ resulting in depletion of Na^+ while Cl^- concentrations do not change and subsequently reduces the Na/Cl ratio.

Bicarbonate and carbonate ions are abundant in fresh groundwater while Cl^- generally occurs in small amounts in groundwater but dominates in sea water (Bear et al. 1999; Todd and Mays 2005). Seawater intrusion may be classified in terms of Simpson ratio ($Cl/HCO_3 + CO_3$), as suggested by Todd (1959), which varied between 0.24 and 1820.33 for study area. This ratio is suggested as a proper indicator and/or criterion for identifying seawater intrusion (Klassen et al. 2014; Sudaryanto 2018). Based on this, the groundwater is grouped into five classes; i.e., about 9% being good water (< 0.5), 19% is slightly contaminated (0.5–1.3), moderately contaminated (1.3–2.8) is 28%, 16% is injuriously contaminated (2.8–6.6) and approximately 30% is highly contaminated groundwater (> 6.6). The spatial variation of the $Cl/HCO_3 + CO_3$ ratio shown in Fig. 3b indicates that groundwater within the southern part of the study area is highly contaminated with seawater.

During seawater–freshwater interactions in coastal aquifers, Na^+ is lost to the aquifer matrix and replaced by Ca^{2+}. The enrichment of calcium has been used as seawater intrusion indicator for mapping seawater intruded areas in arid and semi-arid regions (Carol and Kruse 2012; Klassen et al. 2014; Moujabber El et al. 2006; Sudaryanto 2018). The $Ca/(HCO_3 + SO_4)$ ionic ratio varies between 0.140 and 14.58 for K/Cl ranges of 0.002–0.214, for Mg/Cl ranges of 0.066–1.687 and for SO_4/Cl of 0.02–1.574. The ionic ratio of $Ca/(HCO_3 + SO_4) > 1$ with corresponding low K/Cl, Mg/Cl and SO_4/Cl is used to delineate seawater intrusion (Jones et al. 1999). Approximately 30% of the sampled water recorded higher ratio (1.01–14.580) > 1 and may be classified as seawater intruded. In fact, all the samples with higher $Ca/(HCO_3 + SO_4)$ (> 1) also show Na/Cl < 0.86. The K/Cl ratio ranges between 0.002 and 0.120 for samples showing $Ca/(HCO_3 + SO_4) > 1$. Approximately 85% of the analysed samples recorded low K/Cl ratios lower than that of seawater (0.02); there is an increase in the chloride concentrations relative to that of K ions. When seawater moves into coastal aquifer, K^+ ions are adsorbed on clay particles, which lowers the K/C1 ratios in the water (Vengosh and Rosenthal

Fig. 2 Bivariate plots of some major ions and EC with Chloride ion
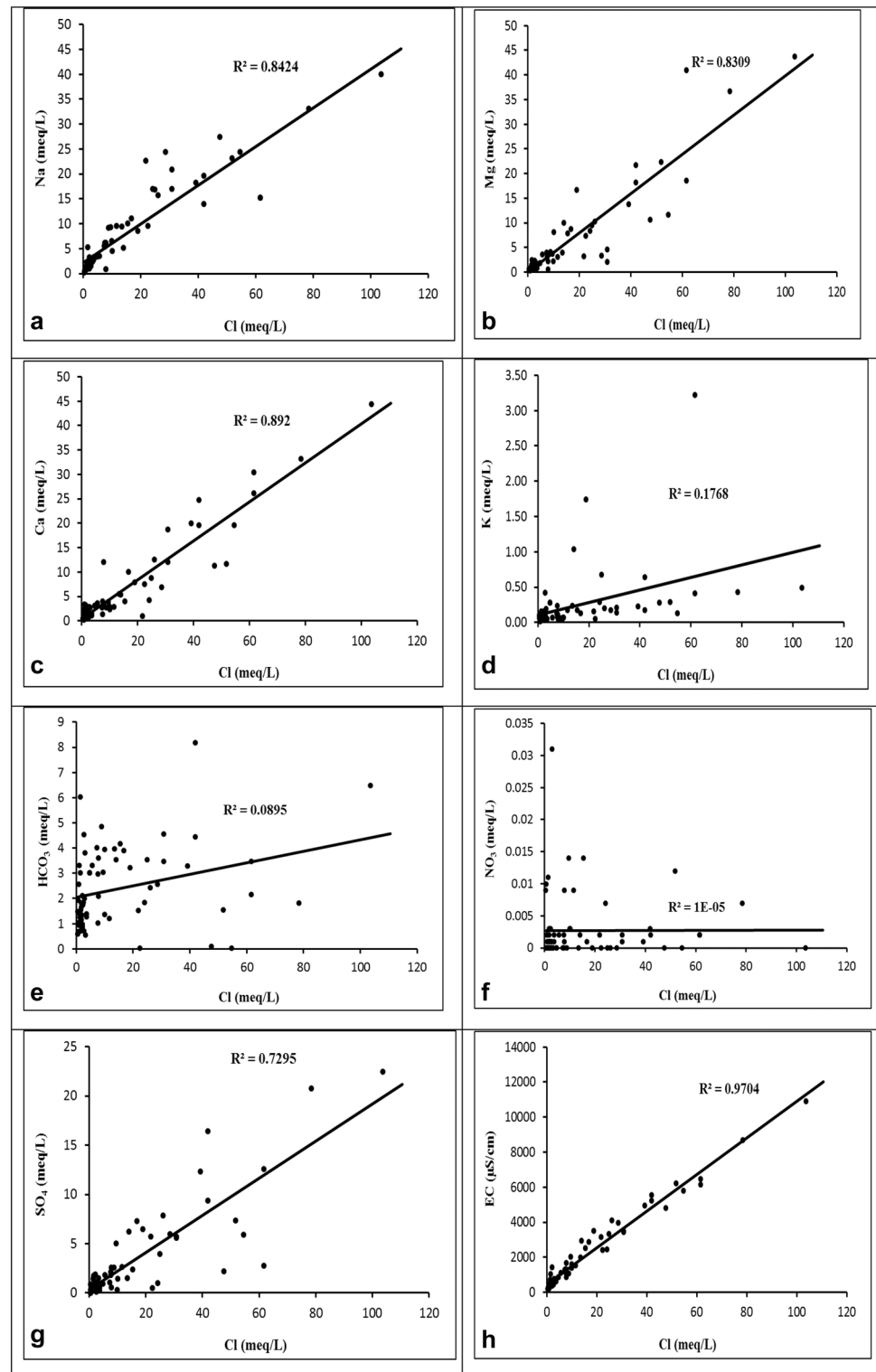
1994). Figure 4a, b show the spatial variations of the Ca/$(HCO_3 + SO_4)$ and K/Cl in the study area, respectively.

The Mg/Cl ratio varies between 0.066 and 1.120 with an average of 0.366; 95% of the sampled groundwater with Ca/$(HCO_3 + SO_4) > 1$ also show Mg/Cl ratios lower than obtained in seawater (< 1), which is an indication of increase in chloride ion concentrations. Figure 4c show the spatial variations of the Mg/Cl ratios. Sulphate (SO_4) and bicarbonates (HCO_3) are the dominant anions in continental freshwater (Domenico and Schwartz 1997) while

Table 2 Summary of the ionic ratios determined from the measured major ions

Ionic ratio	Min	Max	Mean	Median	SD
$Ca/(HCO_3 + SO_4)$	0.140	14.58	1.18	0.76	1.89
Na/Cl	0.110	3.58	0.83	0.76	0.47
Cl/HCO_3	0.240	1820.33	54.62	2.55	259.94
Ca/Na	0.050	13.83	1.07	0.80	1.68
(Ca + Mg)/Cl	0.200	3.66	1.20	0.91	0.79
Ca/Mg	0.280	9.15	1.59	1.20	1.45
SO_4/Cl	0.020	1.57	0.33	0.26	0.28
Mg/Cl	0.066	1.69	0.51	0.45	0.30
Ca/SO_4	0.181	48.00	3.50	2.10	6.02
K/Cl	0.002	0.21	0.04	0.02	0.04
$Cl/(HCO_3 + SO_4)$	0.197	43.08	2.91	1.40	5.80
BEX	− 29.061	6.72	-1.89	0.52	6.73

low concentrations are seen in seawater. When seawater intrudes freshwater, elevated concentration of the Cl^- ions reduces the SO_4/Cl ratio; the reduction may then be used as an indication for seawater intrusion. Figure 4d shows the spatial variations of this ratio in the study area. The SO_4/Cl ratio ranges from 0.022 to 1.083 for samples showing $Ca/(HCO_3 + SO_4) > 1$ with an average of 0.213. The ionic ratios (95%) of the examined samples have $(SO_4/Cl) < 1$, which indicates the dominance of Cl^- over SO_4^{2-} that corroborates the contamination of the aquifer by seawater intrusion (Abdalla 2015). All the ratios show that groundwater in proximity to the sea may have been influenced by seawater intrusion.

The Ca/Na ratio varies between 0.05 and 13.80 for the study area and 32% of the sampled water showed Ca/Na > 1, which is an indication of seawater intrusion as proposed by Giménez and Morell (1997). While Na^+ concentration decreases (aquifer matrix adsorption) as seawater intrudes fresh coastal water (Domenico and Schartz 1997; Giménez and Morell 1997), calcium (dominant) on the other end increases in concentration, resulting in higher Ca/Na ratio than found in seawater (approximately 0.42). The ratio was compared with samples showing high EC (> 1000) and Cl^- concentration (> 8.46 meq/L) for brackish water and it revealed that about 50% of the samples (with Ca/Na > 1) also had EC values greater than 1000 μS/cm whilst approximately 36% of this same high ratio samples had Cl^- concentrations higher than 8.46 meq/L. The spatial map (Fig. 4e) showing the spatial variations in the Ca/Na ratio indicates that, the western and most of the southern part of the study area may have been contaminated by seawater intrusion.

Calcium is dominant in the gneiss and the biotite granites than sodium concentrations; hence, the elevated concentrations may be due to the presence of calcium rich feldspars (plagioclase). Calcium enrichment results mainly from

cation exchange reactions and leads to elevated concentrations of calcium within the coastal area forming CaCl water type. The Ca/SO_4 ratio varies between 0.181 and 48 in the study area; the higher values (> 1) are indications of seawater intrusion into freshwater aquifers with approximately 45% of these samples also showing EC values above 1000 μS/cm (Lee 2007). The Ca^{2+} increases while the sulphate decreases in concentrations. The variation of the Ca/SO_4 ratio shown in Fig. 4f indicates 45% of the sampled communities have groundwater that may have been influenced by seawater intrusion. The southernmost part of the study area is seriously affected by seawater intrusion. Carpenter (1978) demonstrated that when seawater interacts with fresh coastal aquifer, the loss of sulphate has a corresponding increase in the calcium. Thus, there is a possibility of gypsum precipitation taking place.

The Ca/Mg ratio ranges between 0.28 and 3.66 in the study area with the highest ratio observed in the groundwater at Bogyano (Ekumfi District), which is underlain by the volcanoclastic sediments. The spatial map (Fig. 5b) indicates that the south-western part of the study area has significantly been affected by possible seawater-freshwater interactions.
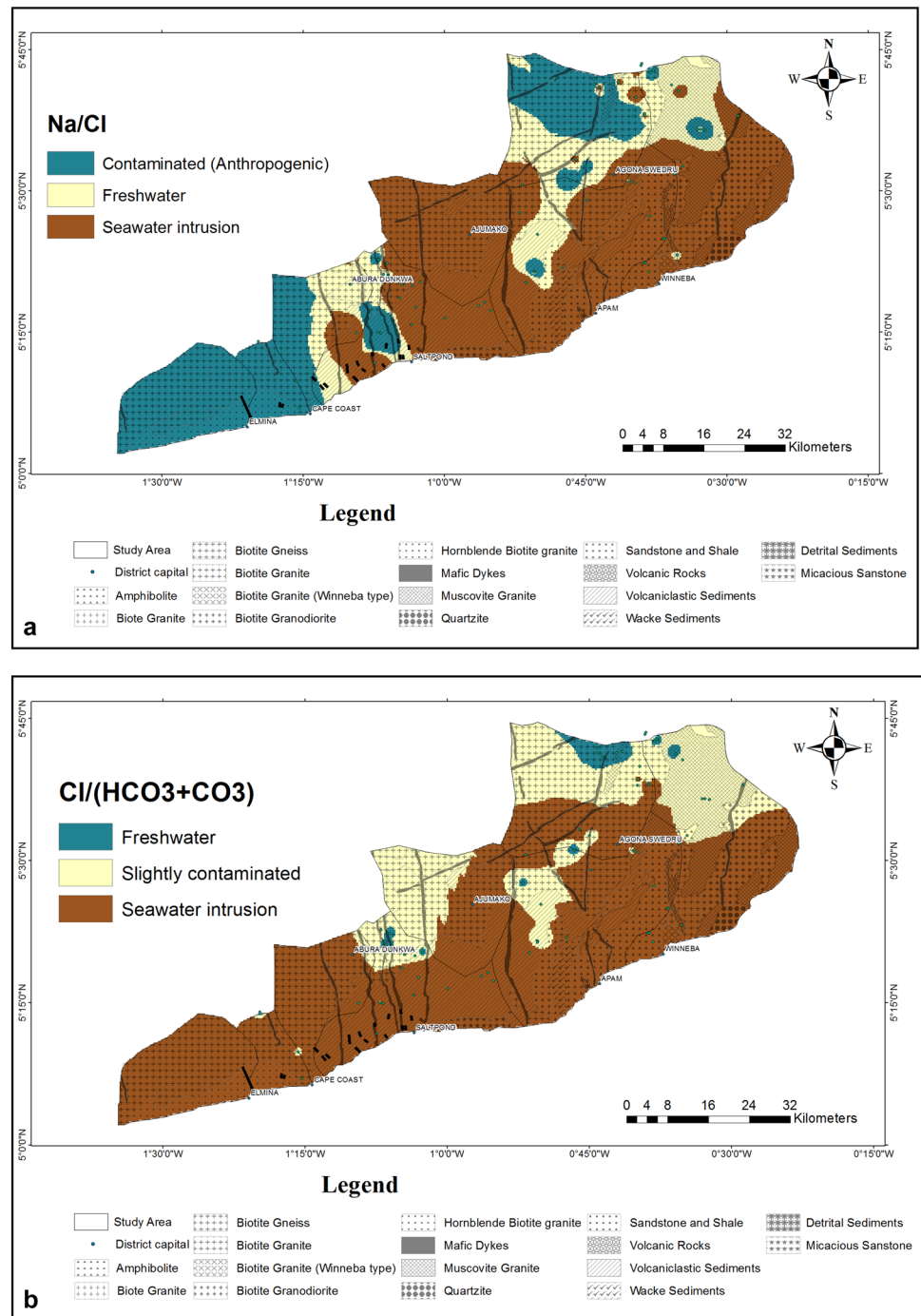
Integrated seawater intrusion

The different ionic ratios revealed different proportions of groundwater in the study area that are likely to be affected by the seawater salinization process. To get the complete effect from all the ionic ratios, the spatial maps for all ionic ratios were combined through the weighted overlay technique in ArcGIS. Figure 6 is the final combined spatial salinity variation map of the study area showing the three distinct levels of possible salinization zones: freshwater zone, slightly contaminated zone and seawater intruded zone. The freshwater zones occupy the northern part of the study area with few zones in the southern part while most of the shallow aquifers close to the shoreline have been affected by high salinity due, possibly, to seawater intrusion. Geologically, the most affected areas are underlain by the volcaniclastic sedimentary rocks, which were formed from clastic sediments of volcanic origin.

Literature reveals that, the study area falls within the Cape Coast basin, dominated mostly by dacitic volcaniclastics and wakes (Leube et al. 1990a, b). Abouchami et al. (1990) indicated that the rocks were deposited on a deformed and metamorphosed basement rocks as volcanic and sediments in an extensive geosyncline. The volcaniclastic sediments accumulated and were lithified; these processes may have created pathways for fluids to have easy flow through it. The salts may have also been entrapped into the sediments during the synorogenic geological activity (Hirdes et al. 1992).

Moreover, the sediments are dominated by basaltic lavas (Siedu et al. 2004), which contains mafic to ultramafic

Fig. 3 Spatial variations of **a** Na/Cl ionic ratio and **b** the Simpson's classification
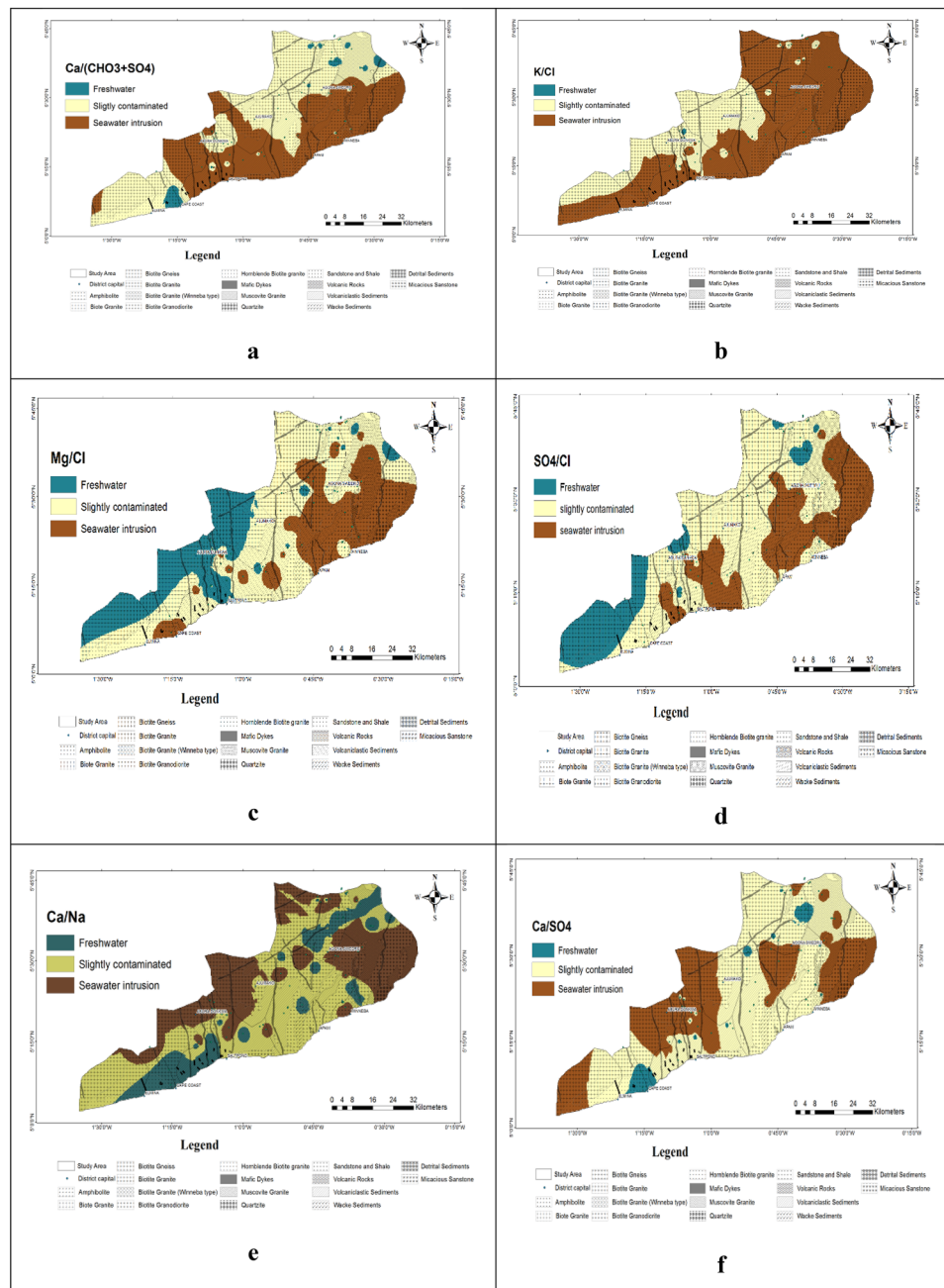

Groundwater water types

The Piper plot of the samples (Fig. 7) shows three distinct classes of the water types in the study area; viz. NaCl (43%), which may be from ancient marine and seawater intrusion sources, $MgHCO_3$ (20%) from freshwater sources, and mixed $CaMgCl$ (20%) and $CaCl$ (12%) may be a result of

minerals. The mafics are less resistant to weathering and in the presence of moisture and carbon-dioxide, chemical weathering will be intensive in creating pathways for the seawater intrusion. The felsic rocks are highly resistant to weathering; with their dominance in granitoids, chemical weathering and dissolution of the minerals may not be as intensive as in the mafics.

**Fig. 4** Spatial variations of some major ionic ratios in the study area

cation exchange reactions and deep gypsum source. The samples were however categorized into two (2) groups; groundwater samples with high Electrical Conductivity (EC) (> 1000 μS/cm), and low EC (182–1000 μS/cm) as seen in Fig. 7.

There was no $NaHCO_3$ water type found in the samples; this may be due to cation exchange processes where the Ca^+ from the freshwater $CaHCO_3$ replaces Na^+ from the intruding saline water, which may have led to the dominance of the mixed CaMgCl water type in some of the wells. However, the abundance of NaCl may be an indication of high salinity in the groundwater due to seawater intrusion since most of the NaCl water types were observed in boreholes close (within 2–5 km) to the seashore. Clark (2015) re-emphasized that low salinity groundwaters are dominated by Ca^{2+} and HCO_3^- resulting from mineral weathering by carbonic acid, while salinity in seawater-contaminated waters is dominated by highly soluble Na^+ and Cl^-. The EC characterisation of the water types revealed that about 50% of the NaCl water type samples also had high EC values above 1000 μS/cm.

Based on the chemical constituents in the groundwater, the dominant ions have been categorised into eight (8)

Fig. 5 Spatial variation of
(Ca + Mg)/Cl and Ca/Mg ionic
ratios
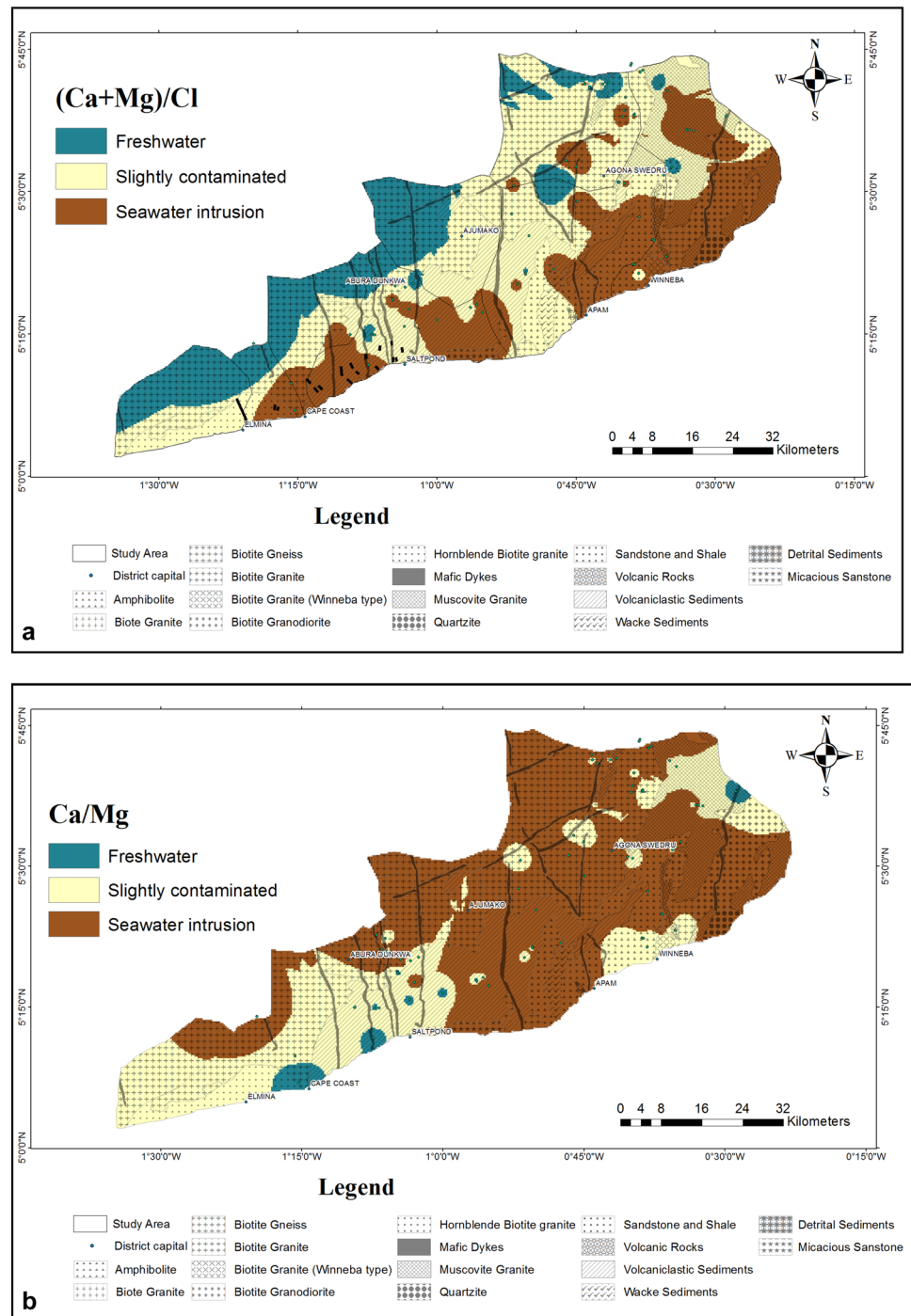
groups, with four (4) each in the two triangles (Fig. 7). Geochemical analysis by Leube et al. (1990a, b) on some sedimentary-basin granitoids (Cape Coast type) revealed that Na_2O element is the fourth most abundant element, making up approximately 4.37% of the elemental composition, with K_2O contributing approximately 3% by weight to the elemental composition of rocks. The abundances of these elements (Na_2O and K_2O) support the high proportions of the sodium and potassium concentrations in the groundwater

from the study area. Sodium and potassium may have been released slowly upon dissolution of these elements. Ca_2O is the fifth most abundant element in the granitoids found within the study area and, therefore, the dissolution of the rocks by the groundwater increases their contribution to the calcium content in the water.

The piper plots also show that about 35% of the samples occurring within the northern part of the region have higher concentrations of bicarbonate (HCO_3^-) than chloride; this

Fig. 6 Variation of the salinity from combined effects of all the ionic ratios
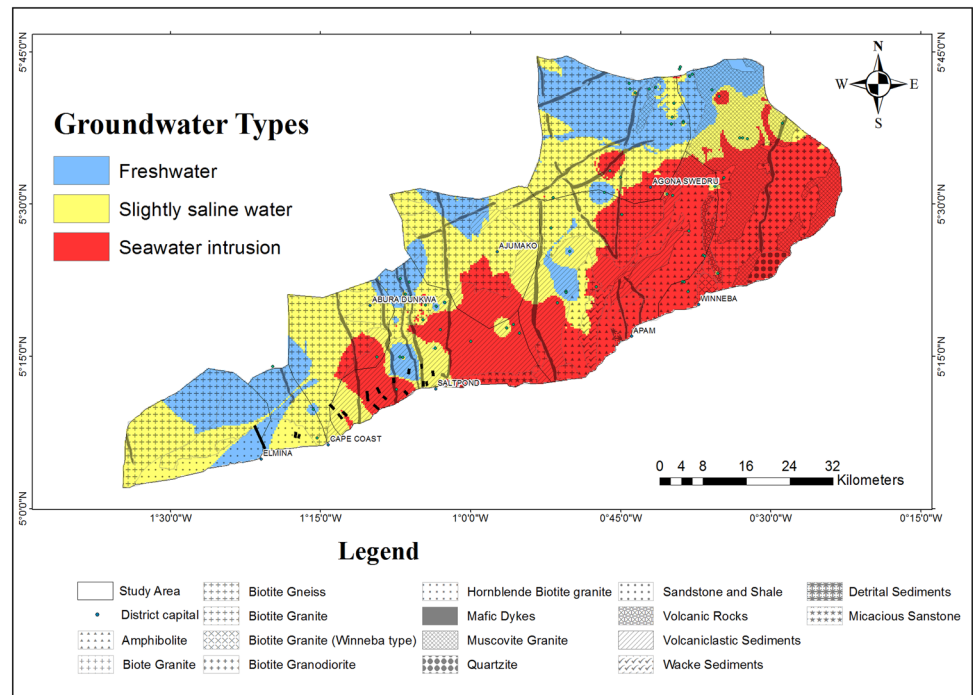
Fig. 7 Piper plot of the chemical constituents in the groundwater of the study area
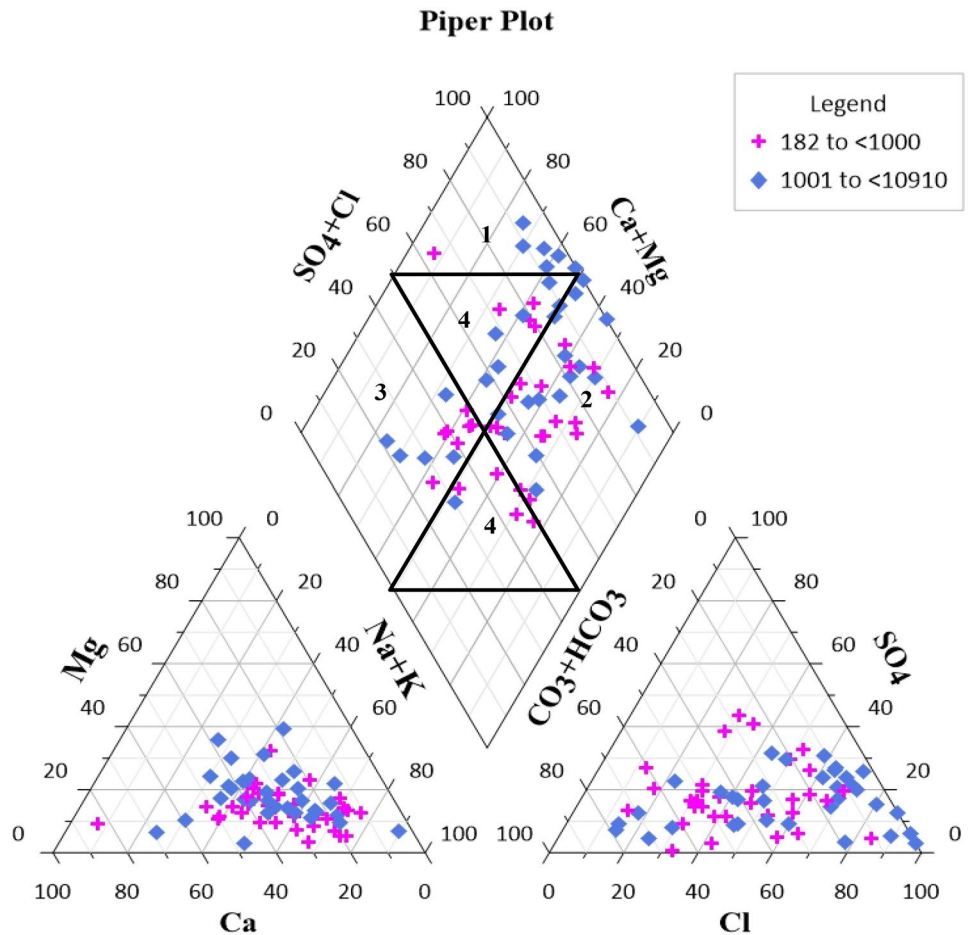
could add up to the existing phenomenon where the closer an abstraction point is to the sea, the higher the chloride concentrations.

Base exchange index

The computed BEX ranges between 29.061 and 6.717 in the study area with most boreholes close to the sea showing negative values (an indication of salinization). Approximately 32% of the samples analysed had negative BEX values, indicating an increase of (Na + Mg + K) in the sampled groundwaters relative to chloride ion concentration (Stuyfzand 1989, 1993, 2008). The spatial variation of BEX (Fig. 8) suggests that, most of the southern parts (close to the sea) of the study area are affected by salinization process.

Conclusion

The study has assessed the possibility of seawater intrusion being responsible for the elevated salinity in groundwater in the communities along the coast of the study area. Different major ionic indicators including bivariate plots, ionic ratios and BEX in a GIS environment were employed in the study. Results from the study indicate that the potential source of salinity in the area is characterized by freshwater–seawater mixing evidenced by high chloride ion concentrations (≥ 8 meq/L) and EC (> 1000 μS/cm).

The plots of the major ions (Na^+, Mg^{2+}, Ca^{2+}, and SO_4^{2-}) versus Cl^- showed a very good coefficient of determination (R^2) ranges with R^2 of 0.71 for SO_4, 0.83 for Mg, 0.84 for Na, 0.89 for Ca and 0.97 for EC. The good correlations indicate common source for the major ions and chloride in the groundwater. The different ionic ratios analysed indicated different levels of influence of the seawater intrusion (salinization) on the groundwater of the study area. The percent of influence is as follows: K/Cl (70%) > Ca/Mg (65%) > Na/Cl (64%) > Mg/Cl (48%) > Cl/(CHO$_3$ + CO$_3$) (46%) > Ca/Na (32%) > Ca/(HCO$_3$ + SO$_4$) (30%) > (Ca + Mg)/Cl (28%) > Ca/SO$_4$ (23%) > SO$_4$/Cl (16%).

Alkali elements (Na^+ and K^+) were the dominant cations, whiles Cl^- dominated over the other anions. The groundwater type in the study area is dominated by NaCl water type (43%), followed by the CaMgCl water type (20%), which may be due to cation exchange as seawater encroaches the fresh coastal aquifers.

BEX analyses show that 22 out of the 69 (32%) samples were indicative of salinization whereas the rest indicated freshening of the groundwater quality. The generated spatial map of the combined ionic ratios shows that, groundwater close to the sea is more likely to be affected by salinization due to seawater intrusion. It was also found that, geology plays an important role in the transport mechanism of the saline water into the coastal aquifers; groundwater in the volcaniclastic sediment formations are more highly affected by the salinization phenomenon than the granitoids. Importantly, zones in the study area where the groundwater is prone to seawater intrusion have been delineated for possible applications in the management and effective development of the groundwater resource.

Fig. 8 Spatial variations of BEX and distribution of water types
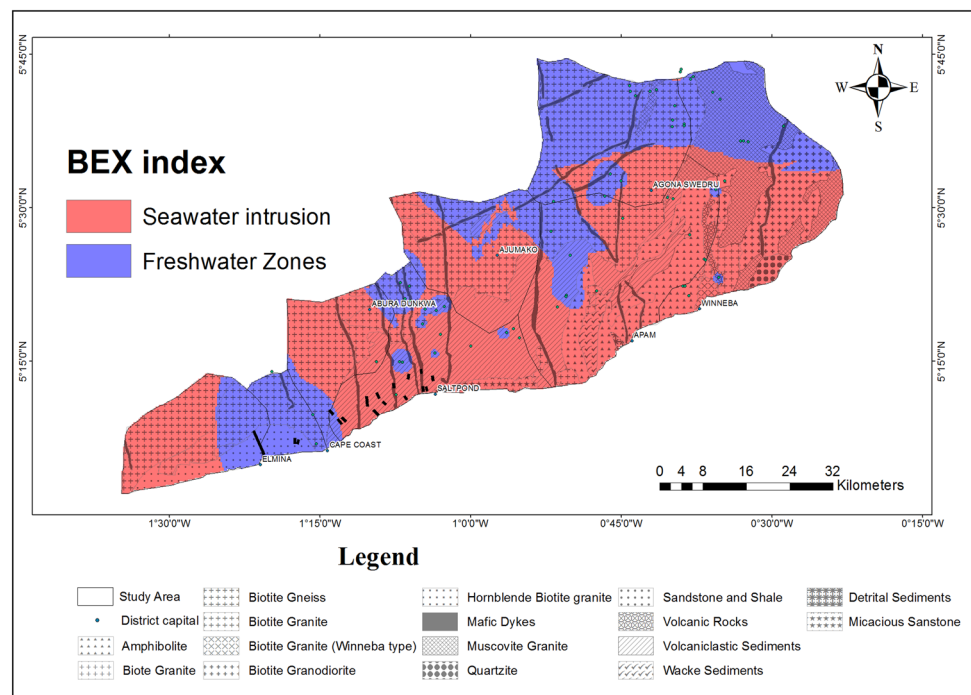
References

Abdalla F (2015) Ionic ratios as tracers to assess seawater intrusion and to identify salinity sources in Jazan coastal aquifer, Saudi Arabia. Arab J Geosci. https://doi.org/10.1007/s12517-015-2065-3

Abouchami W, Boher M, Michard A, Albarede F (1990) A Major 2. 1 Ga Event of Mafic Magmatism in West Africa' An Early Stage of Crustal Accretion regions from the manfie that growth from of sinking mobile of the Ahaggar [Lancelot work by Boher data, 1990) have shown major series of orogenic episodes. J Geol Res 95:605–629

Adams O, Donkor P, Kankam S, Mensah J (2017) A Planners' Guide to Integrated Coastal Management in the Central Region of Ghana. The USAID/Ghana Sustainable Fisheries Management Project (SFMP). Narragansett, RI. Coastal Resources Centre, Graduate School of Oceanography, University of Rhode Island; Spatial Solutions Limited, Accra; Hen Mpoano, Takoradi; and University of Ghana, Cape Coast, Ghana. GH 20 14 _ SC I037_SpS_HM_UCC. 65

American Public Health Association APHA (1995) Standard methods for the examination of water and wastewater, twentieth. American Public Health, Association (APHA), American Water Works Association (AWWA), and Water Pollution Control Federation (WPCF), New York, USA

Appelo CAJ, Postma D (2005) Geochemistry, groundwater and pollution, 2nd edn. A. A. Balkema Publishers, New York

Asiedu DK (2005) Provenance of late Ordovician to early Cretaceous sedimentary rocks from southern Ghana, as inferred from Nd isotopes and trace elements. J Afr Earth Sci 41:316–328. https://doi.org/10.1016/j.jafrearsci.2005.05.003

Bear J, Cheng AH, Sorek S, Ouazar D, Herrera I (1999) Seawater intrusion in coastal aquifers—concepts methods and practices. Springer-Science and Business Media, B.V

Capenter AB (1978) Origin and chemical evolution of brines in sedimentary basins. In: Thirteenth annual forum on the geology of industrail minerals. Michel TP-29 Perfector, 60–77

Carol ES, Kruse EE (2012) Journal of South American Earth Sciences Hydrochemical characterization of the water resources in the coastal environments the outer Río de la Plata estuary, Argentina. J South Am Earth Sci 37:113–121. https://doi.org/10.1016/j.jsames.2012.02.009

Carol E, Kruse E, Mas-pla J (2009) Hydrochemical and isotopical evidence of ground water salinization processes on the coastal plain of Samborombón Bay, Argentina. J Hydrol 365:335–345. https://doi.org/10.1016/j.jhydrol.2008.11.041

Chang SW, Chung I, Kim M, Tolera M, Koh G (2019) Application of GALDIT in assessing the seawater. Water 11:1–17

Clark I (2015) Groundwater geochemistry and isotopes. CRC Press, Taylor & Francis Group, New York

Domenico PA, Schwartz WF (1997) Physical and chemical hydrogeology. John Wiley & Sons Inc, New York, USA

Douaoui A, Bradai A, Bennacer A, Fernández PM (2019) Application of kriging techniques for assessing the salinity of irrigated soils: the case of El Ghrous perimeter, Biskra. Spanish J Soil Sci 9:105–124. https://doi.org/10.3232/SJSS.2019.V9.N2.04

El Moujabber M, Samra BB, Darwish T, Atallah T (2006) Comparison of different indicators for groundwater contamination by seawater intrusion on the Lebanese Coast. Water Resour Manag 20:161–180. https://doi.org/10.1007/s11269-006-7376-4

Ganyaglo SY (2015) Hydrogeochemical and Isotopic Studies of Groundwater in Coastal Aquifers of Ghana: case study in the Central Region. PhD Thesis, University of Ghana.

Ganyaglo SY, Osae S, Akiti TT, Gibrilla A, Bam E (2010) Hydrogeochemical and isotopic studies of groundwater in the Central Region of Ghana. IAEA Symp Isot Hydrol 133:12665

Ganyaglo SY, Osae S, Akiti T, Armah T, Vitvar T, Ito M, Otoo IA, Ganyaglo SY, Osae S, Akiti T, Armah T (2017) Application of geochemical and stable isotopic tracers to investigate groundwater salinity in the Basin. Ochi-narkwa Hydrol Sci J 00:1–16. https://doi.org/10.1080/02626667.2017.1322207

Giménez E, Morell I (1997) Hydrogeochemical analysis of salinization processes in the coastal aquifer of Oropesa (Castellón, Spain). Environ Geol 29:118

Grenholm M (2011) Petrology of Birimian Granitoids in Southern Ghana: Petrography and Petrogenesis, Bachelor thesis, Department of Earth and Ecosystem Sciences, Division of Geology, Lund University

Hirdes W, Davis DW, Eisenlohr BN (1992) Reassessment of Proterozoic granitoid ages in Ghana on the basis of U/P b zircon and monazite dating. Precambrian Res 56:89–96

Jones BF, Vengosh A, Rosenthal E, Yechieli Y (1999) Geochemical investigation of groundwater quality. Seawater Intrusion in Coastal Aquifers-Concepts, Methods and Practices, Springer: Kluwer, The Netherlands, pp 51–71

Kazakis N, Pavlou A, Vargemezis G, Voudouris KS, Soulios G, Pliakas F, Tsokas G (2016) Seawater intrusion mapping using electrical resistivity tomography and hydrochemical data. An application in the coastal area of eastern Thermaikos Gulf. Greece Sci Total Environ 543:373–387. https://doi.org/10.1016/j.scitotenv.2015.11.041

Ketata-rokbani M, Gueddari M, Bouhlila R (2011) Use of geographical information system and water quality index to assess groundwater quality in El Khairat Deep Aquifer (Enfidha, Tunisian Sahel). Iran J Energy Environ 2:133–144

Kim J, Kim R, Koh D, Cheong T, Lee J (2003a) Application of cluster analysis for the hydrogeochemical factors of saline groundwater in Kimje. Korea Geosci J 7:313–322

Kim Y, Lee K, Koh D, Lee D, Lee S, Park W, Koh G, Woo N (2003b) Hydrogeochemical and isotopic evidence of groundwater salinization in a coastal aquifer : a case study in Jeju volcanic island. Korea J Hydrol 270:282–294

Kim R, Kim J, Ryu J, Koh D (2019) Hydrogeochemical characteristics of groundwater influenced by reclamation, seawater intrusion, and land use in the coastal area of Yeonggwang. Korea Geosci J 23:603–619

Klassen J, Allen DM (2017) Assessing the risk of saltwater intrusion in coastal aquifers. J Hydrol 551:730–745. https://doi.org/10.1016/j.jhydrol.2017.02.044

Klassen, J., Allen, D.M., Kirste, D., 2014. Chemical Indicators of Saltwater Intrusion for the Gulf Islands , British Columbia.

Kouzana L, Benassi R, Ben mammou A, Sfar felfoul M (2010) Geophysical and hydrochemical study of the seawater intrusion in Mediterranean semi arid zones. Case of the Korba coastal aquifer (Cap-Bon, Tunisia). J Afr Earth Sci 58:242–254. https://doi.org/10.1016/j.jafrearsci.2010.03.005

Lee J (2007) Groundwater chemistry and ionic ratios in a western coastal aquifer of Buan, Korea: implication for seawater intrusion. Geosci J 11:259–270

Leube A, Hirdes W, Mauer R, Kesse GO (1990a) The early proterozoic birimian supergroup of ghana and some aspects of its associated gold mineralization. Precambrian Res 46:139–165

Leube A, Hirdes W, Mauer R, Kesse GO, RohstoffeKesse GGO (1990b) The early proterozoic birimian supergroup of Ghana and some aspects of its associated gold mineralization. Precambrian Res 46:139–165

Louvat D, Luc J, Franc J (1999) Origin and residence time of salinity in the Aspo groundwater system. Appl Geochem 14:917–925

Machiwal D, Jha MK, Mal BC (2011) Assessment of groundwater potential in a semi-arid region of india using remote sensing, GIS and MCDM techniques. Water Resour Manag. https://doi.org/10.1007/s11269-010-9749-y

Marimuthu S, Reynolds DA, Gal CL, Salle L (2005) A field study of hydraulic, geochemical and stable isotope relationships in a coastal wetlands system. J Hydrol 315:93–116. https://doi.org/10.1016/j.jhydrol.2005.03.041

Martínez J, Benavente J, García-Aróstegui JL, Hidalgo MC, Rey J (2009) Contribution of electrical resistivity tomography to the study of detrital aquifers affected by seawater intrusion-extrusion effects: the river Vélez delta (Vélez-Málaga, southern Spain). Eng Geol 108:161–168. https://doi.org/10.1016/j.enggeo.2009.07.004

Mercado A (1986) The use of hydrgeochemical patterns in carbonate sand and sandstone aquifers to identify intrusion and flushing of saline water. Ground Water 23:635–645

Mtoni Y, Chikira ICM, Bakundukize C, Van Camp M, Martens K, Walraevens K (2013) Saltwater intrusion and nitrate pollution in the coastal aquifer of Dar es Salaam Tanzania. Environ Earth 70:1091–1111. https://doi.org/10.1007/s12665-012-2197-7

Nadler A, Magaritz M, Mazor E (1980) Chemical reactions of seawater with rocks and freshwater: experimental and field observations on brackish waters in Israel. Geochim Cosmochim Acta 44:879–886

Nadler A, Koyumdjisky H, Dan J (1981) The use of Na/Cl ratios to trace solute sources in a semiarid zone. Water Resour Res 17:602–608

Nair IS (2016) Assessment of seawater intrusion in an alluvial aquifer by hydrochemical-isotopic signatures and geochemical modelling, PhD thesis, Faculty of Science and Humanities, Anna University

Panno SV, Hackley KC, Hwang HH, Greenberg SE, Krapac IG, Landsberger S, Kelly DJO (2006) Characterization and identification of Na–Cl sources in ground water. Ground Water 44:176–187. https://doi.org/10.1111/j.1745-6584.2005.00127.x

Pradhan B (2014) Groundwater potential zonation for basaltic watersheds using satellite remote sensing data and GIS techniques Groundwater potential zonation for basaltic watersheds using satellite remote sensing data and GIS techniques. Cent Eur J Geosci Groundw. https://doi.org/10.2478/v10085-009-0008-5

Rao YS, Jugran DK, Rao YS (2016) Delineation of groundwater potential zones and zones of groundwater quality suitable for domestic purposes using remote sensing and GIS. Hydrol Sci J 6667:821–833. https://doi.org/10.1623/hysj.48.5.821.51452

Rosenthal E (1988) Hydrochemical changes induced by overexploitation of groundwater at common outlets of the Bet Shean-Harod multiple-aquifer system Israel. J Hydrol 97:107–128

Scheidleder A (2003) Indicator fact sheet (WQ03b) saltwater intrusion. European Environment Agency. http://www.eea.europa.eu/dataandmaps/indicators/saltwater-intrusion/saltwater-intrusion. Accessed 20 Feb 2020

Serele C, Perez-hoyos A, Kayitakire F (2019) Geoscience Frontiers Mapping of groundwater potential zones in the drought-prone areas of south Madagascar using geospatial techniques. Geosci Front. https://doi.org/10.1016/j.gsf.2019.11.012

Ghana Statistical Service (2013) 2010 Population and housing Census: regional analystical report. Central Region

Schoeller H (1956) Geochemie des eaux souterraines.Application aux eaux des gisements de petrole, Soc. Ed. Technip, Paris, pp 213

Siedu DKA, Ampare SBD, Akyi PASS, Akubo BBA, Sae SO (2004) Geochemistry of Paleoproterozoic metasedimentary rocks from the Birim diamondiferous field, southern Ghana: implications for provenance and crustal evolution at the Archean-Proterozoic boundary. Geochem J 38:215–228

Stoessell RK (1997) Delineating the chemical compoition of salinity sources for saline water: an example from east-central Concordia parish, Louisiana. Ground Water 35:409–417

Stuyfzand PJ (1989) A new hydrochemical classification of water types. In: Regional characterization of water quality. The Netherlands Waterworks Testing and Research Institute KIWA, BB Niewegein, The Netherlands, pp 89–98

Stuyfzand PJ (1993) Hydrochemistry and hydrology of the coastal dune area of the Western Netherlands, PhD, Vrije Universiteit Amsterdam

Stuyfzand PJ (2008) Base exchange indices as indicators of salinization or freshening of (coastal) aquifers. In: 20th salt water intrusion meeting. Naples, Florida, USA, pp 262–265

SudaryantoNaily W (2018) Ratio of major ions in groundwater to determine saltwater intrusion in coastal areas. Earth Environ Sci 118:5

Todd DK (1959) Ground water hydrology. United States. John Wiley and Sons. Inc. pp 277–294

Todd DK, Mays LW (2005) Groundwater Hydrology, 3rd edn. John Wiley & Sons Inc, United States of America

Vengosh A, Pankratov I (1998) Cloride/bromide and chloride/flouride ratios of domestic sewage effluents and associated contaminated groundwater. Ground Water 36:815–825

Vengosh A, Rosenthal E (1994) Saline groundwater in Israel: its bearing on the water crisis in the Country. J Hydrol 1694:389–430

Zarei M, Raeisi E, Merkel BJ (2012) Identifying sources of salinization using hydrochemical and isotopic techniques Konarsiah, Iran. Environ Earth Sci. https://doi.org/10.1007/s12665-012-2143-8